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Sun et al.

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(54) **FREQUENCY AND PHASE COMPENSATION FOR MODULATION FORMATS USING MULTIPLE SUB-CARRIERS**

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(22) Filed: **Mar. 31, 2014**

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(51) **Int. Cl.**

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H04B 10/61	(2013.01)
H04J 14/02	(2006.01)

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

CPC ***H04B 10/6164*** (2013.01); ***H04B 10/6165*** (2013.01); ***H04J 14/02*** (2013.01)

(58) **Field of Classification Search**

CPC H04B 10/6164; H04B 10/6165; H04B 10/63; H04B 10/64; H04B 10/671; H04B 10/69; H04B 10/697; H04J 14/02

USPC 398/208

See application file for complete search history.

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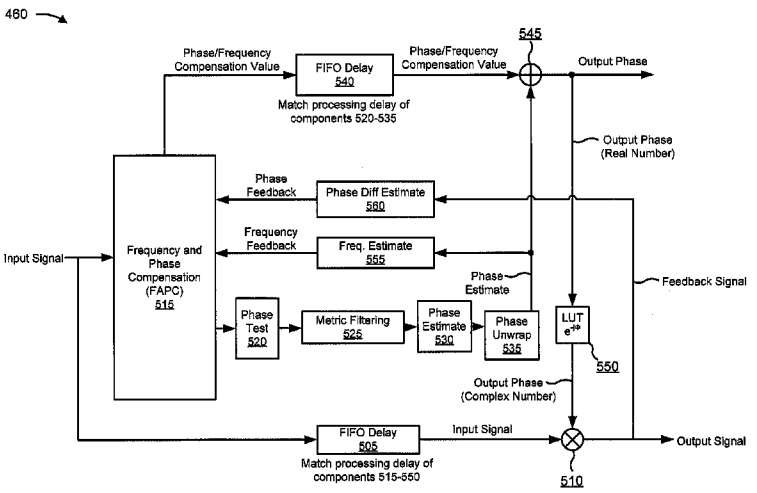
(57) **ABSTRACT**

An optical receiver may receive input signals carried by respective sub-carriers. The optical receiver may determine, based on the input signals, a compensation value to be used to modify an input signal. The optical receiver may use the compensation value to adjust the input signal to form a modified input signal. The compensation value may be used to modify a frequency or a phase of the input signal. The optical receiver may determine, based on the modified input signal, a phase estimate value that represents an estimated phase associated with the input signal. The optical receiver may combine the compensation value and the phase estimate value to form a phase adjustment signal, may combine the input signal and the phase adjustment signal to form an output signal, and may output the output signal.

20 Claims, 20 Drawing Sheets



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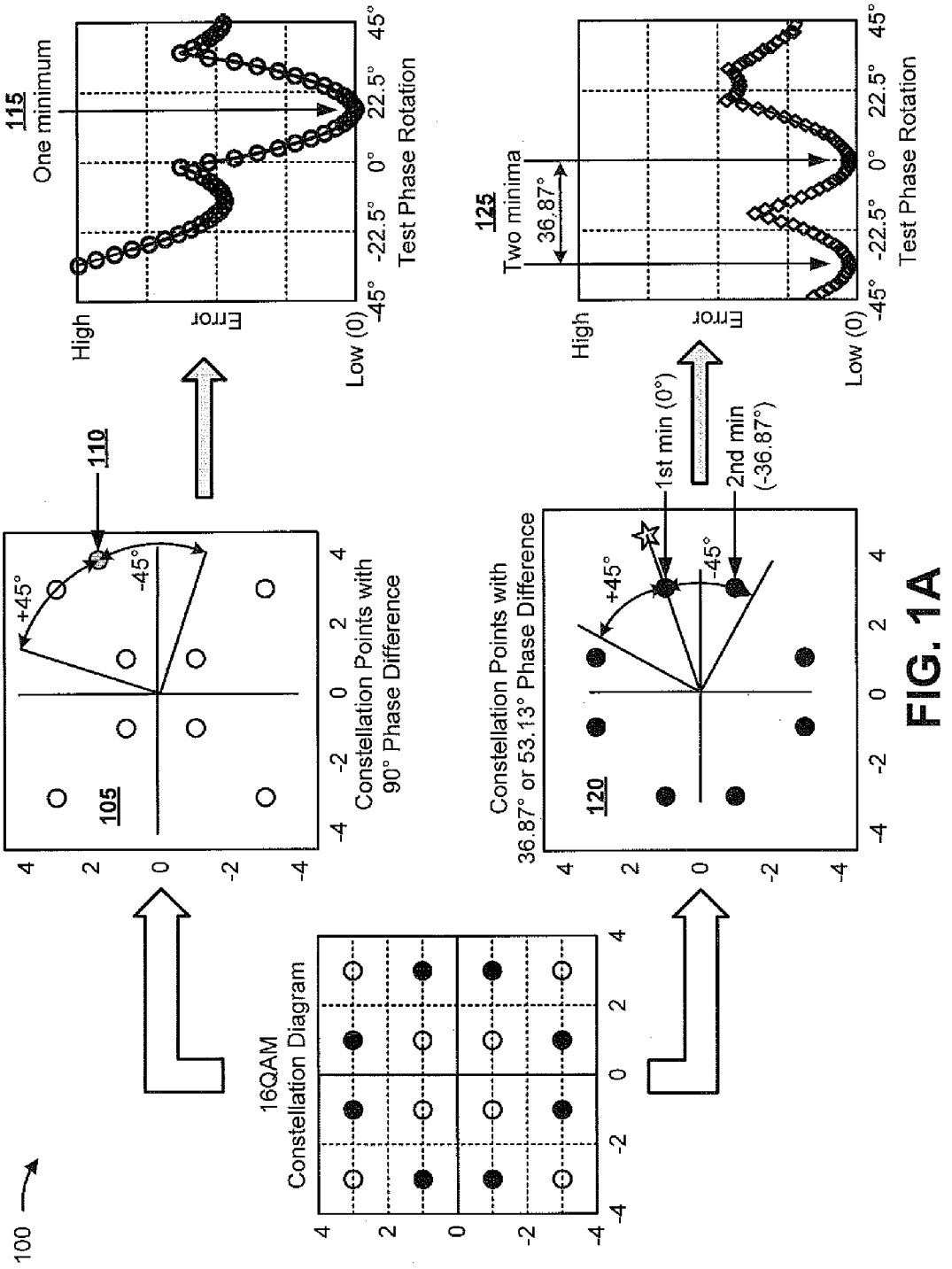
100
16QAM
Constellation Diagram
105
110
Constellation Points with
90° Phase Difference
+45°
-45°
115
One minimum
Error
High
Low (0)
-45° -22.5° 0° 22.5° 45°
Test Phase Rotation
120
Constellation Points with
36.87° or 53.13° Phase Difference
1st min (0°)
2nd min
(-36.87°)
125
Two minima
36.87°

FIG. 1A

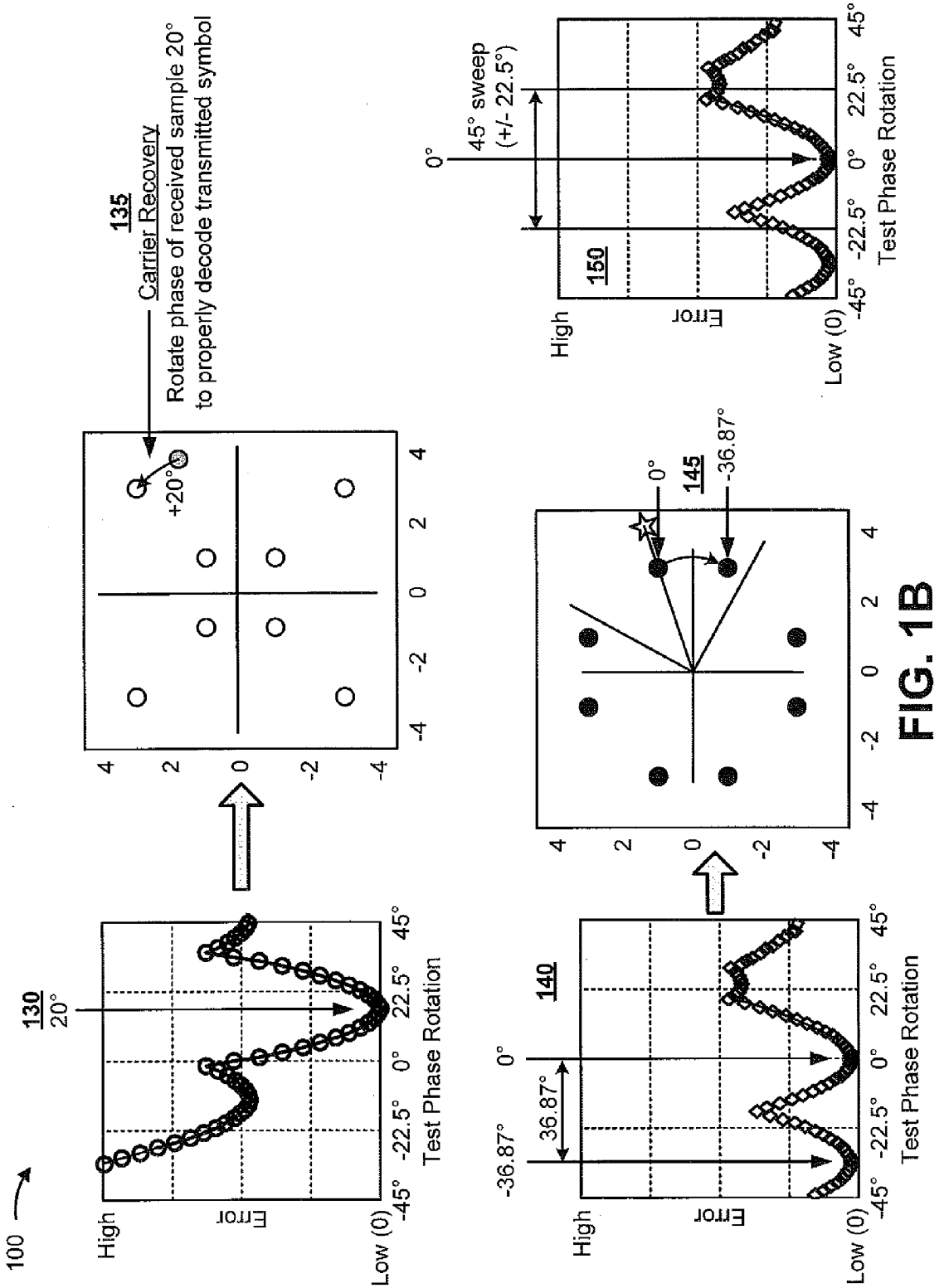
100
130
20°
High
Error
Low (0)
-45°
-22.5°
0°
22.5°
45°
Test Phase Rotation
135
Carrier Recovery
Rotate phase of received sample 20°
to properly decode transmitted symbol
+20°
4
2
0
-2
-4
140
-36.87°
0°
36.87°
145
150
45° sweep
(+/- 22.5°)

