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Ray

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(54) SIGNAL CUEING USING AN IIR FILTER ARRAY WITH INVERTED STATE TREE

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(22) Filed: **May 11, 2020**

(51) **Int. Cl.**

H04B 1/7093	(2011.01)
H04B 1/10	(2006.01)
H04B 1/00	(2006.01)
H03H 17/00	(2006.01)
H03H 17/02	(2006.01)

(52) **U.S. Cl.**
CPC ***H04B 1/7093*** (2013.01); ***H03H 17/0063*** (2013.01); ***H03H 17/0288*** (2013.01); ***H04B 1/0078*** (2013.01); ***H04B 1/1036*** (2013.01); *H03H 2017/009* (2013.01)

(58) **Field of Classification Search**
CPC .. H04B 1/7093; H04B 1/0078; H04B 1/1036; H03H 17/0063; H03H 17/0288; H03H 2017/009
USPC 375/232–235, 316, 343, 349, 350
See application file for complete search history.

(56) References Cited

U.S. PATENT DOCUMENTS

5,640,416	A *	6/1997	Chalmers	H04B 1/7085 375/147
6,256,337	B1 *	7/2001	Hendrickson	H04L 1/24 375/140
9,866,422	B1	1/2018	Ray	
9,954,561	B2	4/2018	Ray et al.	
10,135,475	B1 *	11/2018	Ray	H03M 13/27
10,429,491	B2	10/2019	Ray et al.	
2007/0177690	A1 *	8/2007	Watanabe	H04L 27/066 375/316

OTHER PUBLICATIONS

Zhu et al., "Design and Implementation of a Cueing Wideband Digital EW Receiver," J. Electronic Science and Technology of China, vol. 4, No. 3, Sep. 2006, pp. 257-264.

* cited by examiner

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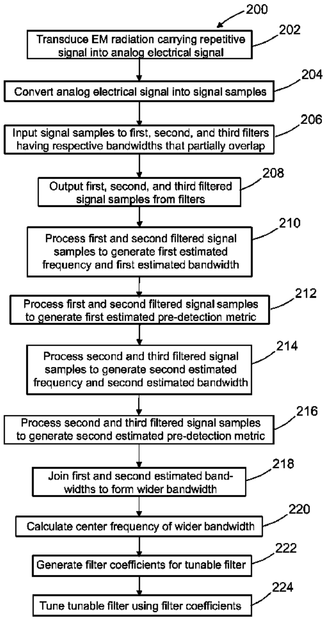
(57) ABSTRACT

Efficient and low-latency cueing means for initiating and updating a process of signal detection and separation in a wideband receiver. The method uses an array of IIR filters that feed an inverted state tree. The inverted state tree provides the directions for separating, detecting, and tracking multiple simultaneous signals that are being received. These signals could be either radar or communications signals and are of widely differing frequencies, bandwidths, and other characteristics. The directions are sent by the cueing system to a set of tunable tracking filters and continuously updated so that the set of tracking filters produce noise-reduced, separated signals on their outputs representing the various simultaneous incoming signals.

20 Claims, 12 Drawing Sheets


200
Transduce EM radiation carrying repetitive signal into analog electrical signal
202
Convert analog electrical signal into signal samples
204
Input signal samples to first, second, and third filters having respective bandwidths that partially overlap
206
Output first, second, and third filtered signal samples from filters
208
Process first and second filtered signal samples to generate first estimated frequency and first estimated bandwidth
210
Process first and second filtered signal samples to generate first estimated pre-detection metric
212
Process second and third filtered signal samples to generate second estimated frequency and second estimated bandwidth
214
Process second and third filtered signal samples to generate second estimated pre-detection metric
216
Join first and second estimated bandwidths to form wider bandwidth
218
Calculate center frequency of wider bandwidth
220
Generate filter coefficients for tunable filter
222
Tune tunable filter using filter coefficients
224

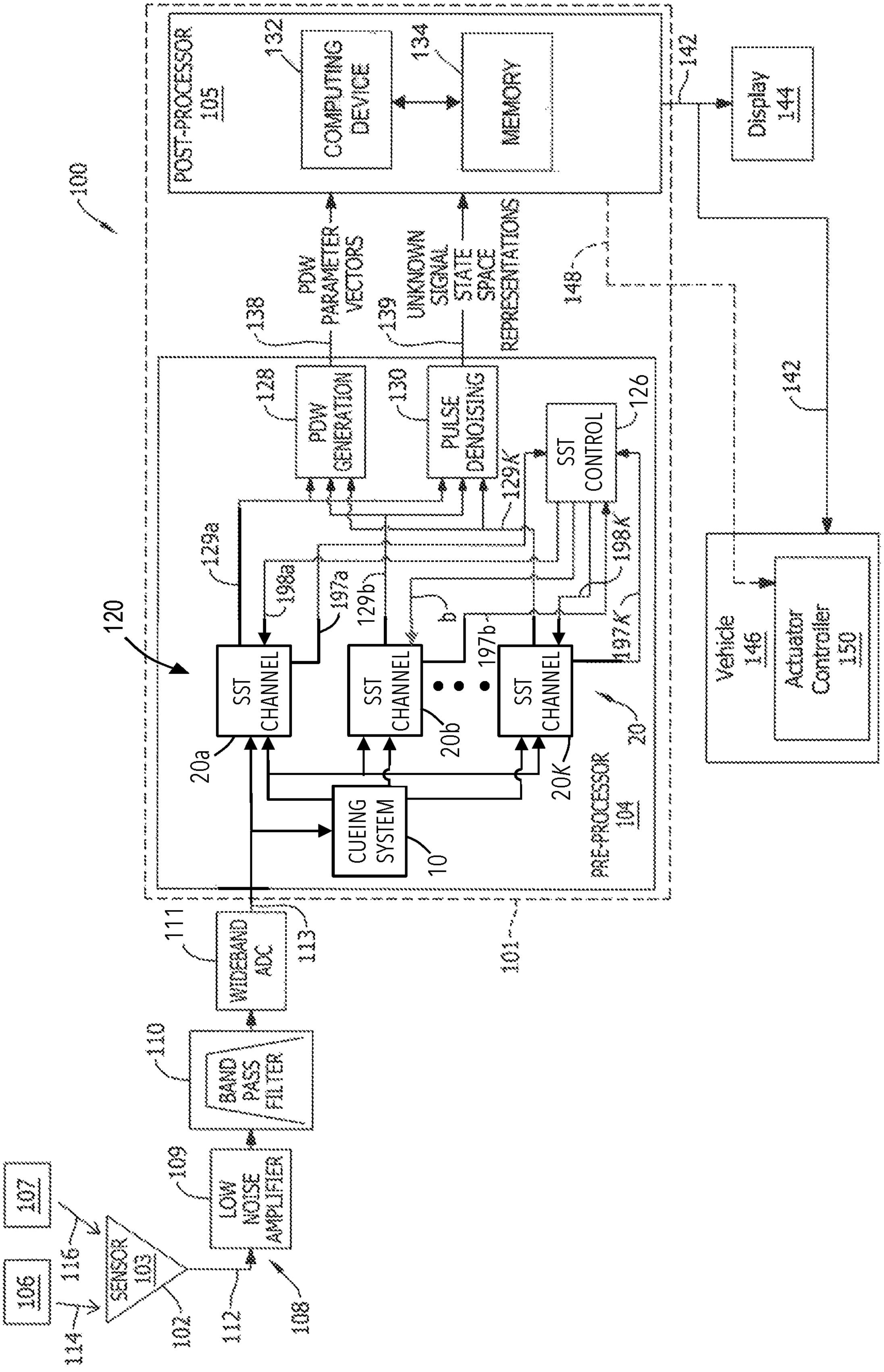

100
POST-PROCESSOR
105
132
COMPUTING DEVICE
134
MEMORY
142
Display
144
PDW PARAMETER VECTORS
UNKNOWN SIGNAL STATE SPACE REPRESENTATIONS
138
139
148
142
120
129a
198a
197a
129b
b
197b
198K
197K
129K
128
PDW GENERATION
130
PULSE DENOISING
SST CONTROL
126
SST CHANNEL
SST CHANNEL
SST CHANNEL
20a
20b
20K
20
CUEING SYSTEM
10
PRE-PROCESSOR
104
101
Vehicle
146
Actuator Controller
150
106
107
114
116
SENSOR
103
102
112
108
LOW NOISE AMPLIFIER
109
BAND PASS FILTER
110
WIDEBAND ADC
111
113

FIG. 1

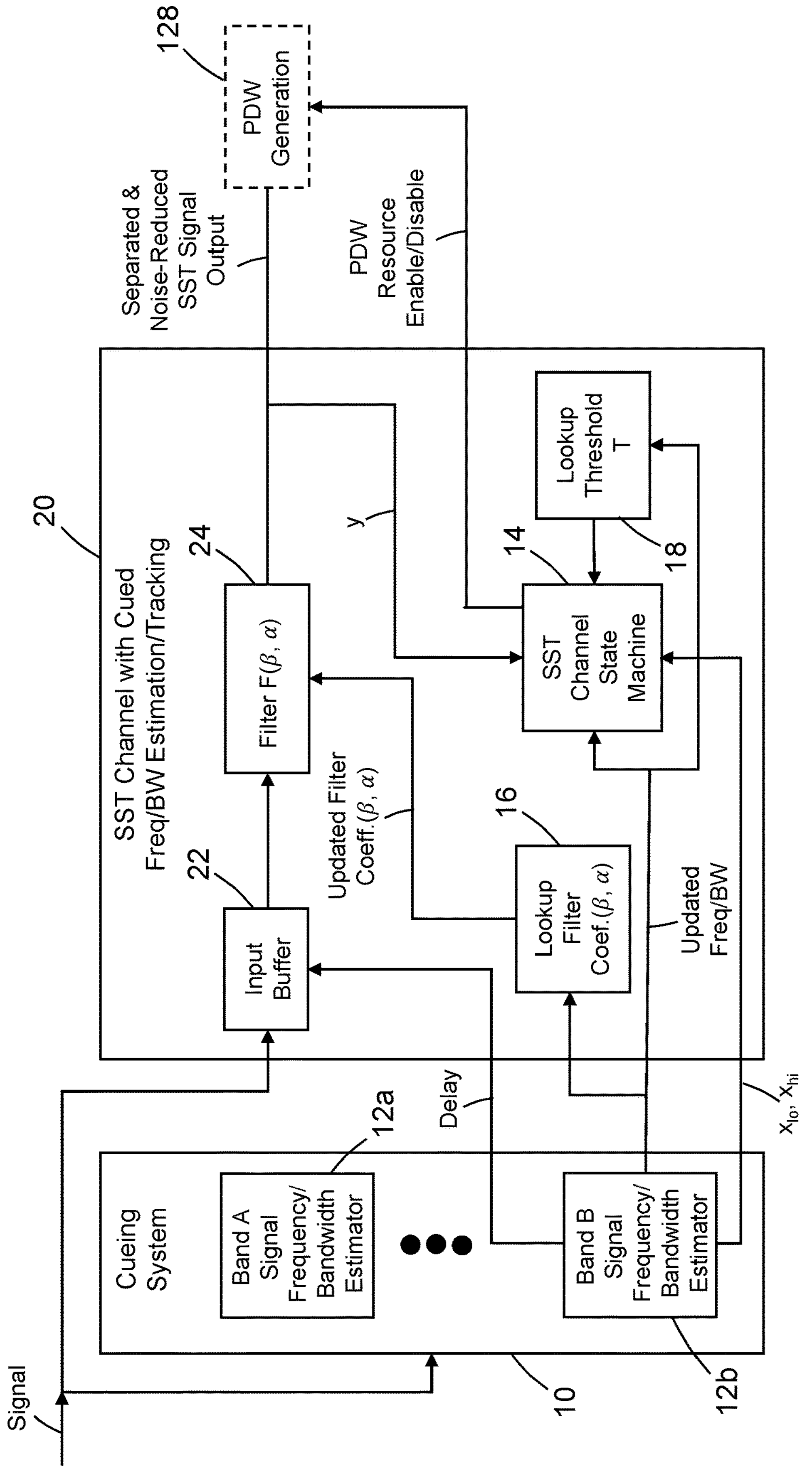

Signal
Cueing System
Band A Signal Frequency/ Bandwidth Estimator
Band B Signal Frequency/ Bandwidth Estimator
10
12a
12b
Delay
x_{lo}, x_{hi}
SST Channel with Cued Freq/BW Estimation/Tracking
20
Input Buffer
22
Filter F(β, α)
24
Updated Filter Coeff.(β, α)
Lookup Filter Coef.(β, α)
16
Updated Freq/BW
y
SST Channel State Machine
14
Lookup Threshold T
18
Separated & Noise-Reduced SST Signal Output
PDW Resource Enable/Disable
PDW Generation
128

FIG. 2

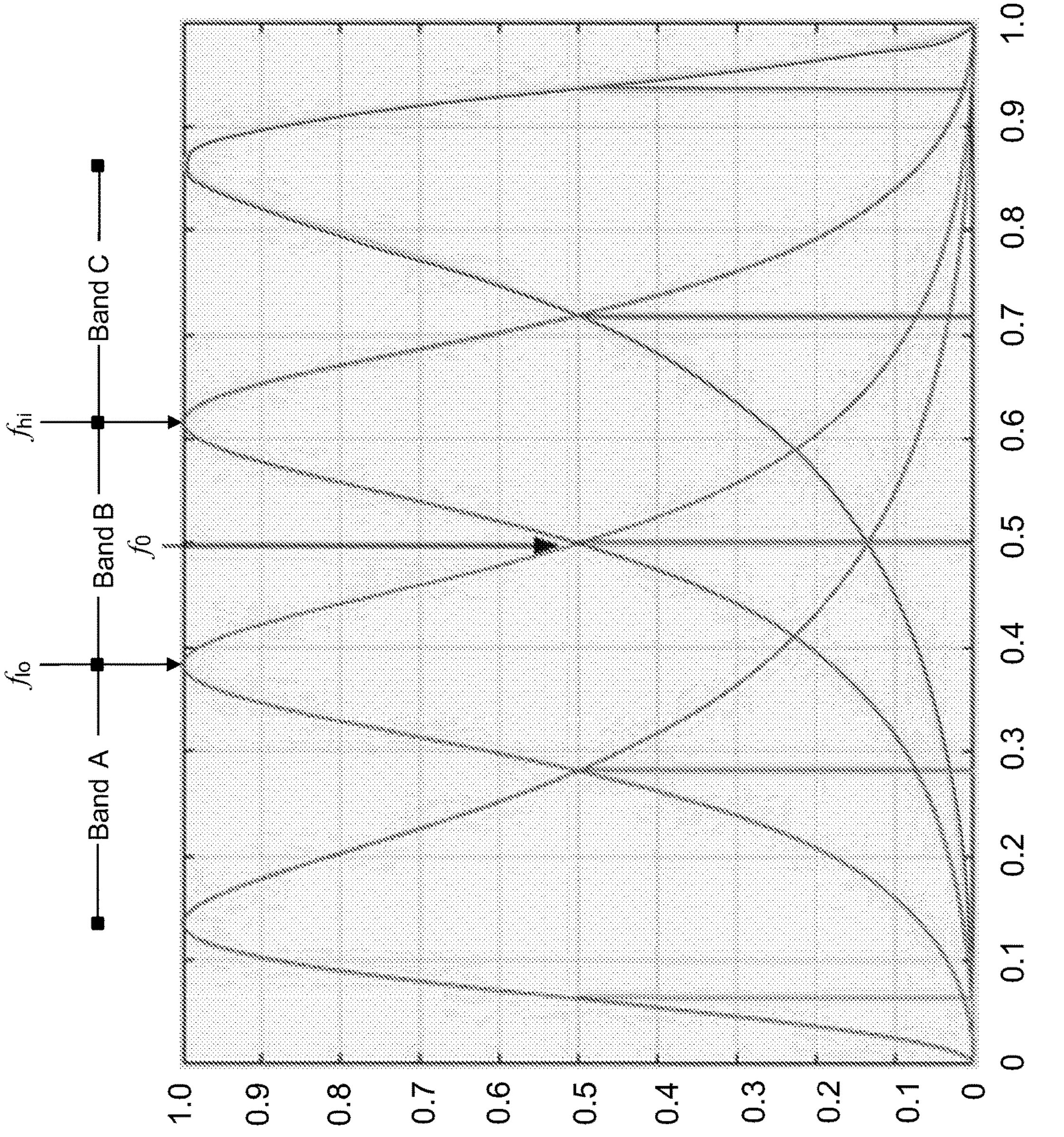

Band A
Band B
Band C
f_{lo}
f_{hi}
f_0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