FIG. 1B

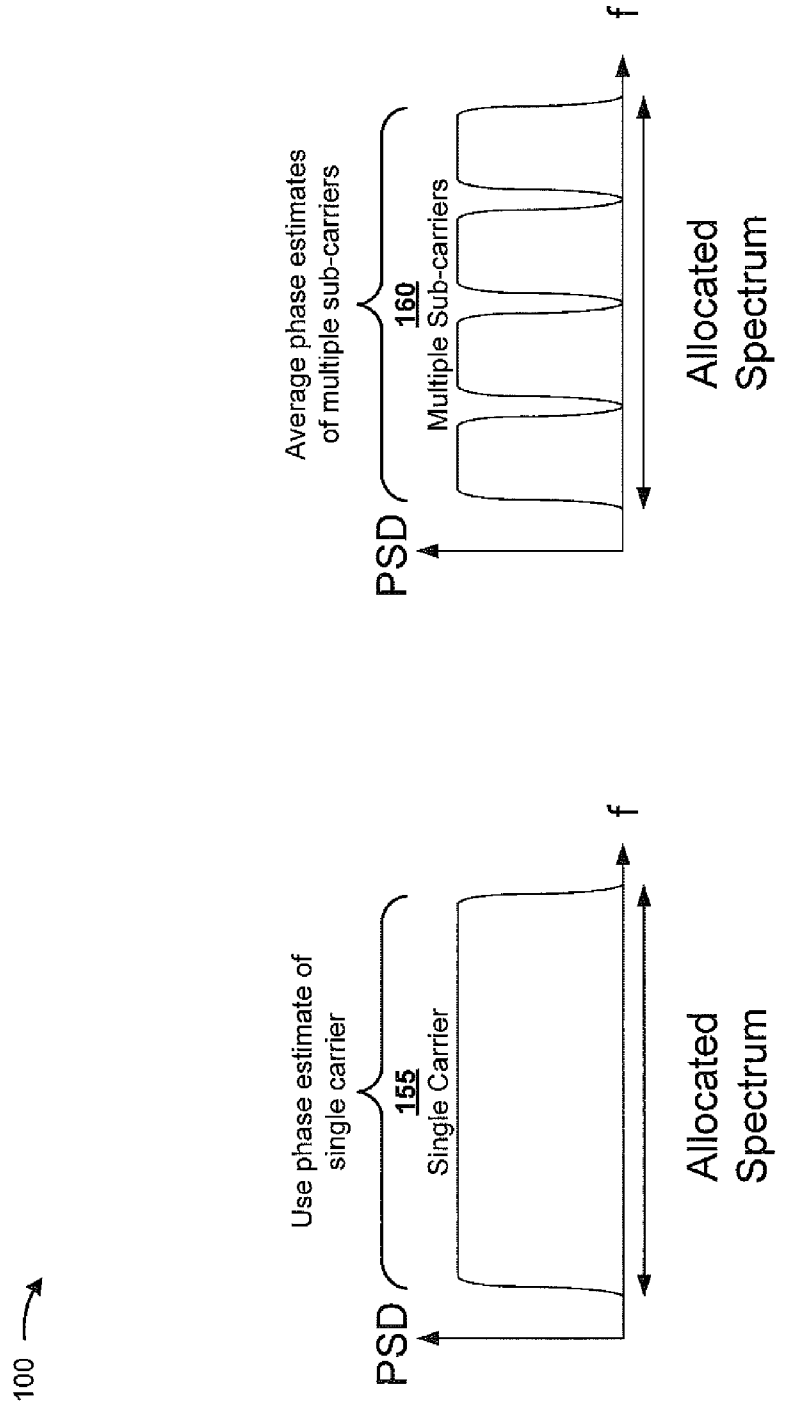
100
PSD
Use phase estimate of single carrier
155
Single Carrier
f
Allocated Spectrum
PSD
Average phase estimates of multiple sub-carriers
160
Multiple Sub-carriers
f
Allocated Spectrum

FIG. 1C

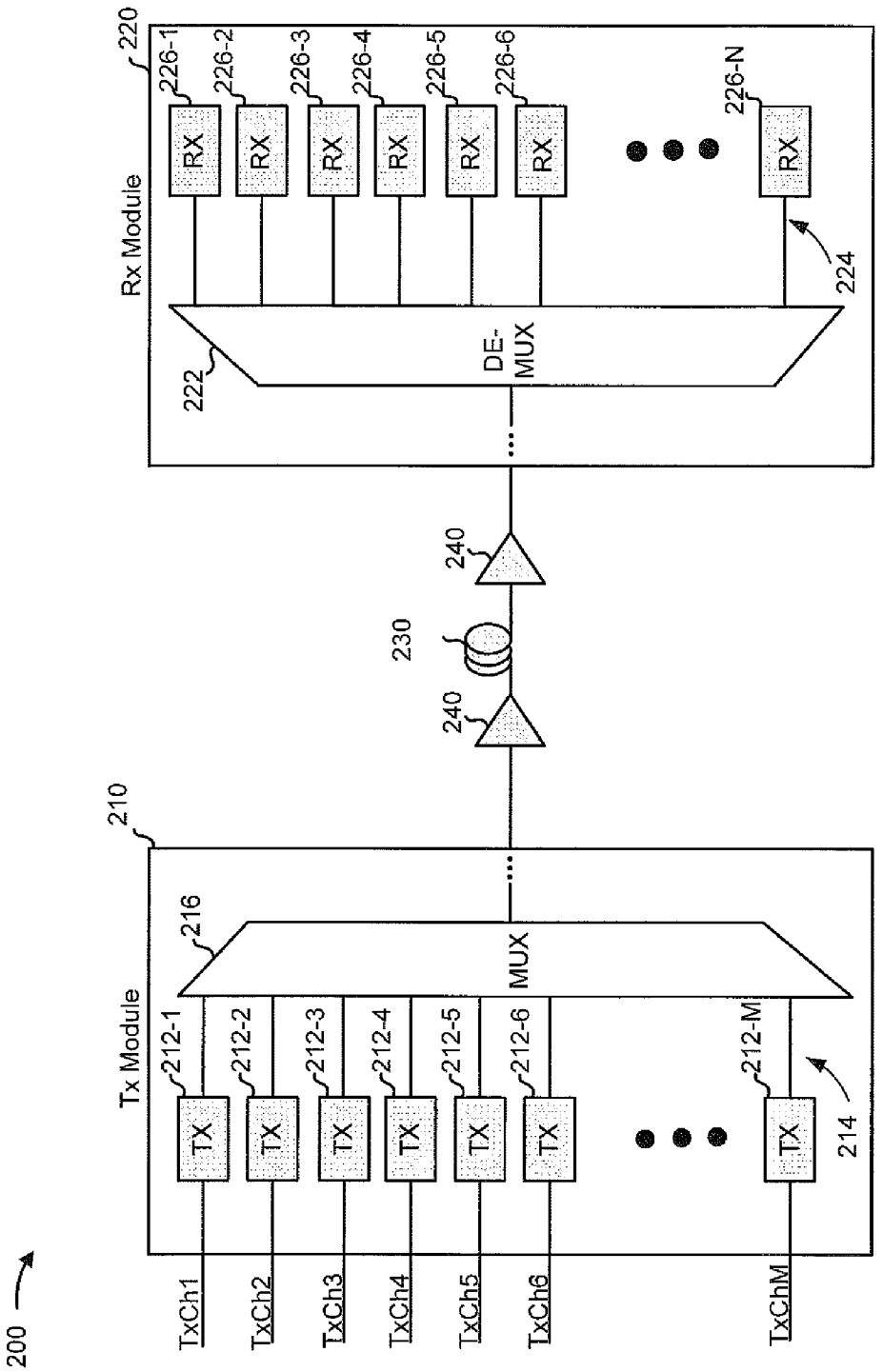
200
Tx Module
210
TX
212-1
212-2
212-3
212-4
212-5
212-6
212-M
214
216
MUX
TxCh1
TxCh2
TxCh3
TxCh4
TxCh5
TxCh6
TxChM
240
230
240
Rx Module
220
RX
226-1
226-2
226-3
226-4
226-5
226-6
226-N
224
222
DE-
MUX

FIG. 2

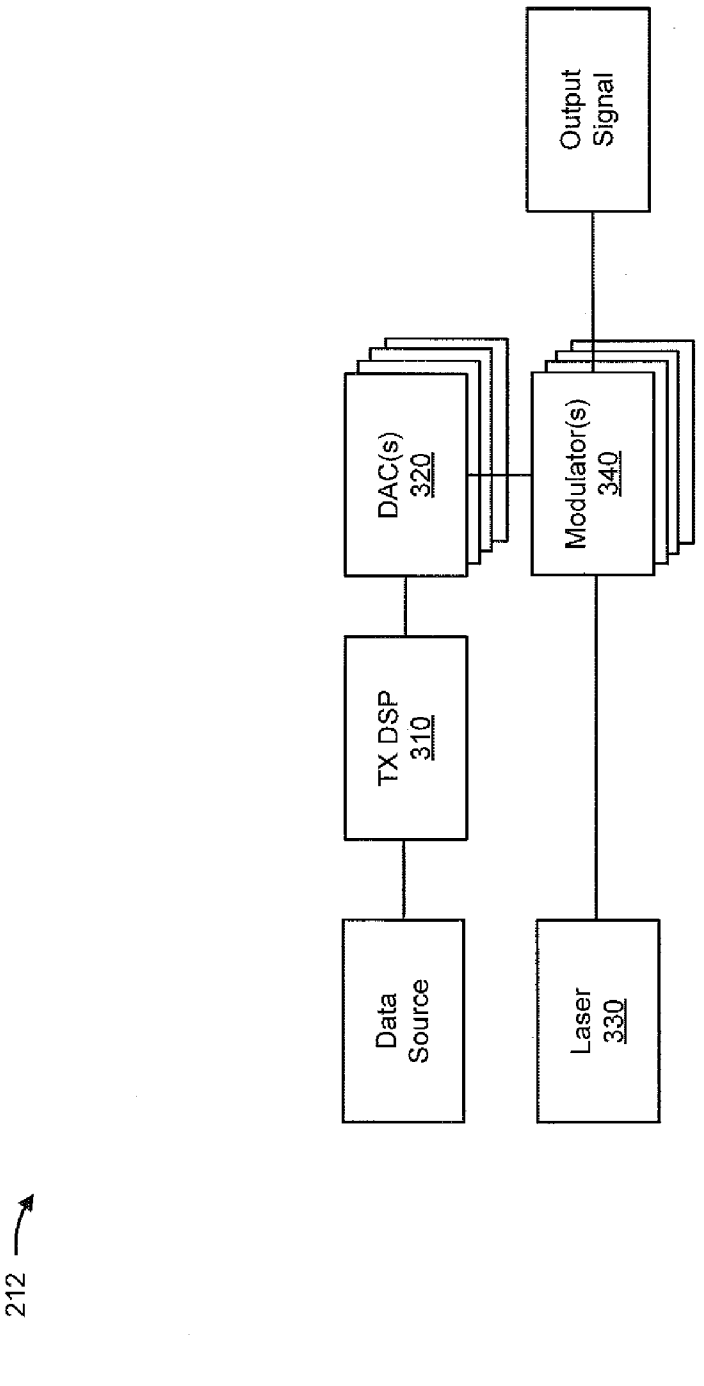
212
Data Source
TX DSP 310
DAC(s) 320
Laser 330
Modulator(s) 340
Output Signal

FIG. 3

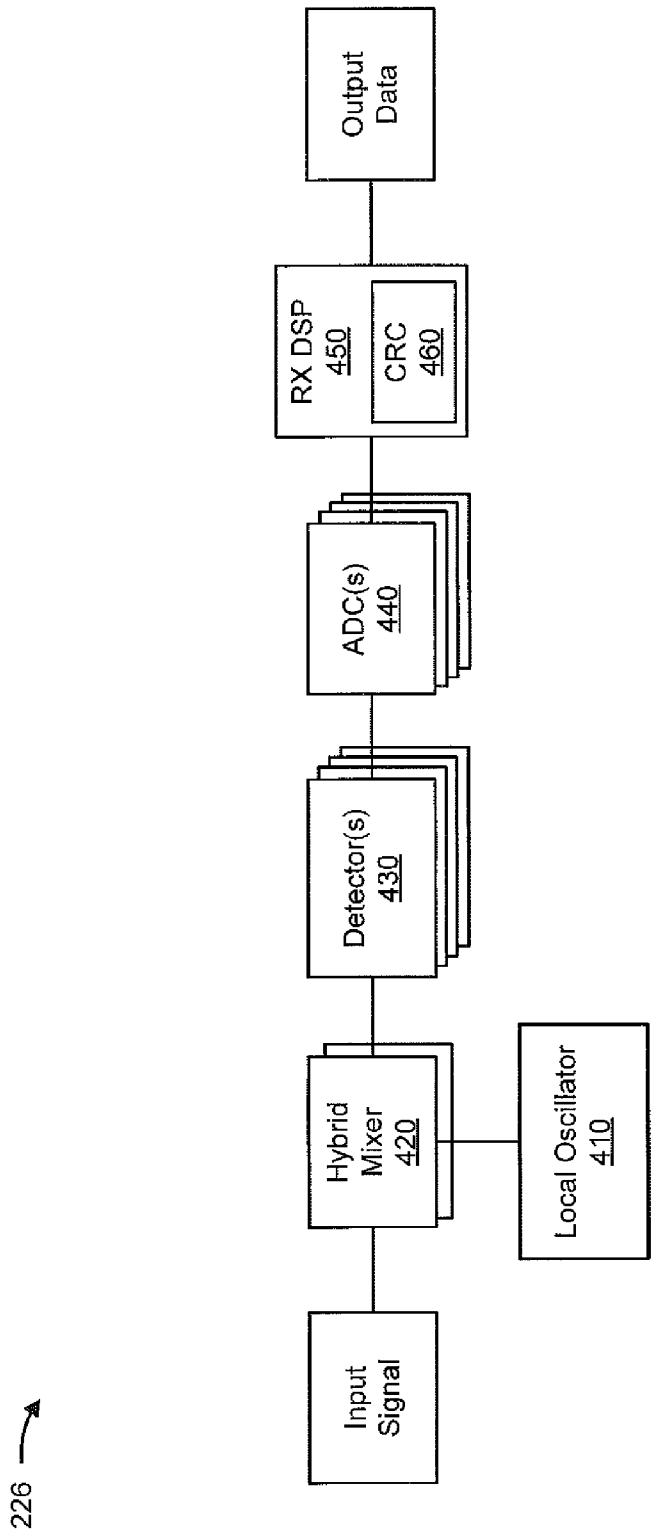
226
Input Signal
Hybrid Mixer 420
Local Oscillator 410
Detector(s) 430
ADC(s) 440
RX DSP 450
CRC 460
Output Data

FIG. 4

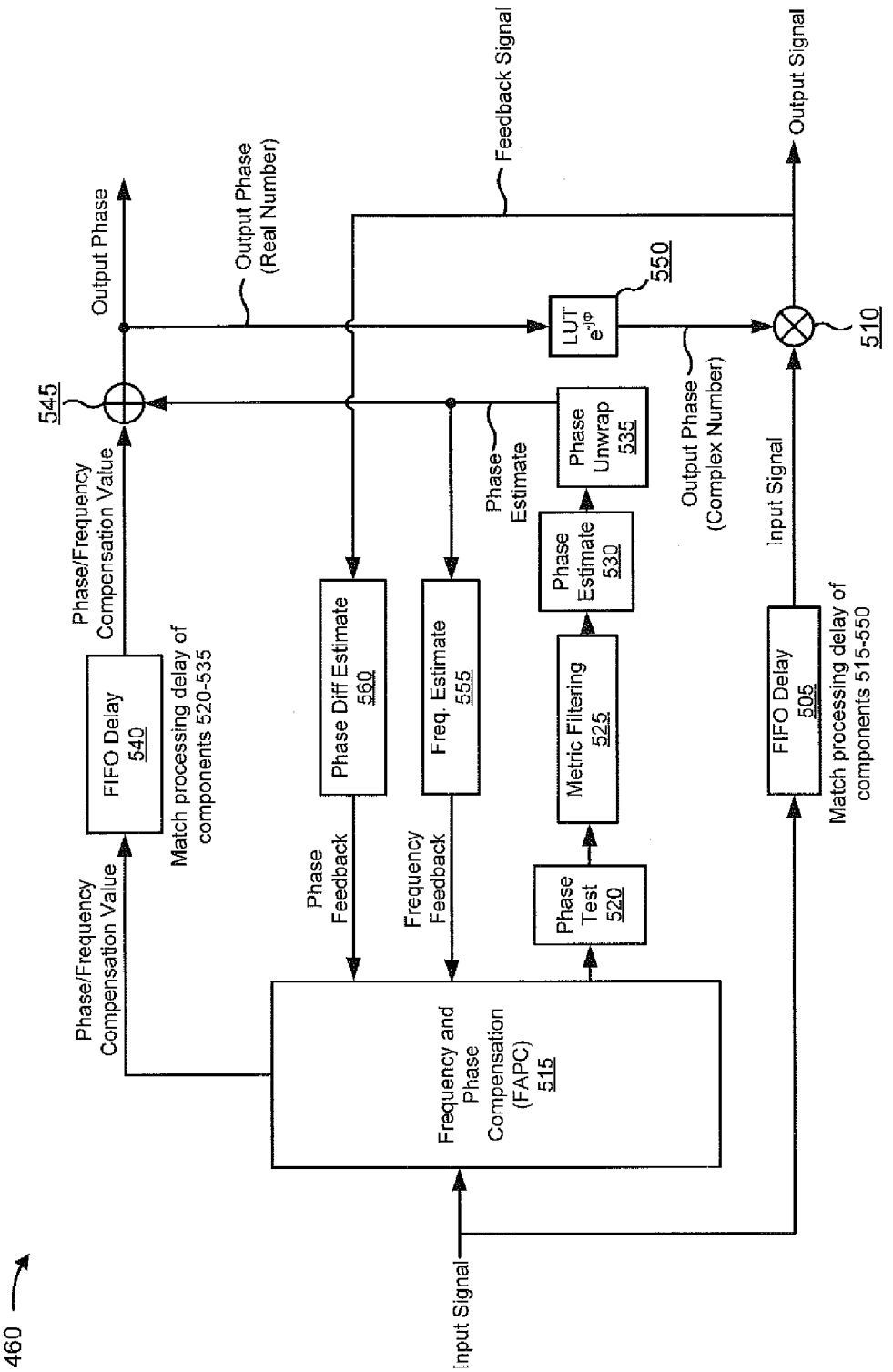
460
Input Signal
Frequency and Phase Compensation (FAPC) 515
Phase/Frequency Compensation Value
Phase Feedback
Frequency Feedback
Phase Test 520
Metric Filtering 525
Phase Estimate 530
Phase Unwrap 535
Phase Diff Estimate 560
Freq. Estimate 555
Phase Estimate
Output Phase (Real Number)
Output Phase
545
Phase/Frequency Compensation Value
FIFO Delay 540
Match processing delay of components 520-535
LUT $e^{j\varphi}$
550
Output Phase (Complex Number)
Feedback Signal
Output Signal
510
Input Signal
FIFO Delay 505
Match processing delay of components 515-550