FIG. 3

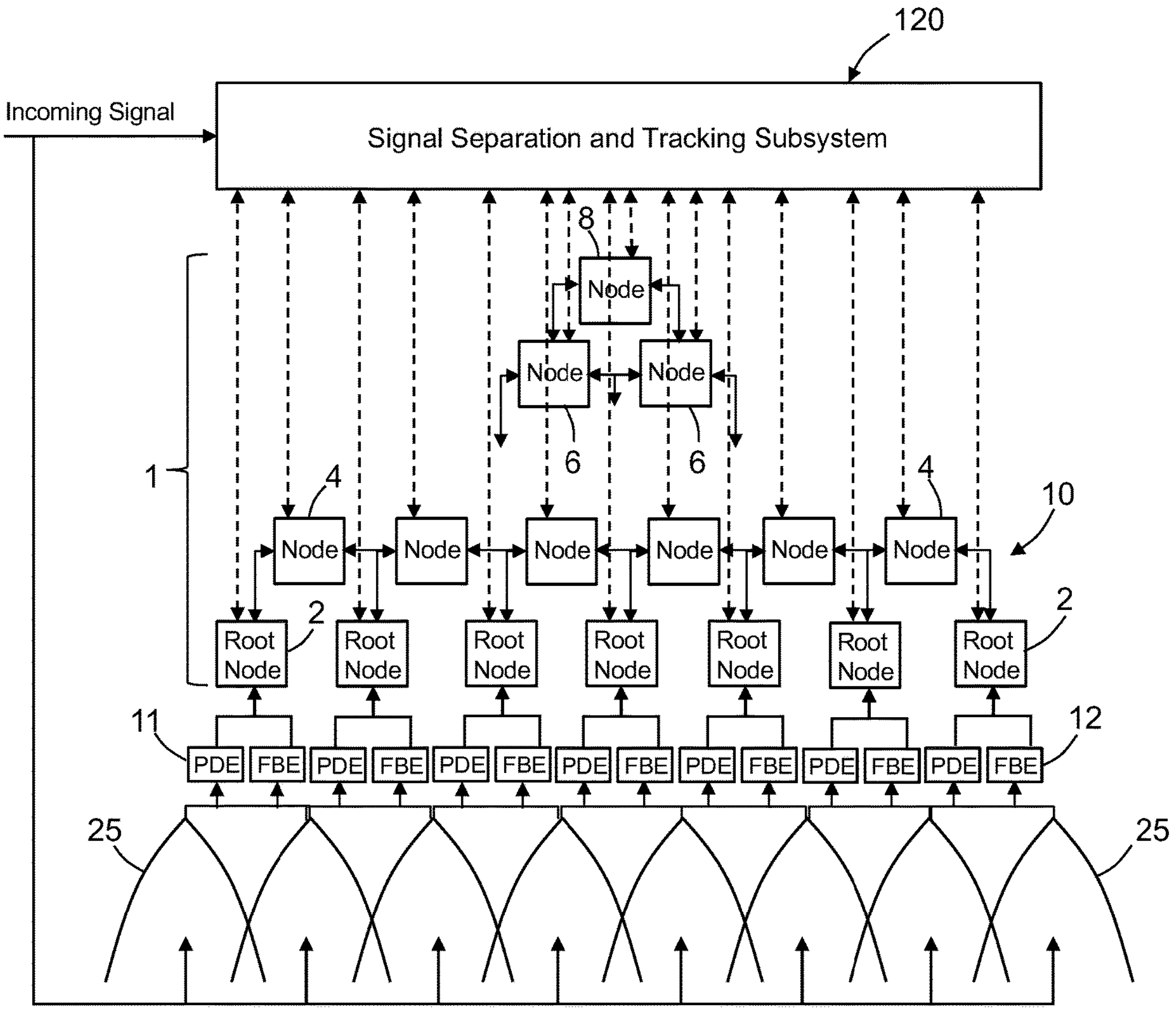

120
Incoming Signal
Signal Separation and Tracking Subsystem
8
Node
Node
Node
6
6
1
4
Node
Node
Node
Node
Node
Node
4
10
2
Root Node
Root Node
Root Node
Root Node
Root Node
Root Node
Root Node
2
11
PDE
FBE
PDE
FBE
PDE
FBE
PDE
FBE
PDE
FBE
PDE
FBE
PDE
FBE
12
25
25

FIG. 4

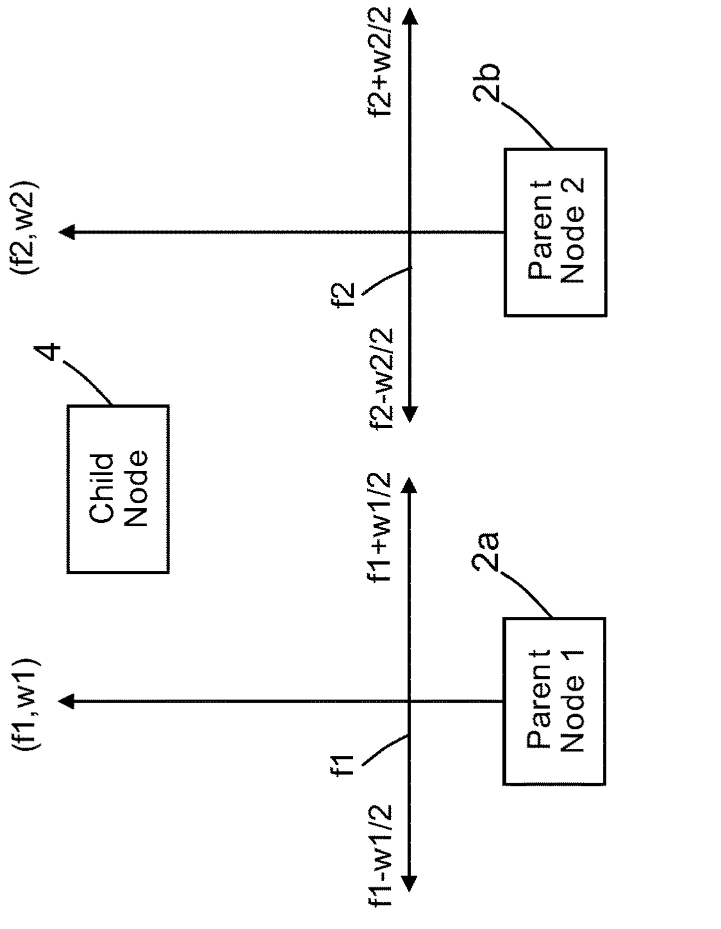

(f1,w1)
(f2,w2)
Child Node
4
f1-w1/2
f1
f1+w1/2
f2-w2/2
f2
f2+w2/2
Parent Node 1
2a
Parent Node 2
2b

FIG. 5A

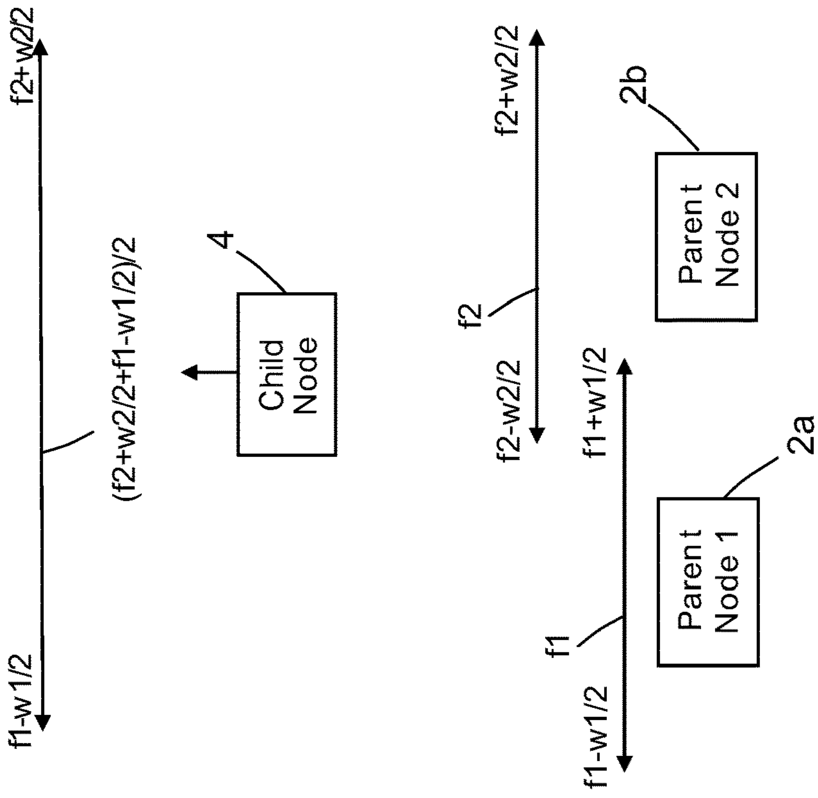

f1-w1/2
(f2+w2/2+f1-w1/2)/2
f2+w2/2
Child Node
4
f2-w2/2
f2
f2+w2/2
f1-w1/2
f1
f1+w1/2
Parent Node 1
2a
Parent Node 2
2b

FIG. 5B

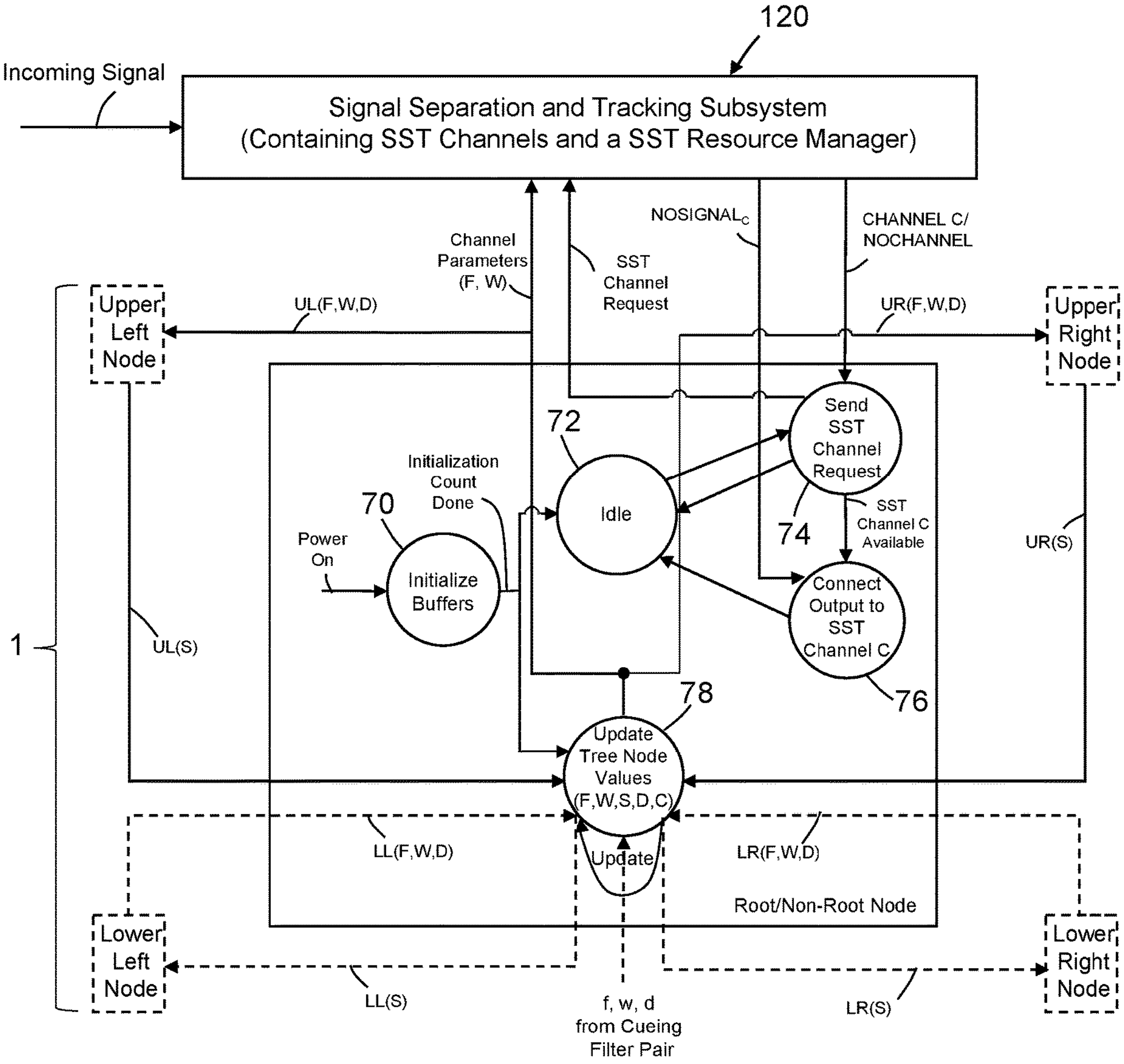

120
Incoming Signal
Signal Separation and Tracking Subsystem
(Containing SST Channels and a SST Resource Manager)
Channel Parameters (F, W)
SST Channel Request
NOSIGNAL$_C$
CHANNEL C/ NOCHANNEL
Upper Left Node
UL(F,W,D)
UR(F,W,D)
Upper Right Node
72
Send SST Channel Request
Initialization Count Done
70
Power On
Initialize Buffers
Idle
74
SST Channel C Available
Connect Output to SST Channel C
UR(S)
1
UL(S)
78
76
Update Tree Node Values (F,W,S,D,C)
LL(F,W,D)
Update
LR(F,W,D)
Root/Non-Root Node
Lower Left Node
LL(S)
f, w, d from Cueing Filter Pair
LR(S)
Lower Right Node

FIG. 6

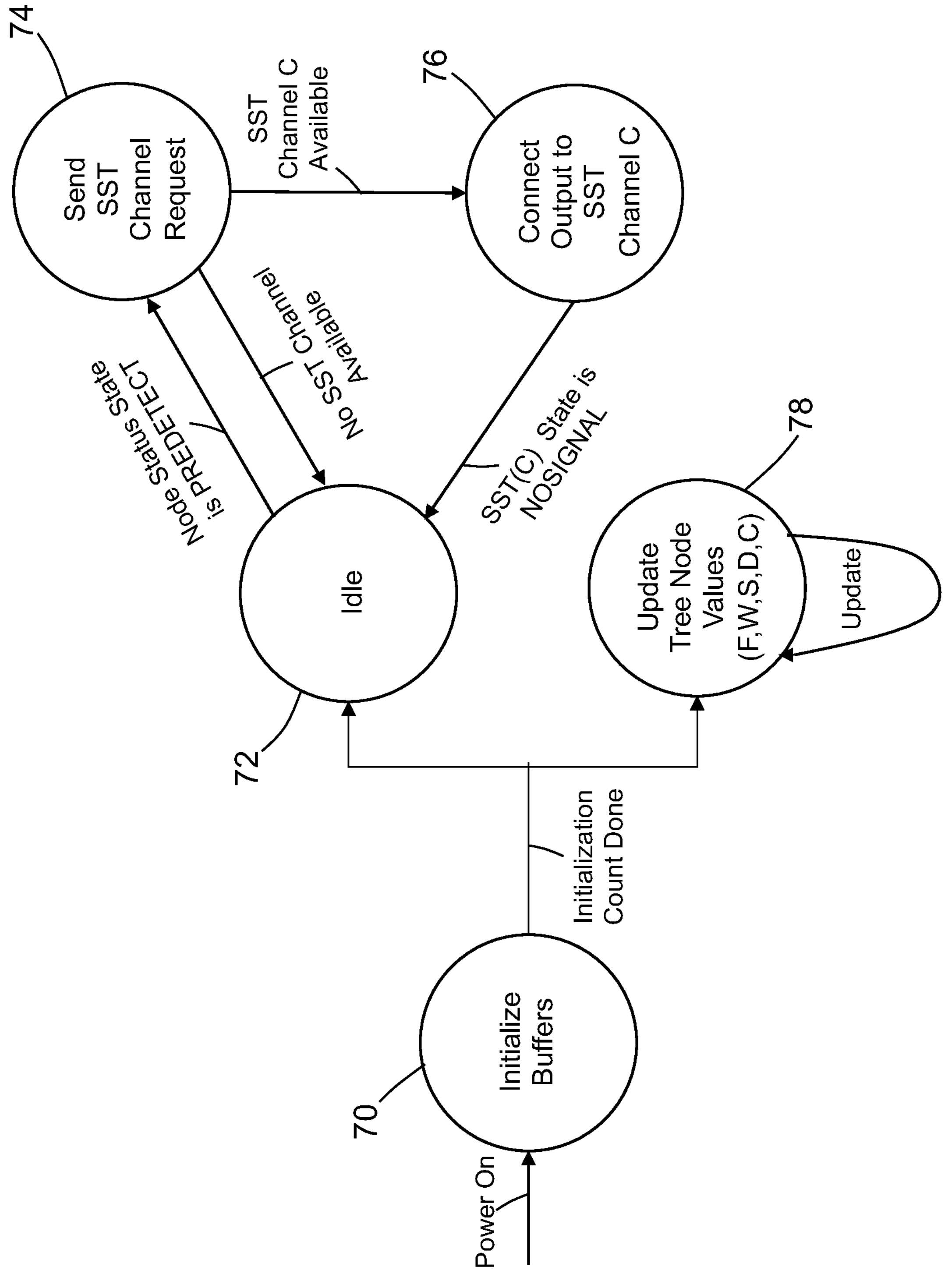

Power On
70
Initialize Buffers
Initialization Count Done
72
Idle
Node Status State is PREDETECT
74
Send SST Channel Request
No SST Channel Available
SST Channel C Available
76
Connect Output to SST Channel C
SST(C) State is NOSIGNAL
78
Update Tree Node Values (F,W,S,D,C)
Update