FIG. 5A

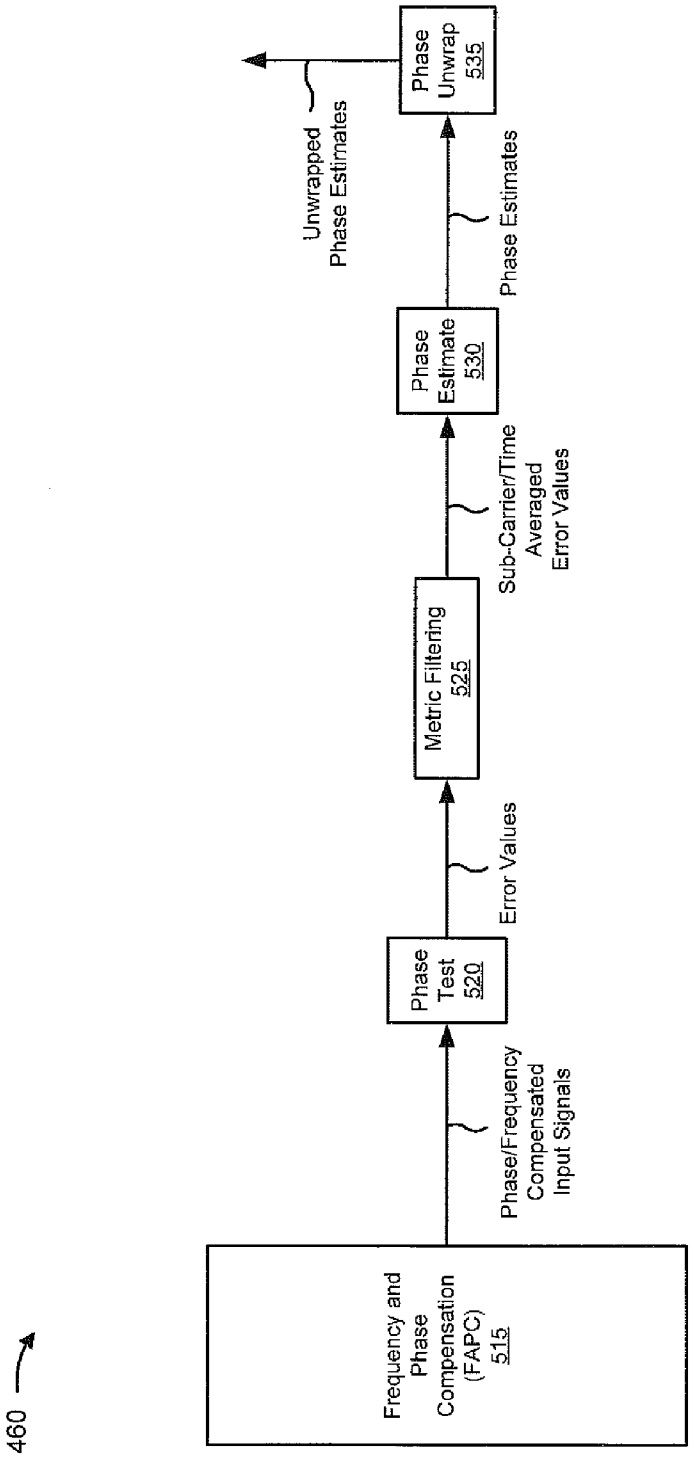
460
Frequency and Phase Compensation (FAPC) 515
Phase/Frequency Compensated Input Signals
Phase Test 520
Error Values
Metric Filtering 525
Sub-Carrier/Time Averaged Error Values
Phase Estimate 530
Phase Estimates
Phase Unwrap 535
Unwrapped Phase Estimates

FIG. 5B

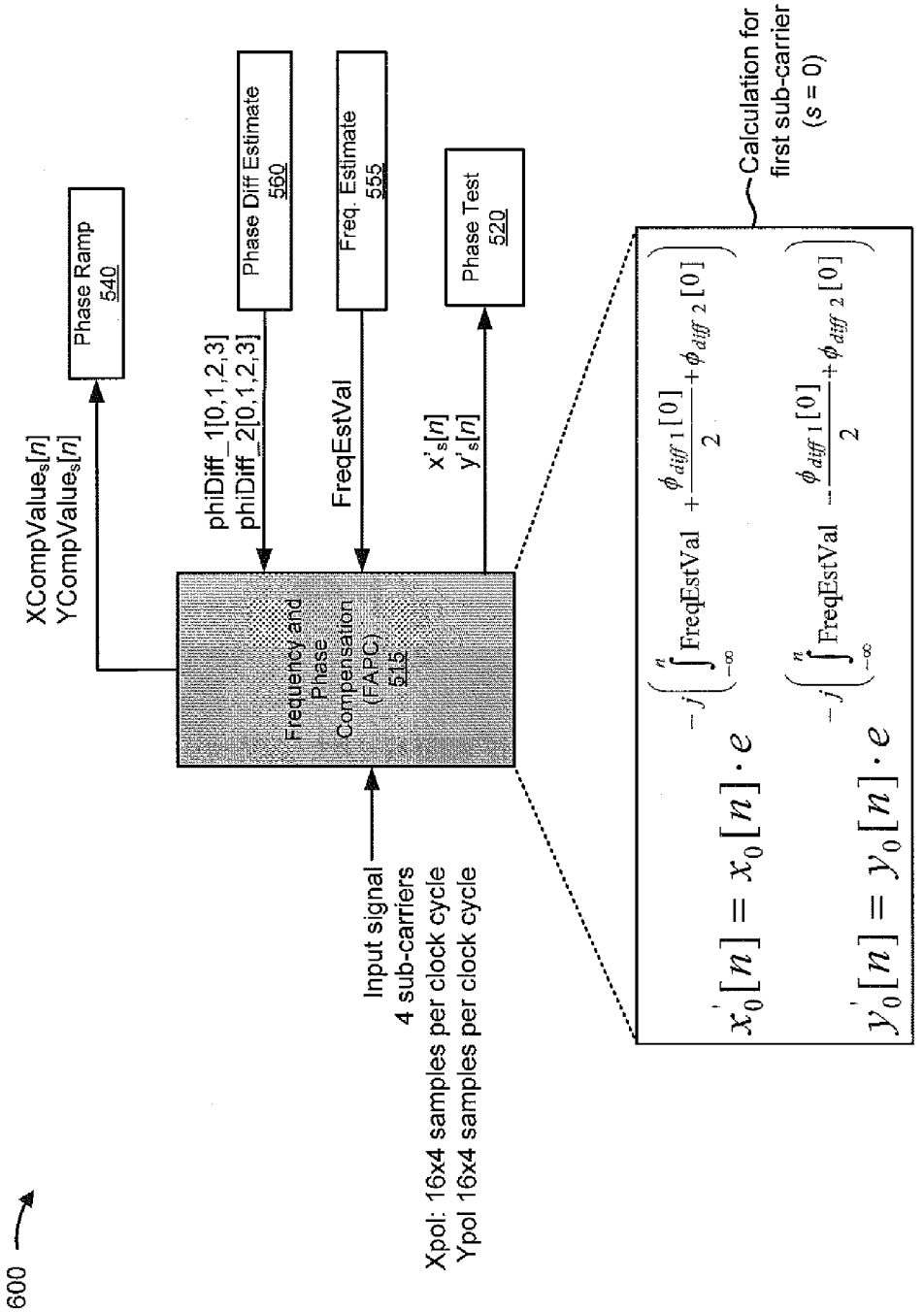
600
Xpol: 16x4 samples per clock cycle
Ypol 16x4 samples per clock cycle
Input signal
4 sub-carriers
Frequency and Phase Compensation (FAPC) 515
XCompValue$_s$[n]
YCompValue$_s$[n]
Phase Ramp 540
phiDiff_1[0,1,2,3]
phiDiff_2[0,1,2,3]
Phase Diff Estimate 560
FreqEstVal
Freq. Estimate 555
x'$_s$[n]
y'$_s$[n]
Phase Test 520
Calculation for first sub-carrier (s = 0)
$x_0'[n] = x_0[n] \cdot e^{-j\left(\int_{-\infty}^{n} \text{FreqEstVal} + \frac{\phi_{diff\,1}[0]}{2} + \phi_{diff\,2}[0]\right)}$
$y_0'[n] = y_0[n] \cdot e^{-j\left(\int_{-\infty}^{n} \text{FreqEstVal} - \frac{\phi_{diff\,1}[0]}{2} + \phi_{diff\,2}[0]\right)}$

FIG. 6

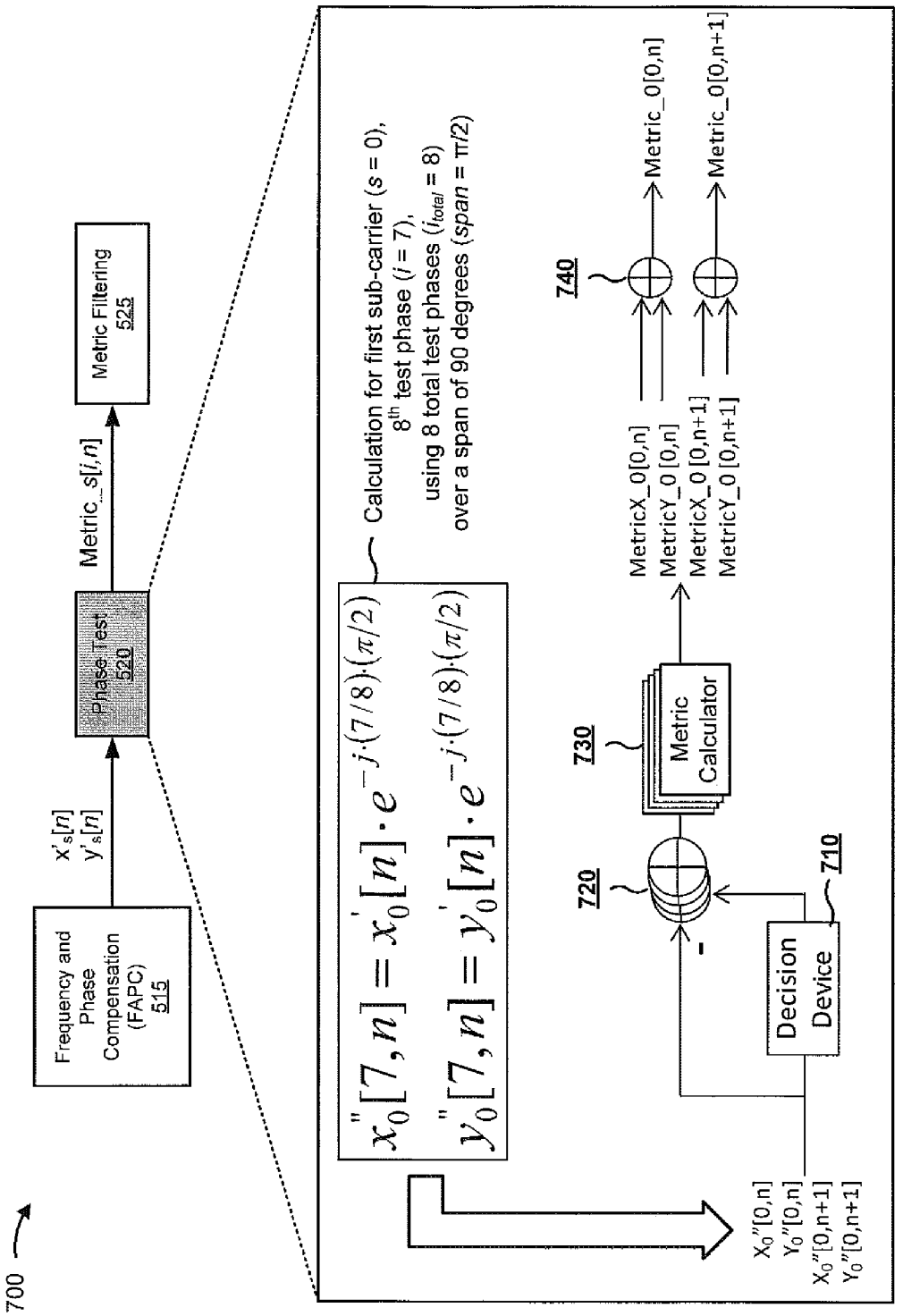
700
Frequency and Phase Compensation (FAPC) 515
x'_s[n]
y'_s[n]
Phase Test 520
Metric_s[i,n]
Metric Filtering 525
Calculation for first sub-carrier (s = 0), 8th test phase (i = 7), using 8 total test phases (i_total = 8) over a span of 90 degrees (span = π/2)
x''_0[7,n] = x'_0[n] · e^{-j·(7/8)·(π/2)}
y''_0[7,n] = y'_0[n] · e^{-j·(7/8)·(π/2)}
X_0''[0,n]
Y_0''[0,n]
X_0''[0,n+1]
Y_0''[0,n+1]
Decision Device
710
720
730
Metric Calculator
740
MetricX_0[0,n]
MetricY_0 [0,n]
MetricX_0 [0,n+1]
MetricY_0 [0,n+1]
Metric_0[0,n]
Metric_0[0,n+1]

FIG. 7

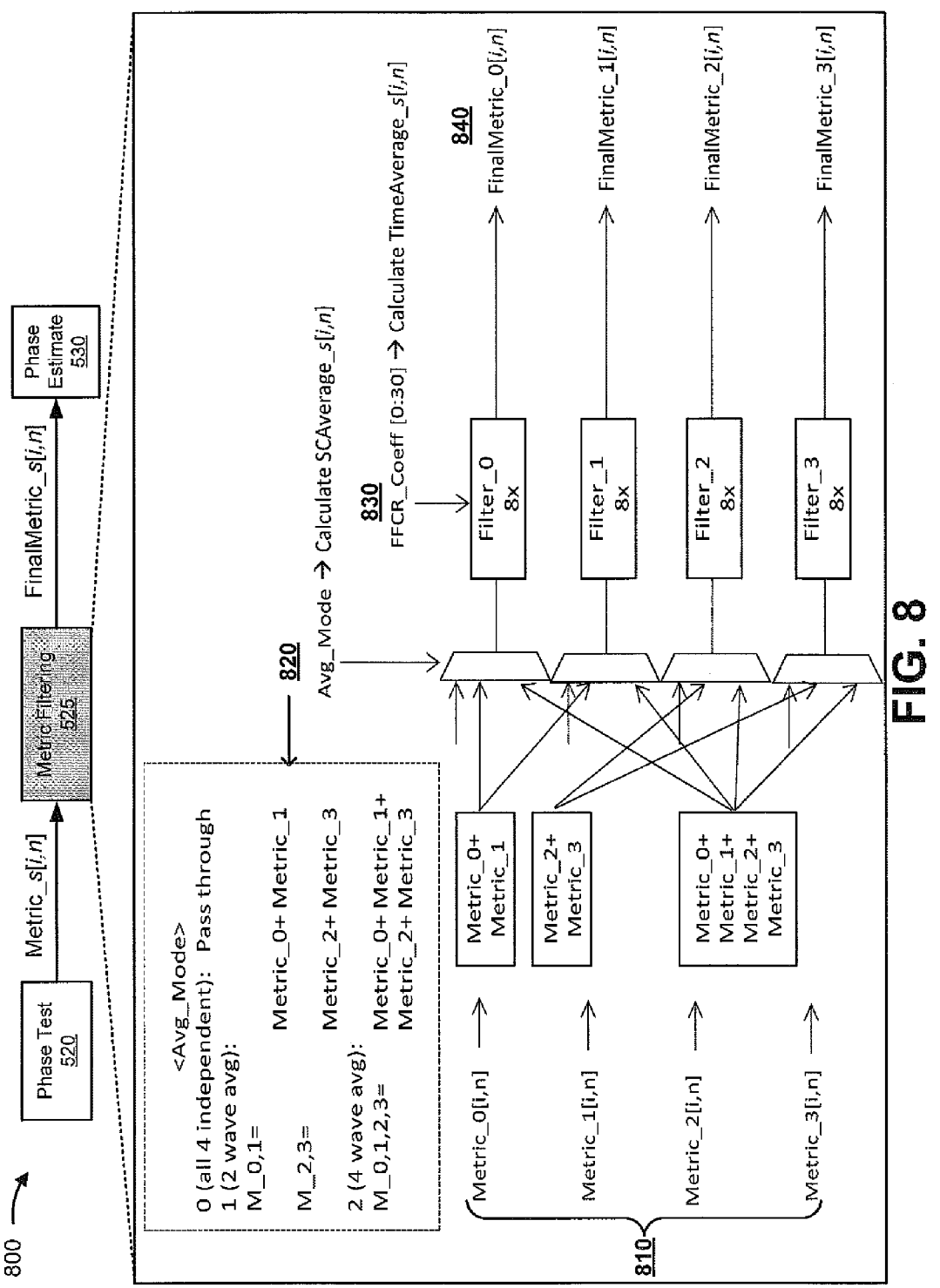
800
Phase Test 520
Metric_s[i,n]
Metric Filtering 525
FinalMetric_s[i,n]
Phase Estimate 530
<Avg_Mode>
0 (all 4 independent): Pass through
1 (2 wave avg):
M_0,1= Metric_0+ Metric_1
M_2,3= Metric_2+ Metric_3
2 (4 wave avg):
M_0,1,2,3= Metric_0+ Metric_1+ Metric_2+ Metric_3
820
Avg_Mode → Calculate SCAverage_s[i,n]
830
FFCR_Coeff [0:30] → Calculate TimeAverage_s[i,n]
840
Filter_0 8x
Filter_1 8x
Filter_2 8x
Filter_3 8x
FinalMetric_0[i,n]
FinalMetric_1[i,n]
FinalMetric_2[i,n]
FinalMetric_3[i,n]
Metric_0+ Metric_1
Metric_2+ Metric_3
Metric_0+ Metric_1+ Metric_2+ Metric_3
Metric_0[i,n]
Metric_1[i,n]
Metric_2[i,n]
Metric_3[i,n]
810