FIG. 6A

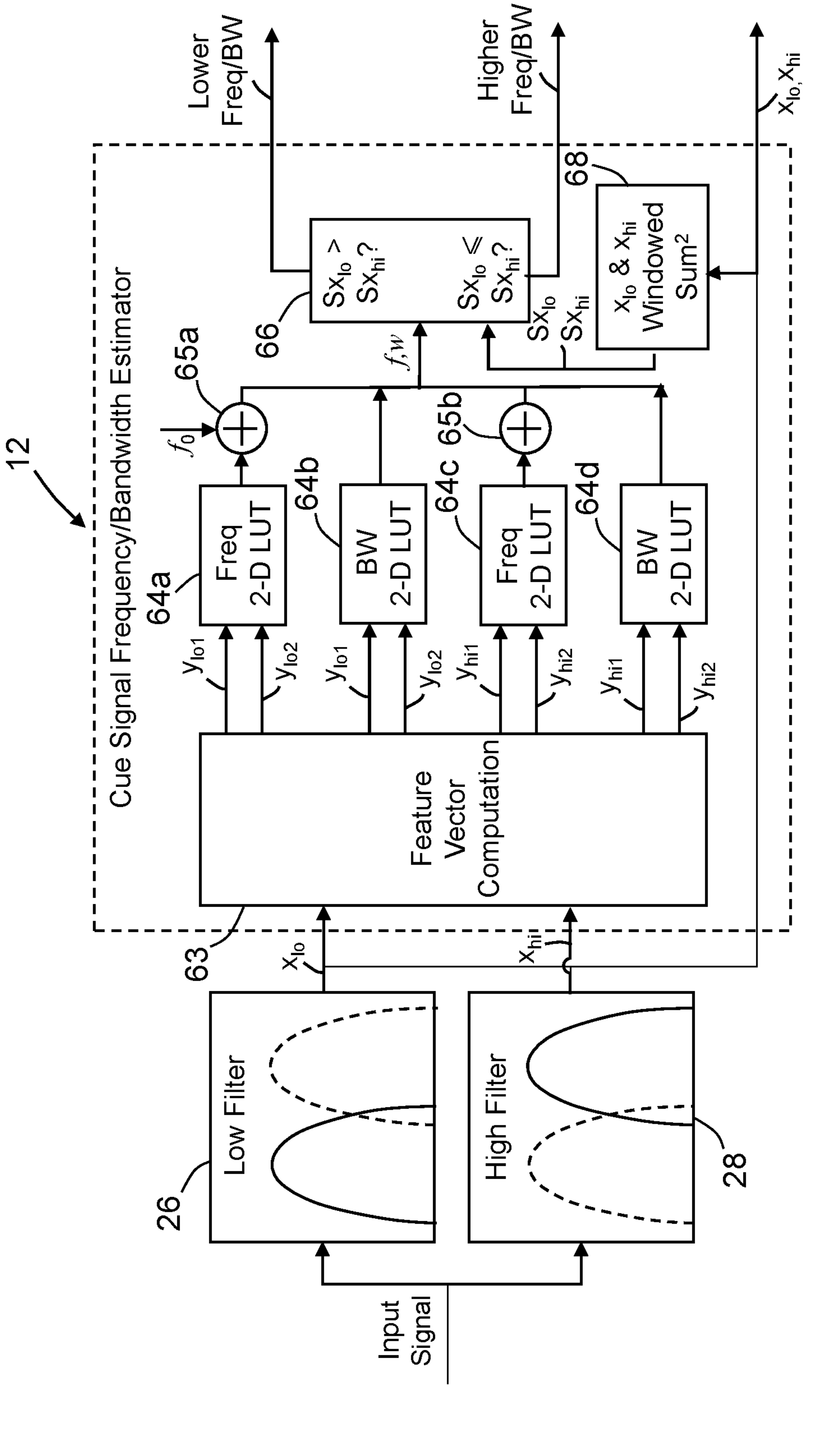
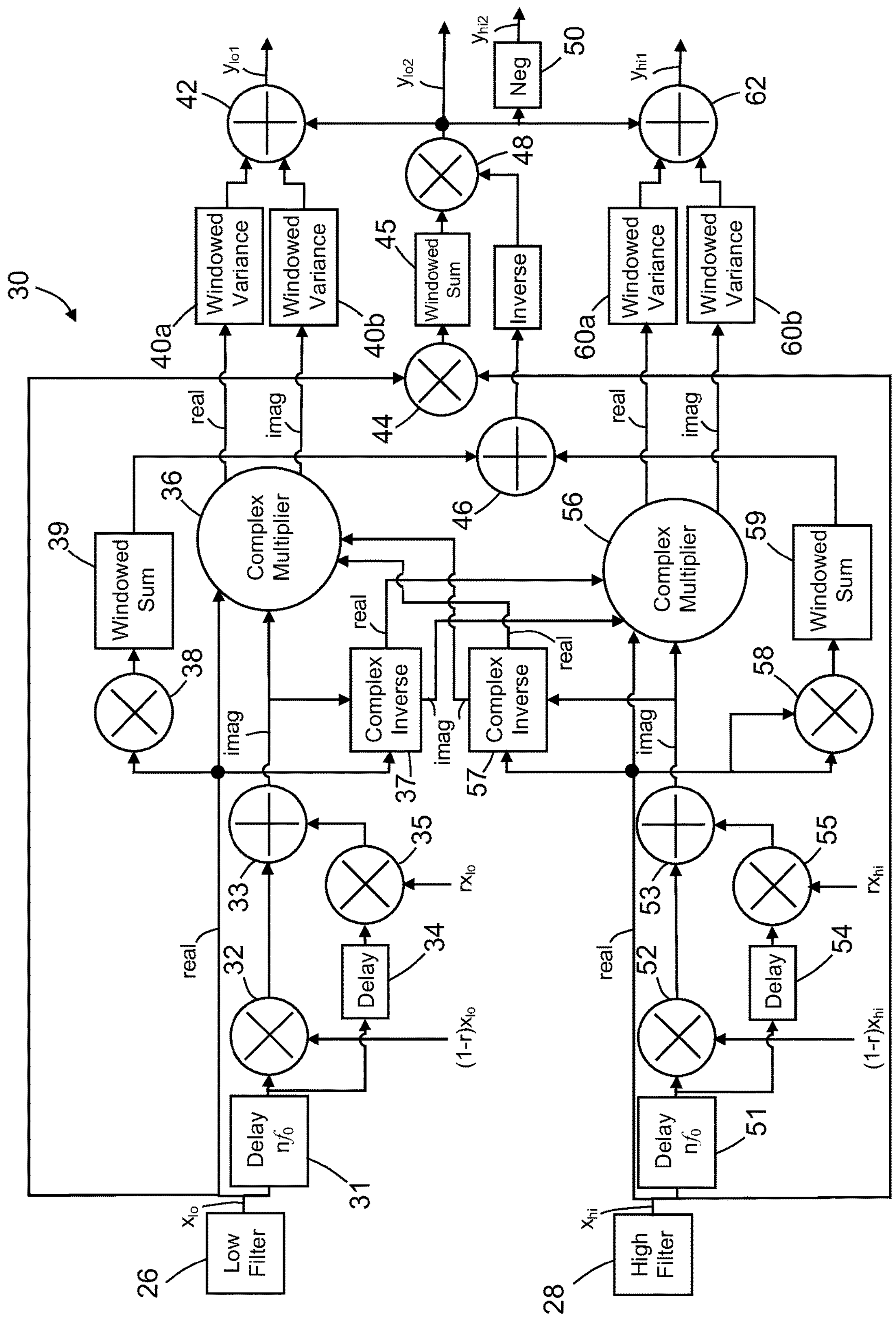

12
Cue Signal Frequency/Bandwidth Estimator
Input Signal
26
Low Filter
High Filter
28
x_{lo}
x_{hi}
63
Feature Vector Computation
y_{lo1}
y_{lo2}
y_{lo1}
y_{lo2}
y_{hi1}
y_{hi2}
y_{hi1}
y_{hi2}
64a
Freq 2-D LUT
64b
BW 2-D LUT
64c
Freq 2-D LUT
64d
BW 2-D LUT
f_0
65a
65b
f,w
66
$Sx_{lo} > Sx_{hi}$?
$Sx_{lo} \leqslant Sx_{hi}$?
Sx_{lo}
Sx_{hi}
68
x_{lo} & x_{hi} Windowed Sum^2
Lower Freq/BW
Higher Freq/BW
x_{lo}, x_{hi}

FIG. 7



30
26
Low Filter
x_{lo}
31
Delay nf_0
32
real
33
34
Delay
35
rx_{lo}
$(1-r)x_{lo}$
36
Complex Multiplier
37
Complex Inverse
imag
real
38
39
Windowed Sum
40a
Windowed Variance
40b
Windowed Variance
42
y_{lo1}
44
45
Windowed Sum
46
48
Inverse
y_{lo2}
50
Neg
y_{hi2}
28
High Filter
x_{hi}
51
Delay nf_0
52
real
53
54
Delay
55
rx_{hi}
$(1-r)x_{hi}$
56
Complex Multiplier
57
Complex Inverse
imag
real
58
59
Windowed Sum
60a
Windowed Variance
60b
Windowed Variance
62
y_{hi1}

FIG. 8

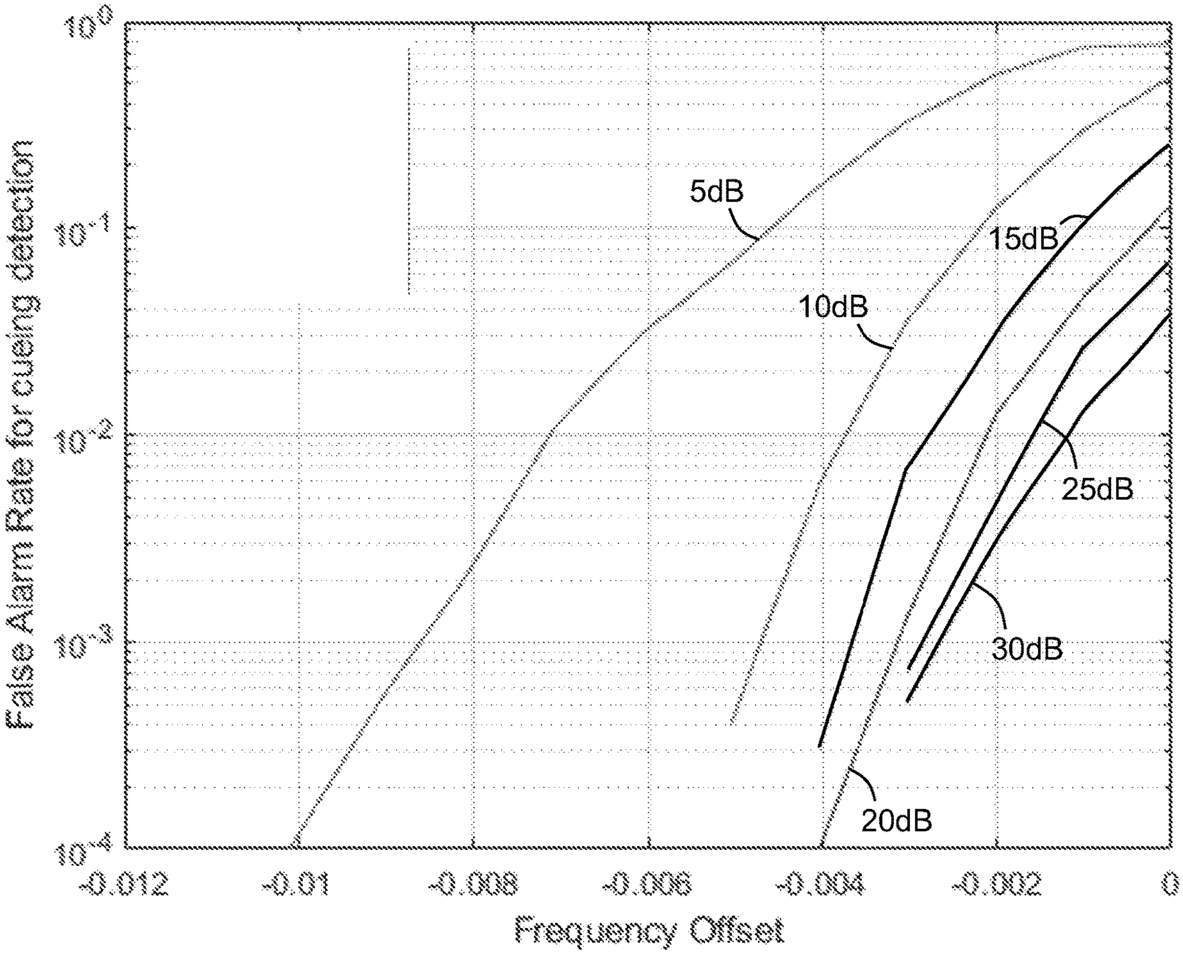

False Alarm Rate for cueing detection
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
-0.012
-0.01
-0.008
-0.006
-0.004
-0.002
0
Frequency Offset
5dB
10dB
15dB
20dB
25dB
30dB