FIG. 8

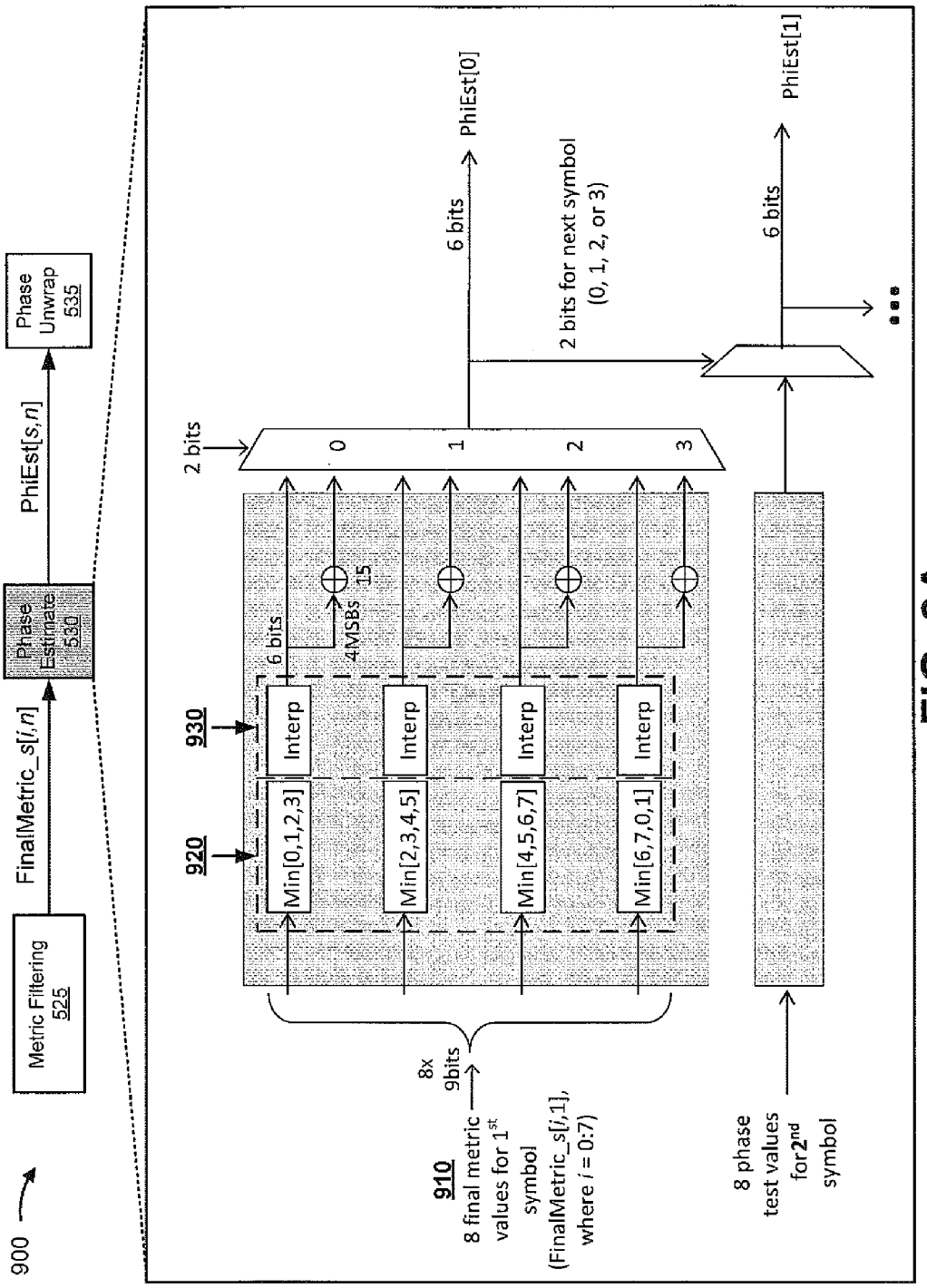
900
Metric Filtering 525
FinalMetric_s[i,n]
Phase Estimate 530
PhiEst[s,n]
Phase Unwrap 535
910
8 final metric values for 1st symbol (FinalMetric_s[i,1], where i = 0:7)
8x 9bits
920
930
Min[0,1,2,3]
Min[2,3,4,5]
Min[4,5,6,7]
Min[6,7,0,1]
Interp
6 bits
4 MSBs
15
2 bits
0
1
2
3
6 bits
PhiEst[0]
2 bits for next symbol (0, 1, 2, or 3)
6 bits
PhiEst[1]
8 phase test values for 2nd symbol

FIG. 9A

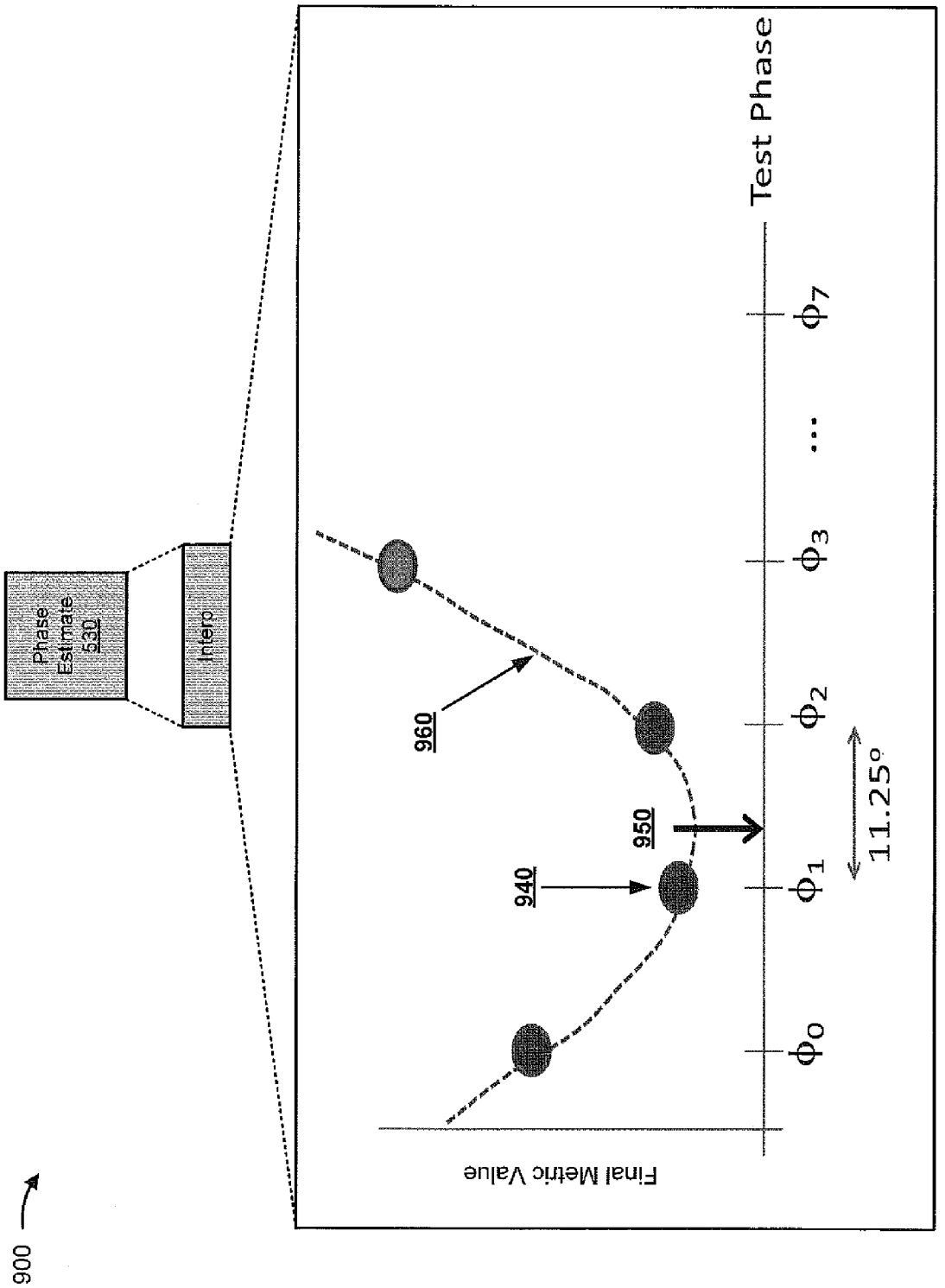
900
Phase Estimate 530
Interp
Final Metric Value
Test Phase
ϕ_0
ϕ_1
ϕ_2
ϕ_3
...
ϕ_7
11.25°
940
950
960

FIG. 9B

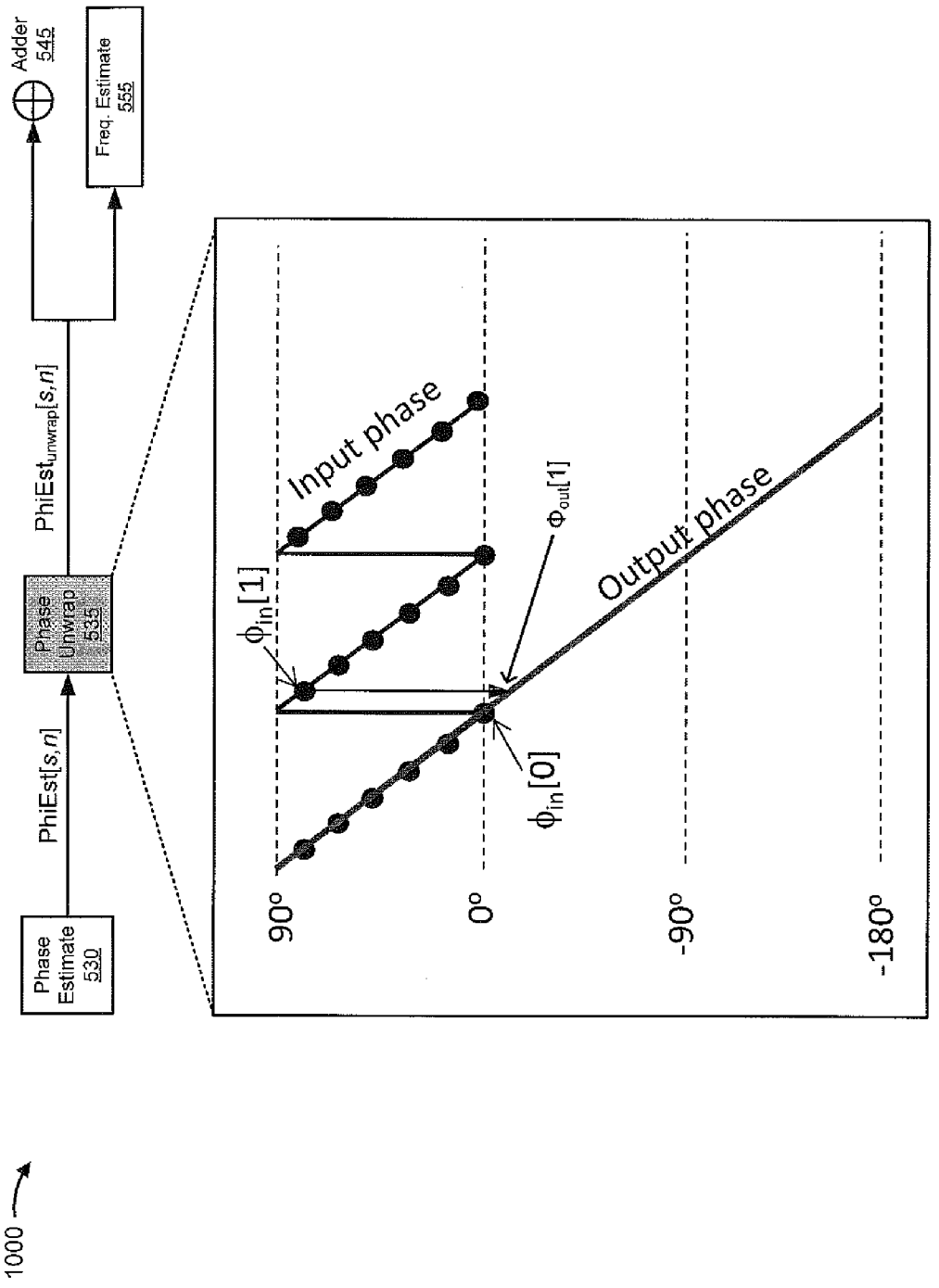
1000
Phase Estimate 530
PhiEst[s,n]
Phase Unwrap 535
PhiEst_unwrap[s,n]
Adder 545
Freq. Estimate 555
Input phase
Output phase
$\phi_{in}[1]$
$\phi_{out}[1]$
$\phi_{in}[0]$
90°
0°
-90°
-180°

FIG. 10

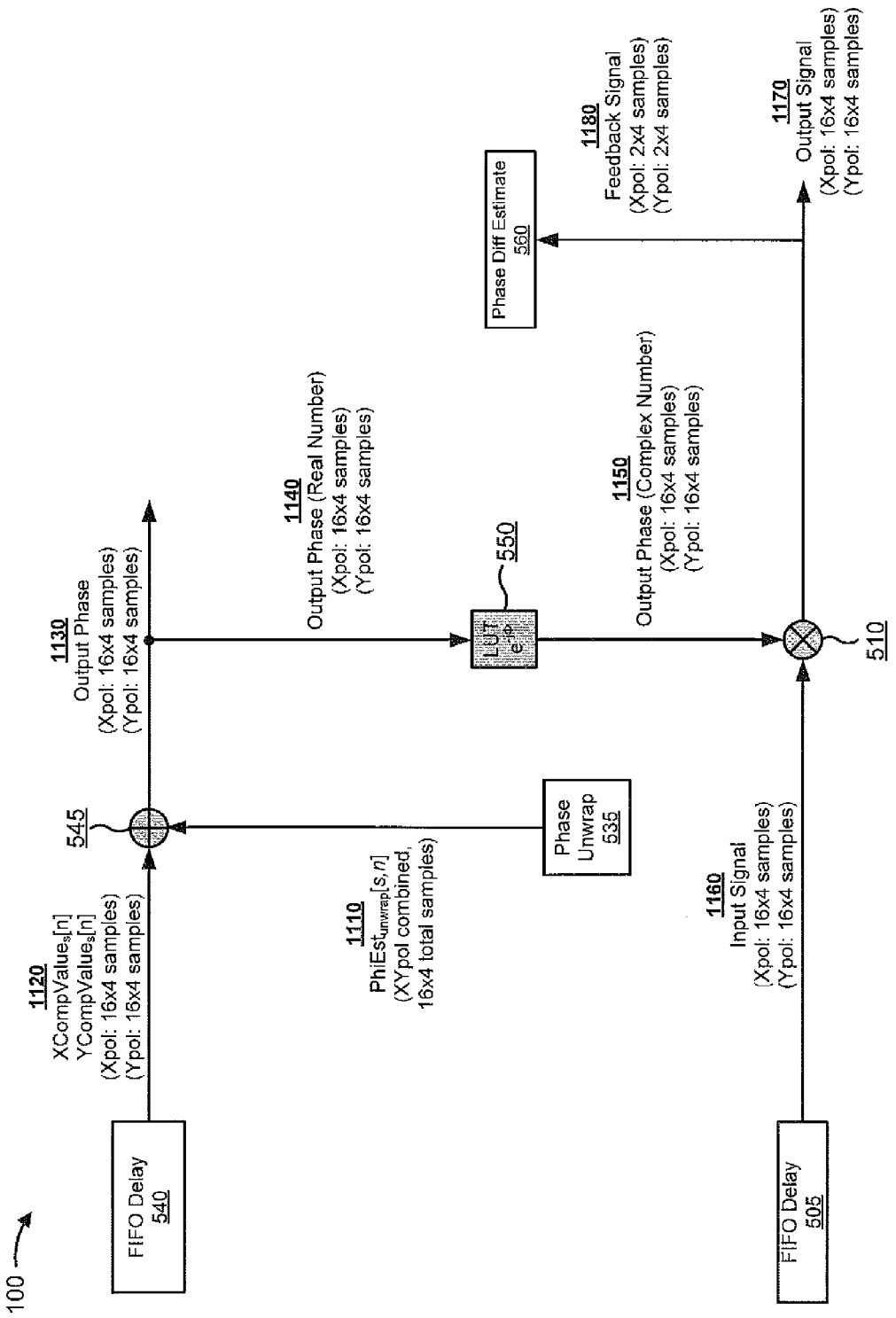
1100
FIFO Delay 540
1120 XCompValue$_s$[n] YCompValue$_s$[n] (Xpol: 16x4 samples) (Ypol: 16x4 samples)
545
1130 Output Phase (Xpol: 16x4 samples) (Ypol: 16x4 samples)
1110 PhiEst$_{unwrap}$[s,n] (XYpol combined, 16x4 total samples)
Phase Unwrap 535
1140 Output Phase (Real Number) (Xpol: 16x4 samples) (Ypol: 16x4 samples)
550
LUT e^jb
1150 Output Phase (Complex Number) (Xpol: 16x4 samples) (Ypol: 16x4 samples)
510
1160 Input Signal (Xpol: 16x4 samples) (Ypol: 16x4 samples)
FIFO Delay 505
Phase Diff Estimate 560
1180 Feedback Signal (Xpol: 2x4 samples) (Ypol: 2x4 samples)
1170 Output Signal (Xpol: 16x4 samples) (Ypol: 16x4 samples)

FIG. 11

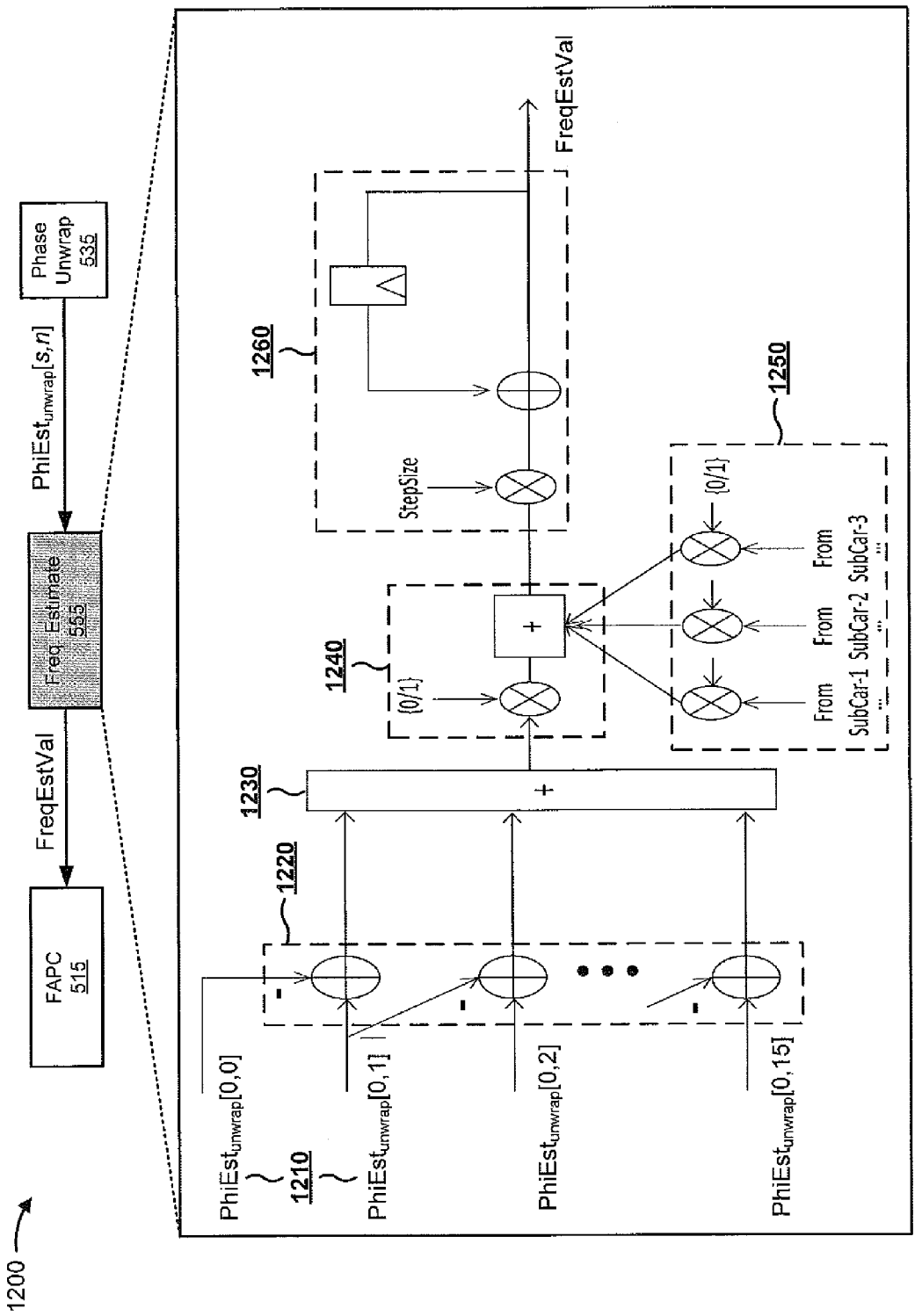
1200
FAPC 515
FreqEstVal
Freq. Estimate 555
PhiEst$_{unwrap}$[s,n]
Phase Unwrap 535
PhiEst$_{unwrap}$[0,0]
PhiEst$_{unwrap}$[0,1]
PhiEst$_{unwrap}$[0,2]
PhiEst$_{unwrap}$[0,15]
1210
1220
1230
1240
1250
1260
{0/1}
From SubCar-1
From SubCar-2
From SubCar-3
StepSize
FreqEstVal