FIG. 9

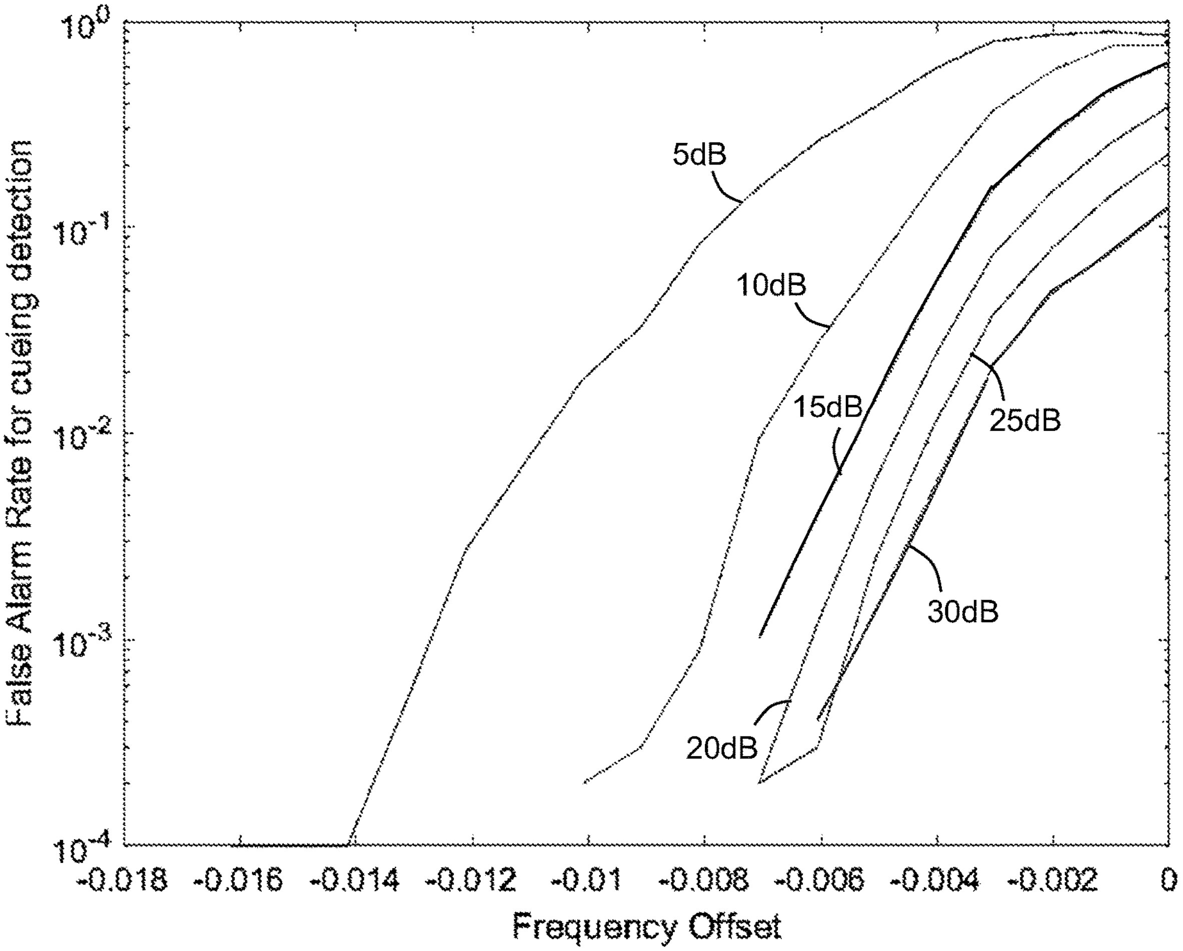

False Alarm Rate for cueing detection
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
-0.018
-0.016
-0.014
-0.012
-0.01
-0.008
-0.006
-0.004
-0.002
0
Frequency Offset
5dB
10dB
15dB
20dB
25dB
30dB

FIG. 10

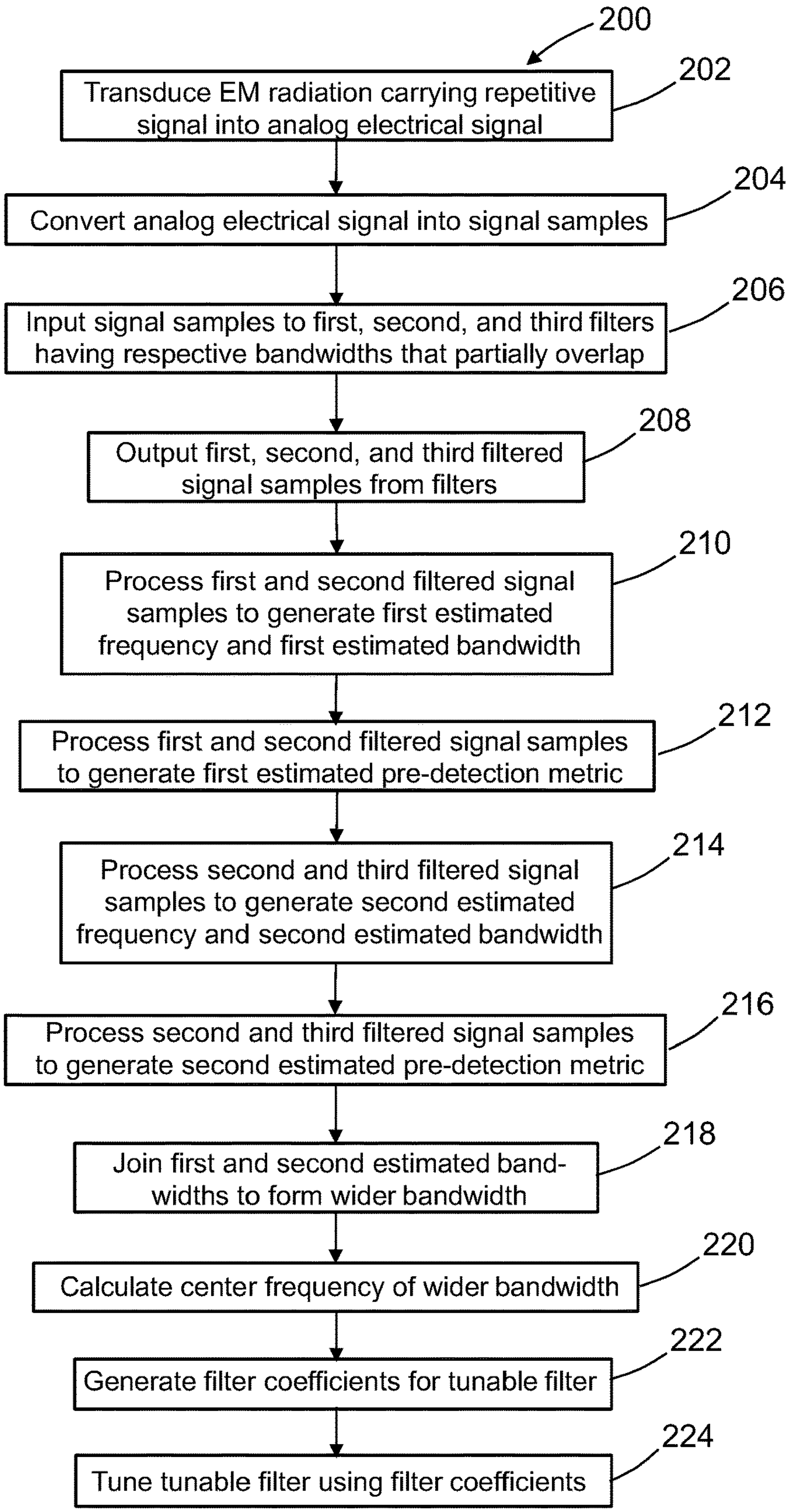

200
Transduce EM radiation carrying repetitive signal into analog electrical signal
202
Convert analog electrical signal into signal samples
204
Input signal samples to first, second, and third filters having respective bandwidths that partially overlap
206
Output first, second, and third filtered signal samples from filters
208
Process first and second filtered signal samples to generate first estimated frequency and first estimated bandwidth
210
Process first and second filtered signal samples to generate first estimated pre-detection metric
212
Process second and third filtered signal samples to generate second estimated frequency and second estimated bandwidth
214
Process second and third filtered signal samples to generate second estimated pre-detection metric
216
Join first and second estimated bandwidths to form wider bandwidth
218
Calculate center frequency of wider bandwidth
220
Generate filter coefficients for tunable filter
222
Tune tunable filter using filter coefficients
224

FIG. 11

SIGNAL CUEING USING AN IIR FILTER ARRAY WITH INVERTED STATE TREE

BACKGROUND

The technology disclosed herein generally relates to methods and apparatus for detecting and classifying repetitive signals and, in particular, relates to signal detection, separation, and tracking of repetitive signals in a wideband receiver.

A receiver system is any system configured to receive and process electromagnetic radiation to identify information carried by the electromagnetic radiation. Typically, a receiver system includes a transducer and a receiver. The transducers used in a receiver system are typically configured to convert received electromagnetic radiation into an analog electrical signal (e.g., antennas). A receiver processes the analog electrical signal generated by the transducer to obtain information about an unknown signal carried by the electromagnetic radiation.

Oftentimes, electromagnetic radiation is used to carry repetitive signals. A repetitive signal is a signal that has a time period over which some aspect of the signal repeats. Repetitive signals are used in timing, synchronization, radar, sonar, and other operations. For example, the characteristics of a repetitive signal may be used to synchronize two or more devices.

In some situations, a receiver system may receive electromagnetic radiation carrying an unknown repetitive signal, but may be unable to identify desired information about the repetitive signal. For example, the receiver system may be unable to detect and/or classify the repetitive signal. Classifying a repetitive signal may include estimating the frequency and bandwidth of the repetitive signal.

Some wideband receivers employ a signal cueing system that initiates signal detection, separation, and tracking. Here cueing means detecting and processing received signals to provide information that can help with signal separation and tracking. Previous cueing solutions either scan for signals or use fixed channels with chosen fixed bandwidths. In the first case, the latency can be very long before a signal is found; and in the second case, the channels are typically not matched to the bandwidths of each incoming signal so that detection/separation has suboptimal reliable and poor quality.

SUMMARY

The subject matter disclosed in some detail below is directed to efficient and low-latency cueing means for initiating and updating a process of signal detection and separation in a wideband receiver. The method proposed herein uses an array of IIR filters that feed an inverted state tree. The inverted state tree provides the directions for separating, detecting, and tracking multiple simultaneous signals that are being received. These signals could be either radar or communications signals and are of widely differing frequencies, bandwidths, and other characteristics. The directions are sent by the cueing system to a set of tunable tracking filters and continuously updated so that the set of tracking filters produce noise-reduced, separated signals on their outputs representing the various simultaneous incoming signals.

The cueing system proposed herein is applicable to a signal separation and tracking stage within an electronic warfare (EW) receiver which must produce pulse descriptor words (PDWs) for a large number of incoming radar signals.

Or the cueing system could be used by a commercial 5G system that monitors a very wide bandwidth and characterizes all the incoming interfering signals as well as its own signals in order to reduce interference or increase bandwidth usage. In addition, the cueing system could also serve as the front end portion of a commercial receiver that monitors aircraft collision avoidance radars near airports.

The innovative cueing system disclosed herein includes an IIR filter array with tree of decision nodes that can cue a set of tunable tracking filters that provide concurrent detection, separation and characterization of large numbers of simultaneous incoming signals of wide bandwidth. Specifically, the proposed cueing method is able to detect signal energy with a latency that is dependent directly on the signal's strength rather than on the bandwidth of a receiver channel. Thus, the cueing system is capable of detecting this energy as quickly as possible for higher-SNR signals while still detecting low-SNR signals within a time interval that is inversely proportional to their SNR (which is theoretically the best that can be done). Thus, the cueing process is not compromised by architectural decisions made in the receiver such as chosen fixed channel bandwidths and other artifacts. In addition, the cueing system proposed herein also provides frequency and bandwidth estimates and from that selects the best filter coefficients (or equivalently center frequency and bandwidth) of each signal detected in order to initialize a separation filter for each such signal. This allows rapid simultaneous separation and characterization of all the incoming signals within the input bandwidth. Thus, approach adopted herein creates an entirely new wideband receiver architecture that does not use channelization.

Although various embodiments of systems and methods for cueing unknown signals using an IIR filter array with inverted state tree will be described in some detail below, one or more of those embodiments may be characterized by one or more of the following aspects.

One aspect of the subject matter disclosed in detail below is a method for cueing signals comprising: (a) transducing electromagnetic radiation carrying a repetitive signal into an analog electrical signal; (b) converting the analog electrical signal into signal samples; (c) inputting the signal samples to first and second filters configured to pass first and second bandwidths respectively which are partially overlapping; outputting first filtered signal samples from the first filter and second filtered signal samples from the second filter in response to inputting the digital signal samples; (d) processing the first and second filtered signal samples to generate digital data representing an estimated frequency and an estimated bandwidth; (e) processing the first and second filtered signal samples to generate digital data representing an estimated pre-detection metric; (f) determining that the pre-detection metric is greater than a specified threshold; (g) generating filter coefficients for a tunable filter which are functions of the estimated frequency and the estimated bandwidth; and (h) tuning the tunable filter in accordance with the filter coefficients. In one proposed implementation, step (e) comprises calculating a normalized signal energy by dividing a sum of energy differences between the outputs of the first and second filters by a sum of the energies of those outputs.

Another aspect of the subject matter disclosed in detail below is a method for cueing signals comprising: transducing electromagnetic radiation carrying a repetitive signal into an analog electrical signal; converting the analog electrical signal into signal samples; inputting the signal samples to first, second, and third filters configured to pass first, second, and third bandwidths respectively, wherein the first and second bandwidths are partially overlapping, the second and third bandwidths are partially overlapping, and the first and third bandwidths are not partially overlapping; outputting first, second, and third filtered signal samples from the first, second, and third filters respectively in response to inputting the digital signal samples; processing the first and second filtered signal samples to generate digital data representing a first estimated frequency and a first estimated bandwidth; processing the first and second filtered signal samples to generate digital data representing a first estimated pre-detection metric; determining that the first estimated pre-detection metric is greater than a specified threshold; processing the second and third filtered signal samples to generate digital data representing a second estimated frequency and a second estimated bandwidth; processing the second and third filtered signal samples to generate digital data representing a second estimated pre-detection metric; determining that the second estimated pre-detection metric is greater than the specified threshold; joining the first and second estimated bandwidths to form a wider bandwidth that is a union of first and second estimated bandwidths; calculating a center frequency of the wider bandwidth; generating filter coefficients for an available tunable filter which are functions of the calculated center frequency and the wider bandwidth; and tuning the available tunable filter in accordance with the filter coefficients.

A further aspect of the subject matter disclosed in detail below is a signal processing system comprising: a sensor configured to transduce electromagnetic radiation carrying a repetitive signal into an analog electrical signal; an analog-to-digital converter configured to convert the analog electrical signal into signal samples; first and second filters connected to receive the signal samples and configured to pass first and second bandwidths respectively which are partially overlapping; a signal frequency/bandwidth estimator connected to receive first and second filtered signal samples from the first and second filters and configured to process filtered signal samples from two filters to generate digital data representing an estimated frequency and an estimated bandwidth; a pre-detection estimator connected to receive first and second filtered signal samples from the first and second filters and configured to process filtered signal samples from two filters to generate digital data representing an estimated pre-detection metric; a plurality of signal separation and tracking channels, each signal separation and tracking channel comprising a respective tunable filter; a signal separation and tracking controller configured to control tuning of the plurality of signal separation and tracking channels; and a root node connected to receive the estimated frequency and the estimated bandwidth from the signal frequency/bandwidth estimator and receive the estimated pre-detection metric from the pre-detection estimator and communicate with the signal separation and tracking controller, wherein the root node is configured to not send a request for available channel to the signal separation and tracking controller if the estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal.

In accordance with one embodiment of the system partly described in the immediately preceding paragraph, the signal separation and tracking controller is further configured to send a channel available signal to the root node in response to receipt of a request for available channel from the root node if one of the plurality of signal separation and tracking channels is available; and the root node is further configured to output state values representing the estimated frequency and the first estimated bandwidth to the available signal separation and tracking channel in response to receipt of the channel available signal from the signal separation and tracking controller.

Yet another aspect of the subject matter disclosed in detail below is a signal cueing system comprising: first, second, and third filters configured to pass first, second, and third bandwidths, respectively, wherein the first and second bandwidths are partially overlapping, the second and third bandwidths are partially overlapping, and the first and third bandwidths are not partially overlapping; a first signal frequency/bandwidth estimator connected to receive first and second filtered signal samples from the first and second filters and configured to process filtered signal samples from two filters to generate digital data representing a first estimated frequency and a first estimated bandwidth; a first pre-detection estimator connected to receive first and second filtered signal samples from the first and second filters and configured to process filtered signal samples from two filters to generate digital data representing a first estimated pre-detection metric; a first root node connected to receive the first estimated frequency and the first estimated bandwidth from the first signal frequency/bandwidth estimator and receive the first estimated pre-detection metric from the first pre-detection estimator, wherein the first root node is configured to not generate a request for available channel if the first estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal; a second signal frequency/bandwidth estimator connected to receive second and the filtered signal samples from the second and third filters and configured to process filtered signal samples from two filters to generate digital data representing a second estimated frequency and a second estimated bandwidth; a second pre-detection estimator connected to receive second and third filtered signal samples from the second and third filters and configured to process filtered signal samples from two filters to generate digital data representing a second estimated pre-detection metric; a second root node connected to receive the second estimated frequency and the second estimated bandwidth from the second signal frequency/bandwidth estimator and receive the second estimated pre-detection metric from the second pre-detection estimator, wherein the second root node is configured to not generate a request for available channel to the signal separation and tracking controller if the second estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal; and a non-root node connected to receive the state values representing the first estimated frequency, the first estimated bandwidth, and the first estimated pre-detection metric from the first root node and the second estimated frequency, the second estimated bandwidth, and the second pre-detection metric from the second root node, wherein the non-root node is configured to calculate and output state values representing a third estimated frequency and a third estimated bandwidth in response to the first and second estimated bandwidths being adjacent or partially overlapping, the third estimated pre-detection metric being a union of the first and second bandwidths, and further configured to not generate a request for available channel to the signal separation and tracking controller if the third estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal.

Other aspects of systems and methods for cueing unknown signals using an IIR filter array with inverted state tree are disclosed and claimed below.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, functions and advantages discussed in the preceding section may be achieved independently in various embodiments or may be combined in yet other embodiments. Various embodiments will be hereinafter described with reference to drawings for the purpose of illustrating the above-described and other aspects.

FIG. **1** is a block diagram showing a cueing architecture incorporated in a signal processing system for generating pulse descriptor words (PDWs) using signal separation and tracking (SST).

FIG. **2** is a block diagram identifying components of a cueing system and a signal separation and tracking channel (hereinafter "SST channel") that may be used in a signal processing system to track both frequency and bandwidth.

FIG. **3** is a graph showing the filter responses as a function of frequency for four consecutive fixed filters with overlapping filter responses that can monitor three bands of interest (as shown) by using each consecutive filter pair.

FIG. **4** is a block diagram identifying components of a cueing system in accordance with one embodiment.

FIG. **5**A is a diagram showing a pair of parent nodes which have detected respective signals that do not overlap in frequency and therefore are not joined by a child node.

FIG. **5**B is a diagram showing a pair of parent nodes which have detected respective signals that partly overlap in frequency and therefore are joined by a child node.

FIG. **6** is a tree node diagram identifying the states, inputs and outputs of a node in an IIR filter array with inverted state tree in accordance with one proposed implementation.

FIG. **6**A is a state diagram showing on a magnified scale the states and state transitions inside the node depicted in FIG. **6**.

FIG. **7** is a diagram representing both functions of a process and functional modules of electronic circuitry which are configured to perform frequency and bandwidth estimation of signals output by a pair of overlapping fixed filters.

FIG. **8** is a flowchart identifying steps (signal processing operations) of a method for cueing frequency and bandwidth estimation in accordance with one proposed implementation.

FIG. **9** is a graph showing the false alarm performance of a pre-detection (cueing) metric for pairs of filters having different signal-to-noise ratios (SNRs) in a simulation wherein the probability of detection was equal to 90% and the bandwidth was 0.01.

FIG. **10** is a graph showing the false alarm performance of a pre-detection (cueing) metric for pairs of filters having different SNRs in a simulation wherein the probability of detection was equal to 90% and the bandwidth was 0.1.

FIG. **11** is a flowchart identifying steps of a signal cueing method in accordance with one embodiment.

Reference will hereinafter be made to the drawings in which similar elements in different drawings bear the same reference numerals.

DETAILED DESCRIPTION

Various embodiments of systems and methods for cueing unknown signals using an IIR filter array with inverted state tree will now be described in detail for the purpose of illustration. At least some of the details disclosed below relate to optional features or aspects, which in some applications may be omitted without departing from the scope of the claims appended hereto. In addition, not all features of an actual implementation are described in this specification. A person skilled in the art will appreciate that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developer's specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

Electronic warfare systems are receive-only real-time systems that have front-end receivers that produce pulse descriptor words (PDW) for each radar pulse they detect. Electronic warfare receivers are unlike radar systems in that they do not naturally produce range and they must handle unknown signals rather than look for reflected versions of their transmitted signals. In the commercial world, 5G analysis systems also cover a very large bandwidth and wideband receivers that characterize 5G signals and interfering signals must also handle many unknown signals. The digital versions of these receivers are typically designed as a filter bank. Within each filter channel, radar/communication signals are separated from other coincident signals and have their noise decreased by the relative filter bandwidth compared to the total input bandwidth. These pulses, with their increased SNR, are processed to estimate PDW elements such as pulse width, frequency, time of arrival, bandwidth, and amplitude for signal classification. While such channelizers have many advantages, they also have key disadvantages such as large size, weight and power due to the multipliers and adders required for very large filter banks that operate continuously whether a signal is present or not. In addition, signals that do not match the bandwidth and frequency of each filter in the filter bank are processed sub-optimally or split across filter channels, resulting in missed, false and inaccurate PDWs. Finally, signals of unknown type that do not match the model of simple pulsed signals largely fail to be processed correctly.

If a channelizer is not used, the two main processing tasks of noise reduction and signal separation must be done using different methods. The innovative signal processing system disclosed herein performs both tasks together. Specifically, on-the-fly real-time custom matched filters are constructed which can both separate signals and reduce their noise. These filters are then adapted in real time to also track the signals and provide input to the final signal characterization system that produces PDWs. Note that in addition, these two tasks must be done with very low latency since EW receivers and interference cancellation both require low latency in order to cue their respective outputs in time to react to signal changes.

The signal processing system takes as input a sampled form of an incoming signal $\{x_n\}$ at sample times $\{t_n\}$. This input may have come from the digitized output of an intermediate frequency (IF) receiver, from a digitized channel within a receiver, or from the output of a noise-reducing front end to a receiver among many options. The sampled signal is modeled as:

$$x_n = \sum_i s_i(t_n) + N_n$$

where a collection of incoming signals is denoted $\{s_i(t)\}$ and samples of the receiver noise are denoted by N_n. In addition, the center frequency and bandwidth of signal $s_i(t)$ are denoted as f(s) and w(s). The signal separation step must construct and update a filter F for each such input signal $s_i(t)$; this is denoted by $F(s_i)$ and can be either an FIR or IIR digital filter with filter coefficient vectors β (e.g., feedforward filter coefficients) and α (e.g., feedback filter coefficients). Here these coefficient vectors are of length o(F) where this denotes the order of the filter. The idea of the separation filters is to find filters so that

$$F(s_i)(s_i(t_n))\approx s_i(t_n)$$

and

$$F(s_i)(s_j(t_n))\approx s_i(t_n)$$

for j≠i. These filters can be designed using standard filter design software by using (for example) the center frequency $f(s_i)$ and bandwidth $w(s_i)$ of the signal to design $F(s_i)$, i.e., to find its coefficient vectors. The cueing technology disclosed in more detail hereinafter accomplishes initial creation and updating of these separation filters in an efficient manner with very low latency.

FIG. **1** is a block diagram identifying components of a signal processing system **100** for generating PDWs using signal cueing, separation, and tracking. The signal processing system **100** includes a signal data processor **101** communicatively coupled to an antenna **102** by way of a pre-conditioner **108**. Antenna **102** may be embodied as a wide-area sensor **103**. Signal data processor **101** includes a pre-processor **104** and a post-processor **105**. Sensor **103** is configured to surveil at least one radar signal emitter (two radar signal emitters **106** and **107** are indicated). Pre-conditioner **108** includes at least one electronic component (e.g., a low-noise amplifier **109**, a band pass filter **110**, and a wideband analog-to-digital converter (ADC) **111**) configured to pre-condition a sensor output signal **112**. In operation, pre-conditioner **108** is configured to convert a sensor output signal **112** received from sensor **103** into a conditioned signal **113** transmitted to pre-processor **104**. Each conditioned signal **113** is derived from a time-varying signal received at sensor **103**. Time-varying signals 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** generated by radar signal emitter **106** or a second radar signal **116** generated by radar signal emitter **107**, which signals are received by sensor **103**.

The pre-processor **104** includes a cueing system **10** and a signal separation and tracking subsystem **120** (hereinafter "SST subsystem **120**). The SST subsystem **120** includes a plurality of signal separation/tracking (SST) channels **20**. The total number of SST channels **20** is expressed as an integer K. In operation, incoming signal **113** is transmitted from pre-conditioner **108** to cueing system **10**, where the frequency and bandwidth of incoming signal **113** are estimated. More specifically, the cueing system **10** includes a respective signal frequency/bandwidth estimator for each frequency band of interest. Each cueing signal frequency/bandwidth estimator includes a pair of overlapping fixed filters and signal processing circuitry that outputs frequency and bandwidth estimates which are used to tune a respective tunable filter in each SST channel **20***a*, **20***b*, . . . , **20**K. The cueing system **10** detects the presence of signals at certain frequencies and bandwidths, without doing noise reduction as the channelizer would have done in a traditional approach. Instead, noise reduction is done in the SST channels **20***a*, **20***b*, . . . , **20**K. The SST subsystem **120** further includes an SST control module **126** coupled to each SST channel **20**. SST control module **126** is configured to transmit a respective SST control signal **198***a* through **198**K to each of SST channels **20**, as further shown and described below with reference to FIG. **2**.

Pre-processor **104** further includes a PDW generation module **128** and a pulse denoising module **130**, both of which are coupled to receive separated signals **129** from the plurality of SST channels **20**. PDW generation module **128** generates PDW parameter vector signals **138** based on respective separated signals **129** (e.g., **129***a*, **129***b*, . . . , **129**K) received from the SST channels **20** (e.g., **20***a*, **20***b*, . . . , **20**K). 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 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 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**.

As seen in FIG. **1**, post-processor **105** includes a computing device **132** and a memory **134**. The memory **134** comprises one or more non-transitory tangible computer-readable storage media. Post-processor **105** is communicatively coupled to pre-processor **104**. In accordance with one embodiment, the computing device **132** is a processor running software. The PDW generation module **128** is configured to receive a respective separated signal **129** from each SST channel **20**. PDW generation module **128** is further configured to transmit a PDW parameter vector signal **138** to post-processor **105**. PDW parameter vector signal **138** received by computing device **132** is stored as computer-readable data in memory **134** including, without limitation, as at least one buffered data set.

The PDW generation module **128** sends each PDW to the computing system **132** as a PDW parameter vector signal **138** similar to (amplitude, time of arrival, center frequency, pulse width and bandwidth)=(amp, toa, f, pw, w). The PDW for each intercepted signal is stored in a pulse buffer for further processing by the computing system **132**. As part of such processing, the PDWs are sorted and deinterleaved by clustering the incoming radar pulses into groups. In principle, each group should have characteristics representative of a single radar source or class of radar sources which allows that radar source or class to be identified. The identity of a particular signal is usually inferred by correlating the observed characteristics of that signal with characteristics stored in a list that also contains the identity of known radars.

In addition, the pulse denoising module **130** is configured to receive separated signals **129** from each SST channel **20**. Pulse denoising module **130** is further configured to transmit an unknown signal state space representation signal **139** to post-processor **105**. Unknown signal state space representation signal **139** received by computing device **132** is stored as computer-readable data in memory **134**, including, without limitation, as at least one buffered data set. In an exemplary implementation, computing device **132** fetches buffered data sets from memory **134** for processing using a computer-based method that employs an operating system running software executed from instruction set data also stored in memory **134**.

The computing device **132** is configured to perform operations based on data contained in the PDW parameter vector signals **138** and unknown signal state space representation signals **139**. Such operations include, without limitation, detecting, processing, quantifying, storing, and controlling a display device **144** for displaying (e.g., in human-readable data form) various characteristics of at least one of the radar signals **114** and **116** represented as data in the PDW parameter vector signals **138** and unknown signal state space representation signals **139**. For example, a PDW parameter vector signal **138** generated by PDW generation module **128** may contain a plurality of PDW vector data blocks structured in a vector format, where each PDW vector data block contains one parameter of the first radar signal **114**. Parameters representative of at least one characteristic of the first radar signal **114** contained in one PDW vector data block may include, without limitation, frequency, bandwidth, time of arrival, time of departure, pulse width, pulse amplitude, pulse repetition interval, and/or AOA.

Resultant data from operations performed by the computing device **132** are stored in memory **134**. Further, in the exemplary implementation, computing device **132** causes post-processor **105** to transmit a human-readable data signal **142** to a human machine interface to facilitate at least one of an interaction, a modification, a visualization, at least one further operation, and a viewable recording of information about at least one radar signal **114** and **116** by a user of signal processing system **100**. The human machine interface may be, for example, a display device **144** which receives the human-readable data signal **142** from post-processor **105**. In one example, characteristics of radar signal emitters **106** and **107** determined by signal processing system **100** are displayed on display device **144** as a map having a grid representative of a physical spatial domain including a surveillable space of sensor **103**, where locations and identifying information of radar signal emitters **106** and **107** are displayed and plotted substantially in real time. The human-readable data signal **142** may also be transmitted from post-processor **105** to at least one device and/or system (e.g., an aerial or ground-based vehicle **146**) associated with signal processing system **100**. Further, the 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 controlled movements thereof. For example, vehicle **146** may be a remotely and/or autonomously operated land vehicle or an unmanned aerial vehicle.

In one mode of operation, at least one of frequency and bandwidth information contained in respective PDWs is plotted on a map on the display device **144** along with locations of respective radar signal emitters **106** and **107** to facilitate accurate tracking of locations and association with those particular radar signal emitters. In cases where at least one radar signal emitter is mobile, the map on display device **144** updates location information of at least one respective mobile radar signal emitter in substantially real time. Furthermore, the computing device **132** determines at least one of a velocity, an acceleration, a trajectory, and a track (i.e., including present and prior locations) of one or more mobile radar signal emitters (e.g., radar signal emitters **106** and **107**). In another mode of operation, characteristics determined by signal data processing methods implemented by the signal data processor **101** may trigger a variety of substantially real-time physical actions in physical devices and systems in communication with the signal processing system **100**. For example, characteristics of various radar signal emitters, including frequency and bandwidth determined by signal data processing methods implemented by signal processing system **100**, may be transmitted in substantially real time as data to actuator controller **150** in vehicle **146** (e.g., rudders and flaps of a unmanned aerial vehicle) to facilitate maneuvers thereof, for example, to avoid an area of operation of an unauthorized radar signal emitter determined to be a threat or to move toward the unauthorized emitter to eliminate the threat. As a further example, characteristics of radar signal emitters **106** and **107** determined by signal data processing methods described herein may be transmitted in substantially real time in a control signal to at least one of an electronic support measure (ESM) device and an EW system associated with signal processing system **100** to direct, for example, a radar jamming signal at a particular radar signal emitter operating in the surveillable environment of sensor **103** without authorization.

Each SST channel **20** in signal processing system **100** implements filtering methods with dynamic updating to generate high-quality PDWs containing at least one of amplitude, frequency, center frequency, bandwidth, pulse time of arrival, and pulse width information. In operation, each SST channel **20** separates a respective detected signal. Each SST channel **20** includes a tunable filter that operates in accordance with filter parameters that include, without limitation, a center frequency and a bandwidth generated by the cueing system **10**. In operation, each tunable may be embodied as a finite impulse response (FIR) filter or an infinite impulse response (IIR) filter. In an exemplary implementation, use of IIR-type filters enables lower-cost filter devices having greater precision than FIR-type filters.

The frequency and bandwidth estimation method disclosed herein uses the filter response of a pair of IIR filters to estimate frequency f and bandwidth w in noise and with very low latency. The method disclosed herein directly measures f and w within a fixed band and thus does not operate in a blind fashion. The method also allows a cueing system to update tracking filters in a plurality of SST channels.

FIG. **2** is a block diagram identifying components of a signal processing system **100** in accordance with one embodiment. The cueing system **10** includes a respective signal frequency/bandwidth estimator for each band of interest. In the example depicted in FIG. **2**, one signal frequency/bandwidth estimator **12***a* for band A and another signal frequency/bandwidth estimator **12***b* for band B are shown. Each cueing signal frequency/bandwidth estimator includes a pair of overlapping fixed filters and signal processing circuitry that performs the process depicted in FIG. **8** (described in detail below). The cueing system **10** detects the presence of signals at certain frequencies and bandwidths. Noise reduction is done using the signal separation and tracking filters (e.g., tunable filter **24** in FIG. **2**).

Each cueing signal frequency/bandwidth estimator outputs data to a corresponding SST channel **20**. Only one such channel, corresponding to signal frequency/bandwidth estimator **12***b*, is shown in FIG. **2**. The SST channel **20** shown in FIG. **2** has the following components: (1) a plurality of filter coefficient lookup tables **16** in which values for respective filter coefficients (β, α) are stored; (2) a threshold lookup table **18** storing threshold values T; (3) an SST channel state machine **14**; (4) a tunable filter **24**; and (5) an input buffer **22**. In response to frequency and bandwidth estimates received from the signal frequency/bandwidth estimator **12***b*, filter coefficient lookup tables **16** output filter coefficients to tunable filter **24**. The frequency and bandwidth estimates output by signal frequency/bandwidth estimator **12***b* are also input to the SST channel state machine

14 and the threshold lookup table **18**. Also the outputs x_{lo} and x_{hi} from high and low filters of the signal frequency/bandwidth estimator **12***b* are input to the SST channel state machine **14**. (As used herein, the terms "low filter" and "high filter" are used in conjunction to refer to a pair of filters having relatively lower and relatively higher center frequencies.) In addition, input buffer module **22** receives a delay signal from signal frequency/bandwidth estimator module **12***b*. This delay signal controls when the filter input signal is sent from the input buffer **22** to the tunable filter **24**.

As used herein, the term "β" in the phrase "filter coefficients (β, α)" refers to a number of feedforward filter coefficients equal to or greater than two; the term "α" in the phrase "filter coefficients (β, α)" refers to a number of feedback filter coefficients equal to or greater than unity. For example, the tunable filter **24** may be a second-order IIR filter having three feedforward filter coefficients β_0, β_1, and β_2 and two feedback filter coefficients α_1 and α_2, for a total of five filter coefficients. In that case, a respective filter coefficient lookup table **16** is provided for each of the five filter coefficients needed to tune the tunable filter **24**. In response to frequency and bandwidth estimates received from the signal frequency/bandwidth estimator **12***b*, those five lookup tables would output the five filter coefficients to tunable filter **24**.

The frequency and bandwidth estimation method employed in the system partly depicted in FIG. **2** requires a pair of partially overlapping fixed filters for each frequency band of interest. FIG. **3** shows the filter responses as a function of frequency for four consecutive fixed filters (hereinafter "cueing filters") with overlapping filter responses that can monitor three bands of interest (bands A, B, and C in FIG. **3**) as shown, by using each consecutive filter pair. For example, a signal frequency/bandwidth estimator based on a consecutive filter pair which covers the frequency range $[f_{lo}, f_{hi}]$, where the center frequency is f_0 (with amplitude response ½ in the case shown in FIG. **3**), will be used in the discussion that follows. Each filter pair includes first and second fixed filters having partially overlapping bandwidths that include a frequency range bounded by lower- and upper-bound frequencies f_{lo} and f_{hi} and having center frequency f_0. The first fixed filter of the pair has a center frequency equal to the lower-bound frequency f_{lo} and the second fixed filter of the pair has a center frequency equal to the upper-bound frequency f_{hi}. For example, signal samples may be input to first, second, and third filters having first, second, and third bandwidths respectively, wherein the first and second bandwidths are partially overlapping, the second and third bandwidths are partially overlapping, and the first and third bandwidths are not partially overlapping;

FIG. **4** is a block diagram identifying components of a cueing system **10** in accordance with one embodiment. The cueing system **10** uses an array of IIR filters that cover a wide input band of interest, together with an inverted state tree **1** of nodes. The parabolic curves in FIG. **4** represent the respective signals **25** which are passed by the IIR filter array (not shown in FIG. **4**). The IIR filters are configured such that adjacent pairs of IIR filters pass signals x_{hi} and x_{lo} having respective frequency bands which partially overlap and have different center frequencies. Those signals are sent to a respective pre-detection estimator **11** (PDE **11** in FIG. **4**) and to a respective frequency/bandwidth estimator **12** (FBE **12** in FIG. **4**). Thus, each pre-detection estimator **11** and associated (paired) frequency/bandwidth estimator **12** receives signals x_{hi} and x_{lo} from a respective pair of adjacent high and low filters (not shown in FIG. **4**, but see high filter **28** and low filter **26** in FIGS. **7** and **8**).

The inverted state tree **1** consists of multiple levels of nodes, the number of nodes in each level decreasing in ascending order. Each non-root node is connected to two nodes in the level below. The first level of nodes includes root nodes **2**. Each root node **2** receives data from a respective pre-detection estimator **11** and associated frequency/bandwidth estimator **12**. The second level of nodes includes non-root nodes **4** (hereinafter "nodes **4**"). Each node **4** receives data from two root nodes. For example, the first node **4** in the second level receives data from the first and second root nodes; the second node **4** in the second level receives data from the second and third root nodes; and so forth. Multiple intervening levels of nodes are not shown in FIG. **4**. Assuming the number of levels of nodes equals N, the (N−1)-th level includes two non-root nodes **6** (hereinafter "nodes **6**"), while the N-th level includes a single non-root node **8** (hereinafter "node **8**"). As seen in FIG. **4**, node **8** receives data from nodes **6**. The vertical double-headed dashed arrows in FIG. **4** indicate that each node is communicatively coupled to the SST subsystem **120**. Via this communication path, the node may send an SST channel request and channel parameters and updates to the SST subsystem **120** and receive NOSIGNAL_C and CHANNEL_C/NOCHANNEL messages (described in more detail below) from the SST subsystem **120**.

There are two main purposes for the inverted state tree **1** of nodes. One purpose is to accurately report frequency intervals to the SST subsystem **120** by joining together intervals for wider bandwidth signals that cover more than one filter pair. The other purpose is to pre-detect the presence of a signal in the reported frequency interval before requesting a tracking channel from the SST subsystem **120**, thereby conserving channel resources within the SST subsystem **120**.

The cueing system **10** depicted in FIG. **4** operates as follows:

Incoming signals **25** pass into the cueing filters at the bottom of FIG. **4** and filter outputs are created for each filter.

The output of each pair of adjacent filters is input to both a pre-detection estimator **11** (described in the following section entitled "Cueing Detection Method") and a frequency/bandwidth estimator **12** (described in the following section entitled "Cueing Signal Frequency/Bandwidth Estimator" with reference to FIGS. **7** and **8**). The estimators input a frequency/bandwidth estimate (f, w) and a pre-detection estimate d into each root node **2**. Each root node **2** has seven inputs and four outputs (except on the left and right ends which have six inputs and three outputs).

The next level of nodes **4** join together (form the union of) any (f, w) intervals (which is the interval in frequency from (f−w/2) to (f+w/2), denoted by [f−w/2, f+w/2]) which are adjacent or overlapping. FIGS. **5**A and **5**B show examples of this joining. (For the purpose of illustration, it is assumed that the parent nodes are root nodes **2** and the child node is a non-root node **4**; however, the same principles apply when the parent nodes and the child node are all non-root nodes.) As seen in FIG. **5**A, if the high and low filters of a pair of adjacent filters pass respective signals having estimated bandwidths which are non-overlapping, then each parent node reports separate (f, w) values to respective SST channels. In this example, parent node #**1** is outputting data representing a bandwidth (frequency interval) $[f_1-w_1/2, f_1+w_1/2]$ having a center frequency f_1, while parent node #**2** is outputting data representing a frequency interval $[f_2-w_2/2, f_2+w_2/2]$) having a center frequency f_2. Conversely, as seen in FIG. **5**B, if the high and low filters pass respective signals having estimated bandwidths which are partially overlapping (or adjacent), then the parent nodes do not report (f, w) values to the SST channels. Instead the child node **4** joins the two frequency intervals and reports (f, w) values for the combined frequency interval to an SST channel. In this example, parent node #**1** is outputting data representing a frequency interval $[f_1-w_1/2, f_1+w_1/2]$ having a center frequency f_1 and parent node #**2** is outputting data representing a frequency interval $[f_2-w_2/2, f_2+w_2/2]$ having a center frequency f_2, which causes node **4** to output data representing a frequency interval $[f-w_1/2, f+w_2/2]$ having a center frequency $(f_2+w_2/2+f_1-w_1/2)$. If higher nodes have no further interval joining, requests for an available SST channel are sent. If an SST channel is made available, parameters and updates including frequency and bandwidth are passed to each channel which is made available. This next level and subsequent ones up to one level below the top node have six inputs and six outputs (except for the left and right nodes which have five inputs and five outputs).

Further levels of nodes continue this process of joining frequency intervals together and sending requests as described above, all the way to the top-level node **8**. The top level node **8** only has four inputs and four outputs.

The details of the process that occurs in each tree node is described as a state machine in the following section entitled "Tree Node State Machine".

Tree Node Description

Each tree node has the job of joining together signal frequency and bandwidth results from nodes below and sending information to nodes above and below to produce final frequency and bandwidth estimates for both narrow and wideband signals and request the signal separation and tracking be started, as shown in FIG. **4**. For example, if the two parent nodes below report signals with bandwidth W and adjacent frequency intervals, the current node would infer that the signal actually has twice the bandwidth **2**W with center frequency halfway between the two. The operation of each tree node (root and non-root) is best described by a state machine diagram.

FIG. **6** shows such a state diagram together with the inputs and outputs of a node. This state diagram is applicable to both root nodes and non-root nodes. If the center node is assumed to be a root node, then the lower left and right nodes would not be present. If the center node is assumed to be the single top-level non-root node, then the upper left and right nodes would not be present. If the center node is assumed to be a non-root node on the second level, then only one upper node (the top-level non-root node) would be present.

Assuming that the central node depicted in FIG. **6** is a root node, then the seven inputs of the root node are the following:

Three inputs from below: the estimates for frequency f and bandwidth w from the frequency/bandwidth estimator **12** and the estimate for pre-detection metric d from the pre-detection metric estimator **11**. These form the basic frequency intervals that the inverted state tree **1** uses to infer the final joined frequency intervals.

Two signals from above: the NOSIGNAL_C from the tracking SST channel and the CHANNEL_C/NOCHANNEL signal from the SST system. NOSIGNAL_C is sent

by the C channel of the SST system to indicate that a signal has gone away. The CHANNEL_C/NOCHANNEL signal is sent back to the requesting cueing node to indicate that either channel C is available for tracking or no channel is available.

Two status states from the upper left and right nodes: UL(S) and UR(S): These are used to prevent the current node from requesting an SST channel if an upper node is doing the requesting.

The four outputs of the root node are the following:

Two outputs of frequency, bandwidth, and pre-detection metric state values (F, W, D) to the nodes above and to the left and right, denoted by UL(F, W, D) and UR(F, W, D). The upper nodes use these values to join together frequency intervals if needed.

An SST Channel Request to the SST system. This is sent if a signal is present in the current frequency interval and no upper nodes have prevented it.

State values (F, W) to channel C of the SST system to initiate tracking. This is sent if a CHANNEL_C available signal has been received previously.

Assuming that the central node depicted in FIG. **6** is a non-root node on the third level or lower, the six inputs of a non-root node are the following:

Two inputs from the lower left and right nodes containing their state values LL(F, W, D) and LR(F, W, D).

Two signals from above: the NOSIGNAL_C signal from the tracking SST channel and the CHANNEL_C/NOCHANNEL signal from the SST system.

Two status states from the upper left and right nodes: UL(S) and UR(S).

The six outputs of the non-root node are the following:

Two outputs of frequency, bandwidth, and pre-detection metric state values (F, W, D) to the nodes above and to the left and right, denoted by UL(F, W, D) and UR(F, W, D).

Two outputs of the current node status S to the nodes below and to the left and right, denoted by LL(S) and LR(S).

An SST Channel Request to the SST system.

State values (F, W) to channel C of the SST system to initiate tracking.

Finally, note that the first and last nodes on each level have fewer inputs and outputs than is listed here due to no node existing to the left or right. Also, the highest node has fewer inputs and outputs. The next section describes what happens in each state to produce these inputs and outputs.

Tree Node State Machine

Each node has five states and the following internal state vector with state values (F, W, D, S, C). The states are as follows: (1) Power on/Initialize buffers; (2) Update Tree Node Values state; (3) Idle state; (4) Request SST Channel state; and (5) Connect Output to SST Channel state. The state machine generally moves through the state machine in the order (1)→(2)→(2) . . . and (1)→(3)→(4)→(5)→(3) . . . as shown on a magnified scale in FIG. **6**A. Each of these state transitions is described in detail below, along with how the state values are updated.

1. Power On/Initialize Buffers. The buffers and registers in the various parts of each tree node are initialized at power-on, including setting all the status values to NOPREDETECT. Then the state transitions to both Idle and Update tree node values.

2. Update Tree Node Values State. This state always runs after power up and continuously updates the state values (F, W, D, S, C). Using the tree node notation, each tree node takes in the state values from the low LL(F, W, D) and high

LR(F, W, D) parent nodes (or f, w, d if it is the root node) below in the inverted tree structure and the status in the child nodes above denoted by UL(S) and UR(S).

(a) First, how the root nodes get updated is explained. In this case, the state values (F, W) are set to the outputs of the learned filter response described in the following section entitled "Cueing Signal Frequency/Bandwidth Estimator". Similarly, the pre-detection state D is set to the cueing detection estimate $d(x_{lo}, x_{hi})$ described in the following section entitled "Cueing Detection Method". Also, the status S is set based on the threshold $D_{pd}=D_{pd}(x_{lo}, x_{hi})$ and the status from the upper nodes UL(S) and UR(S). Specifically if both UL(S) and UR(S) are NOPREDETECT, then if $d<D_{pd}(x_{lo}, x_{hi})$ and both UL(S) and UR(S) are NOPREDETECT, the root node sets S to NOPREDETECT, and otherwise the root node sets S to PREDETECT. Otherwise, if either UL(S) or UR(S) is PREDETECT, then S is set to NOPREDETECT.

(b) Next, how the non-root nodes get updated is explained. In this case, the state values (F, W, D) are set by joining the two frequency intervals from LL(F, W, D) and LR(F, W, D) based on whether the intervals from LL(F, W) and LR(F, W) are adjacent (also overlap as seen in FIG. **5**B) or disjoint (as seen in FIG. **5**A) and what the pre-detection metric state values LL(D) and LR(D) are. Specifically, the non-root node forms new state values (F', W', D') as in FIG. **5**B if the intervals can be joined and if

$$D_0=(LL(D)+LR(D))/2>D_{pd}.$$

In FIGS. **5**A and **5**B, the notation (f1, w1)=LL(F, W) and (f2, w2)=LR(F, W) is used. Otherwise, the state values (F, W, D) are left blank. Similarly, the status S is NOPREDETECT unless the frequency intervals are joined, and the status is set based on the status from the upper nodes UL(S) and UR(S). Specifically if both UL(S) and UR(S) are NOPREDETECT, then S is set to PREDETECT. Otherwise, if either UL(S) or UR(S) are PREDETECT, then S is set to NOPREDETECT. The non-root node has two additional state outputs to the nodes below left and right called LL(S) and LR(S) that get updated based on the current status S.

3. Idle State. The Idle state simply waits for the tree state node status S to change to PREDETECT and then transitions to the Send SST Channel Request state.

4. Send SST Channel Request State. A request is sent to the SST resource manager (which is a module within the SST controller **126** identified in FIG. **1**) requesting an available SST channel **20** for processing a detected signal. Either a channel identifier C is returned or no channel is available. In the first case, the state transitions to the Connect Output to SST Channel state and the current channel C is set in the state vector. In the second case, the state transitions back to the Idle state.

5. Connect Output to SST Channel State. The state values (F, W) are passed to SST channel C as the frequency and bandwidth settings for tuning its tracking filter and the incoming digital signal is connected to the input of the SST channel C tracking filter. When the SST channel goes into a NOSIGNAL state (in other words, it is in its SST Idle state for a given amount of time), the state transitions back to the Idle state with S=NOPREDETECT and C is set back to 0, indicating no channel in use.

Cueing Detection Method

Cueing detection is a pre-detection step that is used to reduce the usage of the limited SST channels available. While the SST channel produces the actual detection decision through a SIGNAL or NOSIGNAL value, the pre-detection step must be used in order to generate this value.

If every cueing filter simply used a SST channel all the time, this would reduce their availability since there would likely be more cueing filters than SST channels. In order to reduce their usage, a pre-detection step is used. This works as follows:

The pre-detection metric $d(x_{lo}, x_{hi})=d=|x_{lo}-x_{hi}|_W/(x_{lo}+x_{hi})_W$ (written in vector form) is computed at every filter update at each tree node in the Update Tree Node Values state. This is shorthand for the following computation:

$$d=\left(\sum_{i\in W}|(x_{lo}(i)-x_{hi}(i))(x_{lo}(i)+x_{hi}(i))|\right)\Big/\left(\sum_{i\in W}(x_{lo}(i)+x_{hi}(i))^2\right)$$

The pre-detection metric d measures a normalized signal energy by dividing the sum of the energy differences between the outputs of the low and high filter pair (the difference between the signal energies) by the sum of the energies of those outputs (the sum of the signal energies). During the Idle state, the pre-detection metric d is compared to the learned metric $D_{pd}(x_{lo}, x_{hi})$ to determine whether $d<D_{pd}(x_{lo}, x_{hi})$ or not. A computer simulation is used to set this value based on the desired probability of detection (P_d) (see FIGS. **9** and **10**). If the pre-detection metric d meets this test, a cueing pre-detection labeled PREDETECT is declared and an SST channel is requested; otherwise NOPREDETECT is declared and no SST channel request is sent.

The learned metric $D_{pd}(x_{lo}, x_{hi})$ is stored in a 2-D interpolating lookup table. The metric can be learned by simulating a pair of filtered signals within a grid of frequencies and bandwidth in various levels of noise at a given probability of detection (P_d=0.9 for example).

FIGS. **9** and **10** show the performance of this metric as a function of frequency offset and SNR for two bandwidth cases: BW=0.01 (FIG. **9**) and BW=0.1 (FIG. **10**). Clearly, except for small frequency offsets near 0 (where the two filters have similar responses and thus are hard to distinguish from noise), the false alarm probability is very small (indicating that except for a small percentage of time, the request for a SST channel is actually needed) and the signal bandwidth has very little effect. Thus, the usage of the SST channel resource is managed very directly and efficiently using the learned metric $D_{pd}(x_{lo}, x_{hi})$.

Cueing Signal Frequency/Bandwidth Estimator

FIG. **7** is a diagram representing both functions of a process and functional modules of electronic circuitry which is configured to perform frequency and bandwidth estimation of signals output by a pair of overlapping fixed filters. The overlapping fixed filters include a low filter **26** and a high filter **28**. The functions of the process identified in FIG. **7** are performed by electronic circuitry configured as data processing modules and lookup tables. The digital data is processed in a streamlined manner as indicated by arrows in FIG. **7**. From left to right, the steps of the process in accordance with one proposed implementation are as follows:

1. The low filter **26** and high filter **28** produce respective outputs at every incoming sample, where x_{lo} is the output of the low filter **26** and x_{hi} is the output of the high filter **28**.

2. The filter outputs x_{lo} and x_{hi} are fed into a feature vector computation module **63** which produces four feature vectors: y_{lo1} and y_{lo2} are the two low-filter feature vectors (to be used when the signal is estimated to have a center frequency less than f_0). Similarly, y_{hi1} and y_{hi2} are the two high-filter

feature vectors (to be used when the signal is estimated to have a center frequency more than f_0).

3. Then pairs of the feature vectors go into four 2-D interpolating lookup tables **64***a*-**64***d* which have been trained through a machine learning process to provide best estimators of frequency offset and bandwidth. More specifically, feature vectors y_{lo1} and y_{lo2} are input to frequency offset lookup table **64***a* and bandwidth lookup tables **64***b*; while feature vectors y_{hi1} and y_{hi2} are input to frequency offset lookup table **64***c* and bandwidth lookup table **64***d*. As a result, frequency offset and bandwidth estimates for the frequency range $[f_{lo}, f_0]$ are read out from frequency offset and bandwidth lookup tables **64***a* and **64***b* respectively; while frequency offset and bandwidth estimates for the frequency range $[f_0, f_{hi}]$ are read out from frequency offset and bandwidth interpolating lookup tables **64***c* and **64***d* respectively. Each lookup table (LUT) produces an interpolated frequency offset and then a respective post-LUT adder **65***a*-**65***d* adds the center frequency f_0 for each LUT to produce the final frequency estimate f.

4. The four output values corresponding to the lower and higher frequency and bandwidth estimates go into a decision process **66** that selects and reports a final frequency and bandwidth estimate depending on whether a windowed sum squared of the output of the low filter **26** (designated Sx_{lo} in FIG. **7**) is less or more than the windowed sum squared of the output of the high filter **28** (designated Sx_{hi} in FIG. **7**) (step **68**).

The feature vector computation module **63** is configured to compute the aforementioned feature vectors. More specifically, electronic circuitry is configured to compute feature vectors in accordance with the process **30** depicted in FIG. **8**. The operations of process **30** are first explained mathematically and then described in more detail.

If x_{lo} is the output of the low filter F_{lo} and x_{hi} is the output of the high filter F_{hi}, one may compute a pair of features (or parameters) (y_{lo1}, y_{lo2}) associated with the frequency range $[f_{lo}, f_0]$ and a pair of features (or parameters) (x_{hi1}, x_{hi2}) associated with the frequency range $[f_0, f_{hi}]$ and then choose the best pair for estimation. The purpose of this split at the center frequency f_0 is to help with creating a grid of points so that learning the frequency offset Δf and bandwidth w estimates from these parameters is robust with respect to noise. Note that when the frequency offset Δf from the center frequency f_0 is estimated, one can then estimate the true frequency using $f_0+\Delta f$.

The process of learning Δf and w from the feature vectors can be done in different ways. One common method uses neural networks which have layers of linear combiners followed by non-linear elements. The learning takes place by generating a training set of data to find the linear combiner coefficients so that when two feature vectors are input, the resulting output of estimated Δf and w is accurate. Essentially, this learning is a means to interpolate an unknown nonlinear function in two dimensions by generating many example values that cover the range of the input and output. However, since one needs to both create a very low latency interpolation method and use resources effectively in an implementation such as an FPGA, an alternative learning method is used whereby a training set of data is generated and then a 2-D grid is imposed on the data with output values assigned to each grid element. This grid is then stored in a lookup table and the output of the lookup table is then interpolated using a linear interpolation in two dimensions. This creates a low latency method to give frequency and bandwidth estimates directly from filter pair outputs. In accordance with one proposed implementation, the 2-D interpolating lookup table may be implemented using block random access memory elements in an ASIC or a FPGA.

If these features on plotted on a graph where each grid point indicates a particular generated signal of a known frequency and bandwidth, a pair of distorted nonlinear 2-D grids would be created. Overlaid on these grids are contours showing both frequency offset and bandwidths. By creating a 2-D lookup table with interpolation for frequency offset and a 2-D lookup table with interpolation for bandwidth, the system has in effect learned an approximation that takes filter values and produces important parameters of interest.

Next, the concepts underlying the feature vectors will be described. The basic idea is to create simply computed independent features that are roughly related to the parameters of interest (namely center frequency and bandwidth) and then use machine learning to make a more direct connection to those parameters. As described in more detail below, the second features (y_{lo2}, y_{hi2}) are produced by the windowed sum of the product of the two filtered signals (x_{lo}, x_{hi}) divided by the windowed sum of the squared sum of their amplitudes. This is then related to a measure of frequency offset because it is essentially the least square solution of the best scalar estimate of $\pm(x_{hi}-x_{lo})/(x_{hi}+x_{lo})$, which essentially measures the overall normalized difference in time between the two signals and this in turn is related to their frequency difference since the closer they are in frequency, the closer this normalized difference is to zero.

The first features (y_{lo1}, y_{hi1}) are based on creating a complex signal from the low filter and a complex signal from the high filter through an approximate I, Q process. However, instead of mixing against a sine and cosine of the appropriate center frequency (as the I, Q process would do), a simple interpolated delay is used, based on the center frequency f_0 of the filter pair. Then each of the two complex signals is inverted and mixed against the other. This creates two complex signals that represent roughly their low-to-high frequency difference and their high-to-low frequency difference. Then the second feature is subtracted/added so that a rough frequency difference is zeroed out. Thus, these complex signals should essentially be nearly constant (and have nearly zero variance) if a zero bandwidth single tone is present. By contrast, when wider bandwidth signals are present, the variance (or standard deviation) of these complex signals is then related to a measure of bandwidth.

Note that these features are not directly frequency offset and bandwidth; that is where the learning takes place through feature generation that trains interpolating lookup tables. Mathematically, the feature vector formation process may be described as follows. First, the construction of a complex signal is approximated through simple delays and interpolation, leading to the complex mixed signal

$$z=(x_{lo}+i\ \widehat{x_{\mathrm{lo}}})/(x_{hi}+i\,\widehat{x_{\mathrm{hi}}}) \tag{1}$$

where

$$\widehat{x_{\mathrm{lo}}}\,(n)=(1-r)x_{lo}(n-d)+rx_{lo}(n-d+1) \tag{2}$$

and similarly for $\widehat{x_{\mathrm{hi}}}$. Here

$$r=\mathrm{rem}\left(\frac{1}{f_0},1\right)$$

and

$$d=\left\lfloor\frac{1}{f_0}\right\rfloor$$

and all frequencies are in normalized form from 0 to 1. Also

$$y_{lo2}=\Sigma_W(x_{hi}x_{lo})/\Sigma_W(x_{hi}^2+x_{lo}^2) \tag{3}$$

Then

$$y_{lo1}=\text{std}_W(\text{real}(z))+\text{std}_W(\text{imag}(z))+y_{lo2} \tag{4}$$

where the function "std" denotes the standard deviation of the sample within a sliding time window W. In a similar manner, the parameters (y_{hi1}, y_{hi2}) may be defined by switching the roles of x_{hi} and x_{lo} in Eqs. (1)-(4).

The step-by-step process shown FIG. **8** will now be explained described in more detail:

1. The inputs to the process are the outputs x_{lo} and x_{hi} from the low and high filters.

2. An approximate complex baseband version of each signal is created ((x_{lo}+i $\widehat{x_{\text{lo}}}$) and (x_{hi}+i $\widehat{x_{\text{hi}}}$)) before inversion and complex multiplication. The imaginary part must be created from a delayed and interpolated version of the original signal as given in Eq. (2) for the low channel. Here delay nf_0 is the number of sample delays represented by d and the other delay is a single sample delay.

3. Each low and high filter channel has an approximate complex signal having real and imaginary parts which are sent along lines labeled "real" and "imag" that lead to each of the complex multipliers **36** and **56**.

(a) The complex signal is sent to a complex multiplier which multiplies it with the complex inverse of the other channel.

(b) The complex signal is sent to a complex inverse lookup table **37** or **57** to compute the complex inverse that is used by the complex multiplier in the opposite channel.

(c) The real part of the complex signal (the original filter output) is sent to a squaring circuit **38** or **58** and then summed over a window of samples to produce $E_W(x_{hi}^2+x_{lo}^2)$.

(d) Lastly, the original real signals x_{lo} and x_{hi} are also sent to a multiplier **44** and then window summed to produce $E_W(x_{hi}x_{lo})$ before computing the final ratio for the outputs y_{lo2} and y_{hi2} (where the sign is inverted).

4. Then the real and imaginary parts of the two complex channels (x_{lo}+i $\widehat{x_{\text{lo}}}$)/(x_{hi}+i $\widehat{x_{\text{hi}}}$) and (x_{hi}+i $\widehat{x_{\text{hi}}}$)/(x_{lo}+i $\widehat{x_{\text{lo}}}$) have their standard deviations computed in a windowed fashion and summed before outputting viol and y_{hi1}.

To comply with the requirement that all numbered elements in a drawing be described in the specification, the following more detailed description of the methodology depicted in FIG. **8** is provided.

The low filter output x_{lo} is processed in five different ways. First, the low filter output x_{lo} is the real part input to a complex multiplier **36**. Second, the low filter output x_{lo} is delayed by a time nf_0 (step **31**), which delayed value is further processed (as explained below) to produce the complex part which is input to complex multiplier **36**. Third, the amplitude of the low filter output x_{lo} is squared by the squaring circuit **38**. Fourth, the low filter output x_{lo} is mixed with the high filter output x_{hi} to from their product (step **44**). Fifth, the low filter output x_{lo} is input to the complex inversion lookup table **37**.

The delayed low filter output x_{lo} is processed in two ways to derive an imaginary part. First, the delayed low filter output x_{lo} is mixed with parameter $(1-r)x_{lo}$ (step **32**) Second, the delayed low filter output x_{lo} is further delayed (step **34**), which further delayed value is mixed with parameter rx_{lo} (step **35**). The results of mixing steps **32** and **35** are then summed (step **33**) to form an imaginary part which is sent to complex multiplier **36**. The real and imaginary parts are also complex inverted by the complex inversion lookup table **37** and sent to complex multiplier **56**.

The complex multiplier **36** outputs real and complex parts of a complex number (see Eq. (1)). Those real and imaginary parts are respectively received by windowed variance circuits **40***a* and **40***b*, which compute the standard deviation of the samples within a sliding window (see Eq. (4)).

Likewise, the high filter output x_{hi} is processed in five different ways. First, the high filter output x_{hi} is the real part input to the complex multiplier **56**. Second, the high filter output x_{hi} is delayed by a time nf_0 (step **51**), which delayed value is further processed (as explained below) to produce a complex part which is input to complex multiplier **56**. Third, the high filter output x_{hi} is squared by the squaring circuit **58**. Fourth, the high filter output x_{hi} is mixed with the low filter output x_{hi} to from their product (step **44**). Fifth, the high filter output x_{hi} is input to the complex inversion lookup table **57**.

The delayed high filter output x_{hi} is processed in two ways to derive an imaginary part. First, the delayed high filter output x_{hi} is mixed with parameter $(1-r)x_{hi}$ (step **52**). Second, the delayed high filter output x_{hi} is further delayed (step **54**), which further delayed value is mixed with parameter rx_{hi} (step **55**). The results of mixing steps **52** and **55** are then summed (step **53**) to form an imaginary part which is sent to complex multiplier **56**. The real and imaginary parts are also complex inverted by the complex inversion lookup table **57** and sent to complex multiplier **36**.

The complex multiplier **56** outputs real and complex parts of a complex number. Those real and imaginary parts are respectively received by windowed variance circuits **60***a* and **60***b*, which compute the standard deviation of the samples within a sliding window.

Still referring to FIG. **8**, it can be seen that the low filter output x_{lo} and the high filter output x_{hi} are mixed (step **44**), while squaring circuit **38** forms the square of the amplitude of low filter output x_{lo} and squaring circuit **58** forms the square of the amplitude high filter output x_{hi}. The outputs of windowed sum circuits **39** and **59** are summed (step **46**) and then inverted (step **47**). The outputs of the mixer that performs step **44** and the inverter that performs step **47** are then mixed (step **48**) to form parameter y_{lo2} (see Eq. (3)). The windowed variances output by windowed variance circuits **40***a* and **40***b* and the parameter y_{lo2} are summed (step **42**) to form the parameter y_{lo1}. The windowed variances output by windowed variance circuits **60***a* and **60***b* and the parameter y_{lo2} are summed (step **62**) to form the parameter y_{hi1}. The sign of parameter y_{lo2} is reversed (step **50**) to form the parameter y_{hi2}.

Signal Tracking Lookup Table for Filter Coefficients

A tunable filter, such as the tracking filter in an SST channel, requires updating filter coefficients. To do this quickly, a lookup table method is required. U.S. Pat. No. 9,954,561 discloses an embodiment in which the filter module implements an interpolation process to enable determination of the final values of filter coefficients α and β to provide the updates within two hardware clock cycles. The updated center frequency and bandwidth signal contained at least one of a frequency word and a bandwidth word including a frequency value and a bandwidth value, respectively. Substantially simultaneous with transmission of the updated center frequency and bandwidth signal from the BSS channel state machine module, the tracking algorithm used a lookup and interpolation routine with a table of fixed coefficients stored in memory to determine the updated filter coefficient values α and β 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 α and β were updated in memory to enable subsequent cycles of lookup, interpolation, and update of filter coefficients α and β for subsequent instances of filter input signal. Thus, in two hardware clock cycles, the filter module enabled the signal processing system to quickly and adaptively track quickly changing incoming radar signals (e.g., broad band chirps) without glitches as fast as the updated center frequency and bandwidth signal is transmittable from the BSS channel state machine module, and to switch between radar signals at widely separated frequencies in real time.

The tracking filter disclosed in U.S. Pat. No. 9,954,561 used frequency as its only input parameter for adjusting the coefficients of a second-order IIR filter. In the approach described herein with the SST channel, both frequency and bandwidth need to be used to both track in frequency and bandwidth. For example, with a triple pipelined second-order IIR filter, there would need to be nine 2-D interpolating lookup tables.

Signal Tracking Lookup Table for Threshold

The threshold T controls the starting and stopping of signal tracking in the SST channel **20**. Specifically, the SST channel **20** determines whether a signal is present in the tracking filter or not by estimating the SNR and when SNR is above a certain threshold T for reliable tracking, a signal is declared present. If r=S/N (the SNR, where S is the signal energy and N is noise), then

$$S/(S+N)=r/(r+1).$$

Assuming a window of time t, take E(y) to be the estimated signal energy S over that time, i.e., signal power. The cueing filters must contain both signal and noise with energy (S+N) over time t. The signal energy S will be overestimated because the only measurements from the filter energies $E(y_{lo})$ and $E(y_{hi})$ contain a certain amount of overlap. Taking the filter responses and overlaps and the frequency and bandwidth (f, w) of the signal into account for a fixed value of r, a single parametric function $T=T_r(f, w)$ can be learned for each filter pair in the cueing system and each frequency and bandwidth value through an offline learning step like the previous one for frequency an d bandwidth. From this, a lookup table can be created so that it is approximately true that

$$E(y)/(E(y_{lo})+E(y_{hi}))\approx T_r(f,w)$$

for an SNR value r. Therefore, a value of r can be chosen as the operating SNR level for the SST channel and a single two-input lookup table (with optional interpolation as shown below) can be created to regulate the starting and stopping of tracking in the SST channel at the correct operating SNR level. The implementation of this table on an FPGA or ASIC is described below.

In view of the foregoing detailed description, a method for cueing signals in accordance with one embodiment may be characterized as indicated in FIG. **11**, which is a flowchart identifying steps of a signal cueing method **200**. The signal cueing method **200** starts by transducing electromagnetic radiation that carries a repetitive signal into an analog electrical signal (step **202**). Then the analog electrical signal is converted to digital signal samples (step **204**). The signal samples are input to first, second, and third filters configured to pass signals having first, second, and third bandwidths respectively (step **206**). The first and second bandwidths are partially overlapping; the second and third bandwidths are partially overlapping; and the first and third bandwidths are not partially overlapping. First, second, and third filtered signal samples are output from the first, second, and third filters respectively in response to inputting the digital signal samples (step **208**). Then the first and second filtered signal samples are processed to generate digital data representing a first estimated frequency and a first estimated bandwidth (step **210**) and generate digital data representing a first estimated pre-detection metric (step **212**). Similarly, the second and third filtered signal samples are processed to generate digital data representing a second estimated frequency and a second estimated bandwidth (step **214**) and generate digital data representing a second estimated pre-detection metric (step **216**). The first and second estimated bandwidths are joined to form a wider bandwidth that is a union of first and second estimated bandwidths (step **218**). Also, a center frequency of the wider bandwidth is calculated (step **220**). Then filter coefficients which are functions of the calculated center frequency and the wider bandwidth are generated for an available tunable filter if the first and second pre-detection metrics are greater than a specified threshold (step **222**). Finally, the available tunable filter is tuned in accordance with the filter coefficients (step **224**). The incoming signals samples are then filtered by the tuned filter.

The system described above provides an efficient and low-latency means for cueing the process of signal separation, detection, and tracking in a wideband receiver. The disclosed method uses an array of IIR filters that provide the directions for separating, detecting, and tracking multiple simultaneous signals being received. To summarize, the innovative cueing process disclosed herein has the following advantageous features: (1) low latency cueing pre-detection of signals to reduce SST channel usage; (2) detection performance is dependent directly on the signal bandwidth and SNR rather than on the receiver channel bandwidth; (3) directly commands filter coefficients (or equivalently center frequency and bandwidth) tailored to separate each detected signal; and (4) efficient implementation as an array of IIR filters with a tree of decision nodes that together create the cueing system.

These provide benefits including low latency and efficient signal separation and classification as part of any wideband receiver. Thus, the approach adopted herein replaces a channelized approach that is inefficient in terms of hardware usage and has higher latency and poorer signal classification. Therefore, this solution helps to enable EW or 5G receivers to be made smaller, cost less, and use less power. Correspondingly, this solution can also enable higher performance than is currently possible by enabling more accurate signal extraction and characterization under more difficult signal environments than previous systems.

While systems and methods for cueing unknown signals using an IIR filter array with inverted state tree have been described with reference to various embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the teachings herein. In addition, many modifications may be made to adapt the concepts and reductions to practice disclosed herein to a particular situation. Accordingly, it is intended that the subject matter covered by the claims not be limited to the disclosed embodiments.

The embodiments disclosed above use one or more processing or computing devices. Such devices typically include a processor, processing device, or controller, such as a general-purpose central processing unit, a microcontroller, a reduced instruction set computer processor, an ASIC, a programmable logic circuit, an FPGA, a digital signal processor, 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 non-transitory tangible computer-readable storage 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.

As used herein, "to estimate a pre-detection metric" means to compute a value using an equation that defines the pre-detection metric.

The invention claimed is:

1. A method for cueing signals comprising:

transducing electromagnetic radiation carrying a repetitive signal into an analog electrical signal;

converting the analog electrical signal into digital signal samples;

inputting the digital signal samples to first and second filters configured to pass first and second bandwidths respectively which are partially overlapping;

outputting first filtered signal samples from the first filter and second filtered signal samples from the second filter in response to inputting the digital signal samples;

processing the first and second filtered signal samples to generate digital data representing an estimated frequency and an estimated bandwidth;

processing the first and second filtered signal samples to generate digital data representing an estimated pre-detection metric;

determining that the estimated pre-detection metric is greater than a specified threshold;

generating filter coefficients for an available tunable filter which are functions of the estimated frequency and the estimated bandwidth following a determination that the estimated pre-detection metric is greater than the specified threshold; and

tuning the available tunable filter in accordance with the filter coefficients.

2. The method as recited in claim **1**, wherein processing the first and second filtered signal samples to generate digital data representing an estimated pre-detection metric comprises calculating a normalized signal energy by dividing a sum of energy differences between the outputs of the first and second filters by a sum of the energies of those outputs.

3. The method as recited in claim **1**, further comprising:

inputting digital signal samples to the tunable filter after tuning; and

outputting filtered signal samples from the tunable filter after tuning and in response to inputting the digital signal samples.

4. The method as recited in claim **3**, further comprising: processing the filtered signal samples from the tunable filter to generate pulse descriptor words comprising respective data sets of parameter values of the repetitive signal, wherein each data set of parameter values making up a pulse descriptor word comprises amplitude, time of arrival, and frequency.

5. The method as recited in claim **4**, further comprising identifying a source of the repetitive signal based on the data sets of parameter values.

6. The method as recited in claim **4**, further comprising directing movement of a vehicle based on the data sets of parameter values.

7. A method for cueing signals comprising:

transducing electromagnetic radiation carrying a repetitive signal into an analog electrical signal;

converting the analog electrical signal into digital signal samples;

inputting the digital signal samples to first, second, and third filters configured to pass first, second, and third bandwidths respectively, wherein the first and second bandwidths are partially overlapping, the second and third bandwidths are partially overlapping, and the first and third bandwidths are not partially overlapping;

outputting first, second, and third filtered signal samples from the first, second, and third filters respectively in response to inputting the digital signal samples;

processing the first and second filtered signal samples to generate digital data representing a first estimated frequency and a first estimated bandwidth;

processing the first and second filtered signal samples to generate digital data representing a first estimated pre-detection metric;

determining that the first estimated pre-detection metric is greater than a specified threshold;

processing the second and third filtered signal samples to generate digital data representing a second estimated frequency and a second estimated bandwidth;

processing the second and third filtered signal samples to generate digital data representing a second estimated pre-detection metric;

determining that the second estimated pre-detection metric is greater than the specified threshold;

joining the first and second estimated bandwidths to form a wider bandwidth that is a union of first and second estimated bandwidths;

calculating a center frequency of the wider bandwidth;

generating filter coefficients for a tunable filter which are functions of the calculated center frequency and the wider bandwidth following a determination that the first and second estimated pre-detection metrics are greater than the specified threshold; and

tuning the tunable filter in accordance with the filter coefficients.

8. The method as recited in claim **7**, wherein processing the first and second filtered signal samples to generate digital data representing an estimated first pre-detection metric comprises calculating a normalized signal energy by dividing a sum of energy differences between the outputs of the first and second filters by a sum of the energies of those outputs.

9. The method as recited in claim **7**, further comprising:

inputting digital signal samples to the tunable filter after tuning; and

outputting filtered signal samples from the tunable filter after tuning and in response to inputting the digital signal samples.

10. The method as recited in claim **9**, further comprising: processing the filtered signal samples from the tunable filter to generate pulse descriptor words comprising respective data sets of parameter values of the repetitive signal, wherein each data set of parameter values making up a pulse descriptor word comprises amplitude, time of arrival, and frequency.

11. A signal processing system comprising:

a sensor configured to transduce electromagnetic radiation carrying a repetitive signal into an analog electrical signal;

an analog-to-digital converter configured to convert the analog electrical signal into signal samples;

first and second filters connected to receive the signal samples and configured to pass first and second bandwidths respectively which are partially overlapping;

a first signal frequency/bandwidth estimator connected to receive first and second filtered signal samples from the first and second filters and configured to process filtered signal samples from two filters to generate digital data representing a first estimated frequency and a first estimated bandwidth;

a first pre-detection estimator connected to receive first and second filtered signal samples from the first and second filters and configured to process filtered signal samples from two filters to generate digital data representing a first estimated pre-detection metric;

a plurality of signal separation and tracking channels, each signal separation and tracking channel comprising a respective tunable filter;

a signal separation and tracking controller configured to control tuning of the plurality of signal separation and tracking channels; and

a first root node connected to receive the first estimated frequency and the first estimated bandwidth from the first signal frequency/bandwidth estimator and receive the first estimated pre-detection metric from the first pre-detection estimator and communicate with the signal separation and tracking controller, wherein the first root node is configured to not send a request for available channel to the signal separation and tracking controller if the first estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal.

12. The system as recited in claim **11**, wherein the first pre-detection estimator is configured to calculate a normalized signal energy by dividing a sum of energy differences between the outputs of the first and second filters by a sum of the energies of those outputs.

13. The system as recited in claim **11**, wherein:

the signal separation and tracking controller is further configured to send a channel available signal to the first root node in response to receipt of a request for available channel from the first root node if one of the plurality of signal separation and tracking channels is available; and

the first root node is further configured to output state values representing the first estimated frequency, the first estimated bandwidth, and the first estimated pre-detection metric in response to receipt of the channel available signal from the signal separation and tracking controller.

14. The system as recited in claim **13**, further comprising:

a third filter connected to receive the signal samples and configured to pass a third bandwidth which partially overlaps the second bandwidth;

a second signal frequency/bandwidth estimator connected to receive second and the filtered signal samples from the second and third filters and configured to process filtered signal samples from two filters to generate digital data representing a second estimated frequency and a second estimated bandwidth;

a second pre-detection estimator connected to receive second and third filtered signal samples from the second and third filters and configured to process filtered signal samples from two filters to generate digital data representing a second estimated pre-detection metric;

a second root node connected to receive the second estimated frequency and the second estimated bandwidth from the second signal frequency/bandwidth estimator and receive the second estimated pre-detection metric from the second pre-detection estimator and communicate with the signal separation and tracking controller, wherein the second root node is configured to not send a request for available channel to the signal separation and tracking controller if the second estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal.

15. The system as recited in claim **14**, wherein:

the signal separation and tracking controller is further configured to send a channel available signal to the second root node in response to receipt of a request for available channel from the second root node if one of the plurality of signal separation and tracking channels is available; and

the second root node is further configured to output state values representing the second estimated frequency, the second estimated bandwidth, and the second pre-detection metric in response to receipt of the channel available signal from the signal separation and tracking controller.

16. The system as recited in claim **15**, further comprising a non-root node connected to receive the state values representing the first estimated frequency, the first estimated bandwidth, and the first estimated pre-detection metric from the first root node and the second estimated frequency, the second estimated bandwidth, and the second pre-detection metric from the second root node and communicate with the signal separation and tracking controller, wherein the non-root node is configured to calculate and output state values representing a third estimated frequency and a third estimated bandwidth in response to the first and second estimated bandwidths being adjacent or partially overlapping, the third estimated pre-detection metric being a union of the first and second bandwidths and further configured to not send a request for available channel to the signal separation and tracking controller if the third estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal.

17. The system as recited in claim **16**, wherein:

the signal separation and tracking controller is further configured to send a channel available signal to the non-root node in response to receipt of a request for available channel from the non-root node if one of the plurality of signal separation and tracking channels is available; and

the non-root node is further configured to output state values representing the third estimated frequency, the second estimated bandwidth, and the second pre-detection metric in response to receipt of the channel available signal from the signal separation and tracking controller.

18. The system as recited in claim **11**, further comprising a pulse descriptor word generator connected to receive filtered signal samples from a tunable filter and configured to process the filtered signal samples from the tunable filter to generate pulse descriptor words comprising respective data sets of parameter values of the repetitive signal, wherein each data set of parameter values making up a pulse descriptor word comprises amplitude, time of arrival, and frequency.

19. A signal cueing system comprising:

first, second, and third filters configured to pass first, second, and third bandwidths, respectively, wherein the first and second bandwidths are partially overlapping, the second and third bandwidths are partially overlapping, and the first and third bandwidths are not partially overlapping;

a first signal frequency/bandwidth estimator connected to receive first and second filtered signal samples from the first and second filters and configured to process filtered signal samples from two filters to generate digital data representing a first estimated frequency and a first estimated bandwidth;

a first pre-detection estimator connected to receive first and second filtered signal samples from the first and second filters and configured to process filtered signal samples from two filters to generate digital data representing a first estimated pre-detection metric;

a first root node connected to receive the first estimated frequency and the first estimated bandwidth from the first signal frequency/bandwidth estimator and receive the first estimated pre-detection metric from the first pre-detection estimator, wherein the first root node is configured to not generate a request for available channel if the first estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal;

a second signal frequency/bandwidth estimator connected to receive second and the filtered signal samples from the second and third filters and configured to process filtered signal samples from two filters to generate digital data representing a second estimated frequency and a second estimated bandwidth;

a second pre-detection estimator connected to receive second and third filtered signal samples from the second and third filters and configured to process filtered signal samples from two filters to generate digital data representing a second estimated pre-detection metric;

a second root node connected to receive the second estimated frequency and the second estimated bandwidth from the second signal frequency/bandwidth estimator and receive the second estimated pre-detection metric from the second pre-detection estimator, wherein the second root node is configured to not generate a request for available channel to the signal separation and tracking controller if the second estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal; and

a non-root node connected to receive the state values representing the first estimated frequency, the first estimated bandwidth, and the first estimated pre-detection metric from the first root node and the second estimated frequency, the second estimated bandwidth, and the second pre-detection metric from the second root node, wherein the non-root node is configured to calculate and output state values representing a third estimated frequency and a third estimated bandwidth in response to the first and second estimated bandwidths being adjacent or partially overlapping, the third estimated pre-detection metric being a union of the first and second bandwidths, and further configured to not generate a request for available channel to the signal separation and tracking controller if the third estimated pre-detection metric does not indicate that the signal samples were derived from a repetitive signal.

20. The system as recited in claim **19**, wherein each of the first and second pre-detection estimators is configured to calculate a normalized signal energy by dividing a sum of energy differences between the outputs of two filters by a sum of the energies of those outputs.

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