FIG. 12

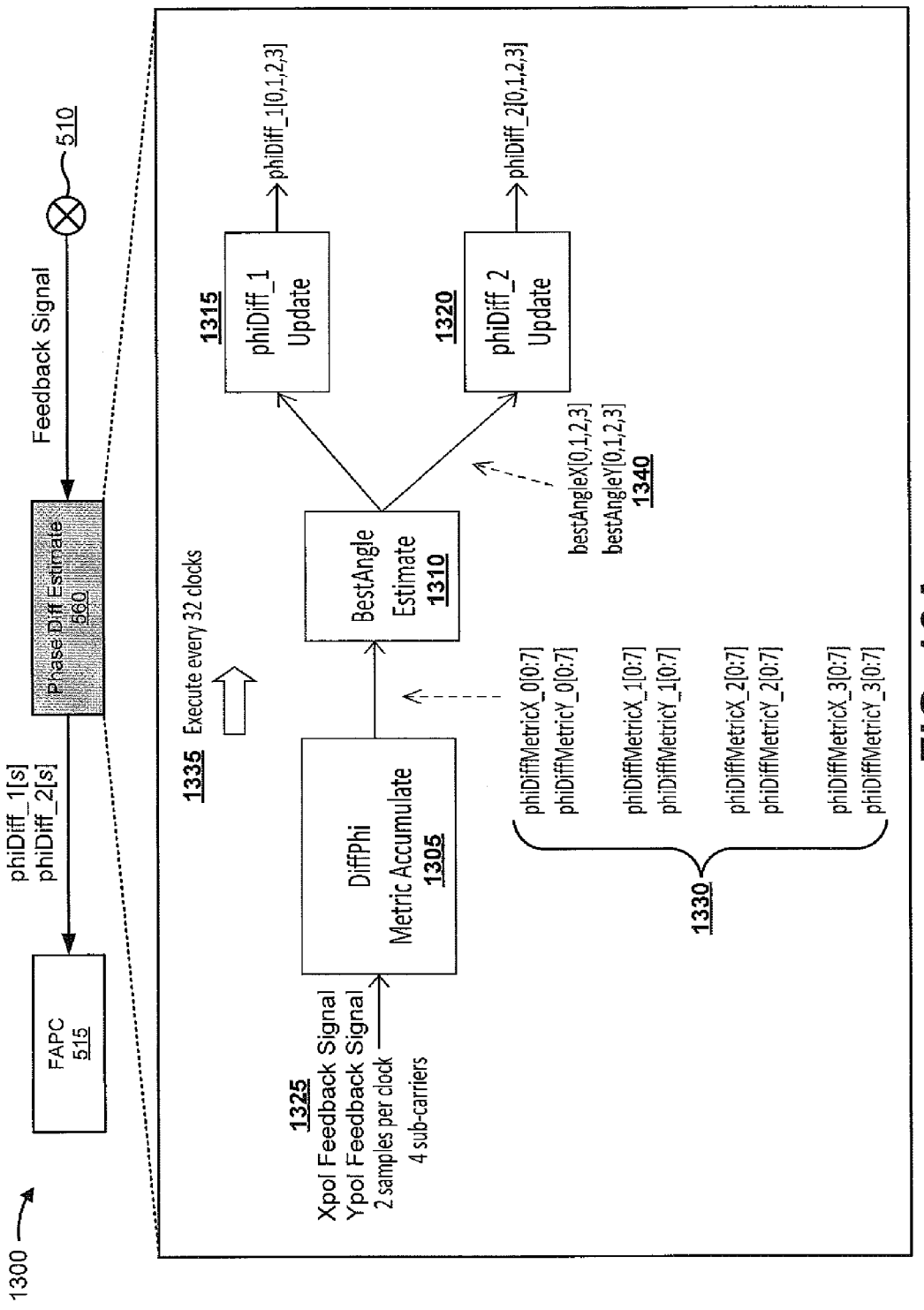
1300
510
Feedback Signal
Phase Diff Estimate
660
phiDiff_1[s]
phiDiff_2[s]
FAPC
515
1335 Execute every 32 clocks
1315
phiDiff_1
Update
1320
phiDiff_2
Update
phiDiff_1[0,1,2,3]
phiDiff_2[0,1,2,3]
BestAngle
Estimate
1310
bestAngleX[0,1,2,3]
bestAngleY[0,1,2,3]
1340
DiffPhi
Metric Accumulate
1305
1325
Xpol Feedback Signal
Ypol Feedback Signal
2 samples per clock
4 sub-carriers
phiDiffMetricX_0[0:7]
phiDiffMetricY_0[0:7]
phiDiffMetricX_1[0:7]
phiDiffMetricY_1[0:7]
phiDiffMetricX_2[0:7]
phiDiffMetricY_2[0:7]
phiDiffMetricX_3[0:7]
phiDiffMetricY_3[0:7]
1330

FIG. 13A

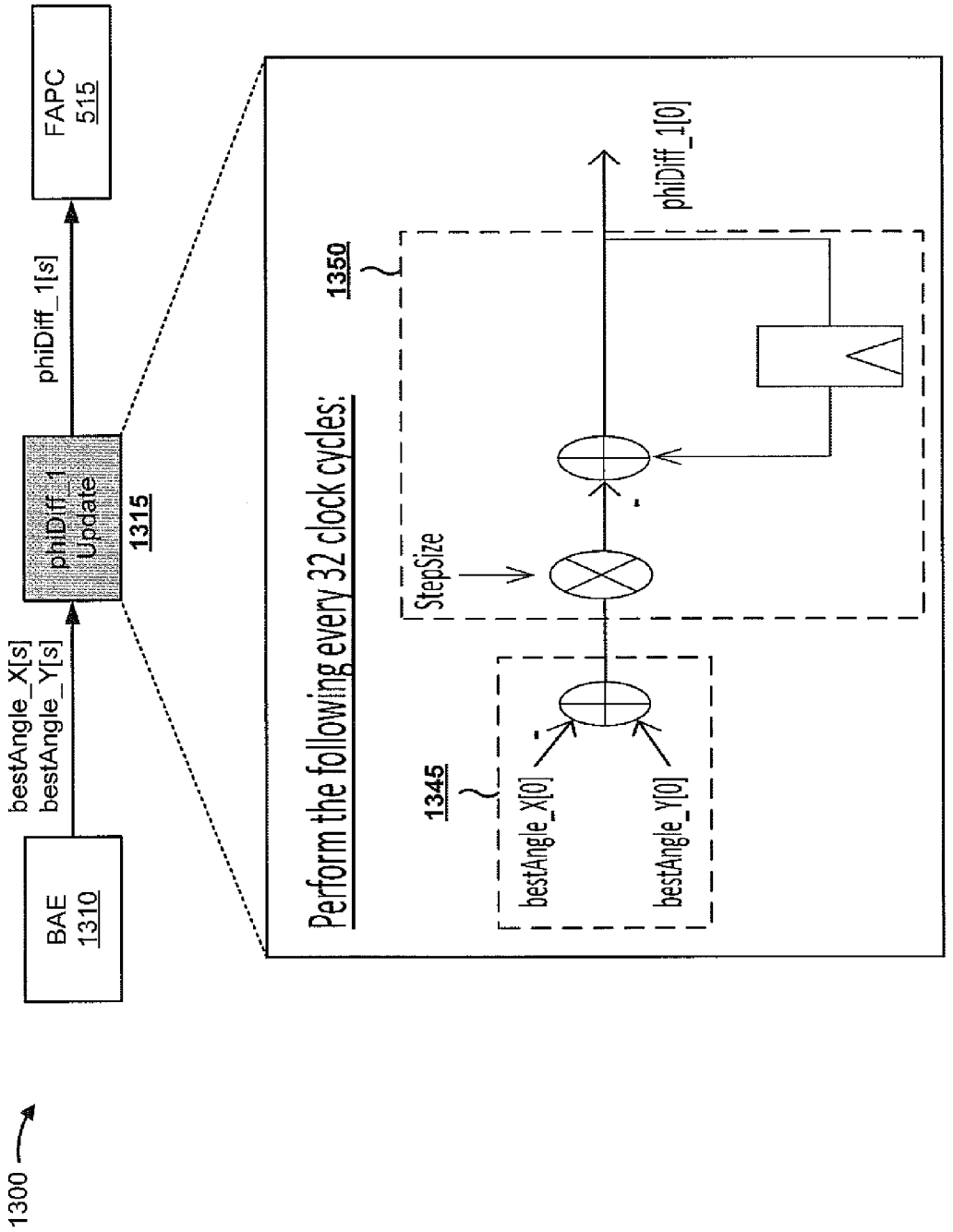
1300
BAE
1310
bestAngle_X[s]
bestAngle_Y[s]
phiDiff_1
Update
1315
phiDiff_1[s]
FAPC
515
Perform the following every 32 clock cycles:
1350
StepSize
1345
bestAngle_X[0]
bestAngle_Y[0]
phiDiff_1[0]

FIG. 13B

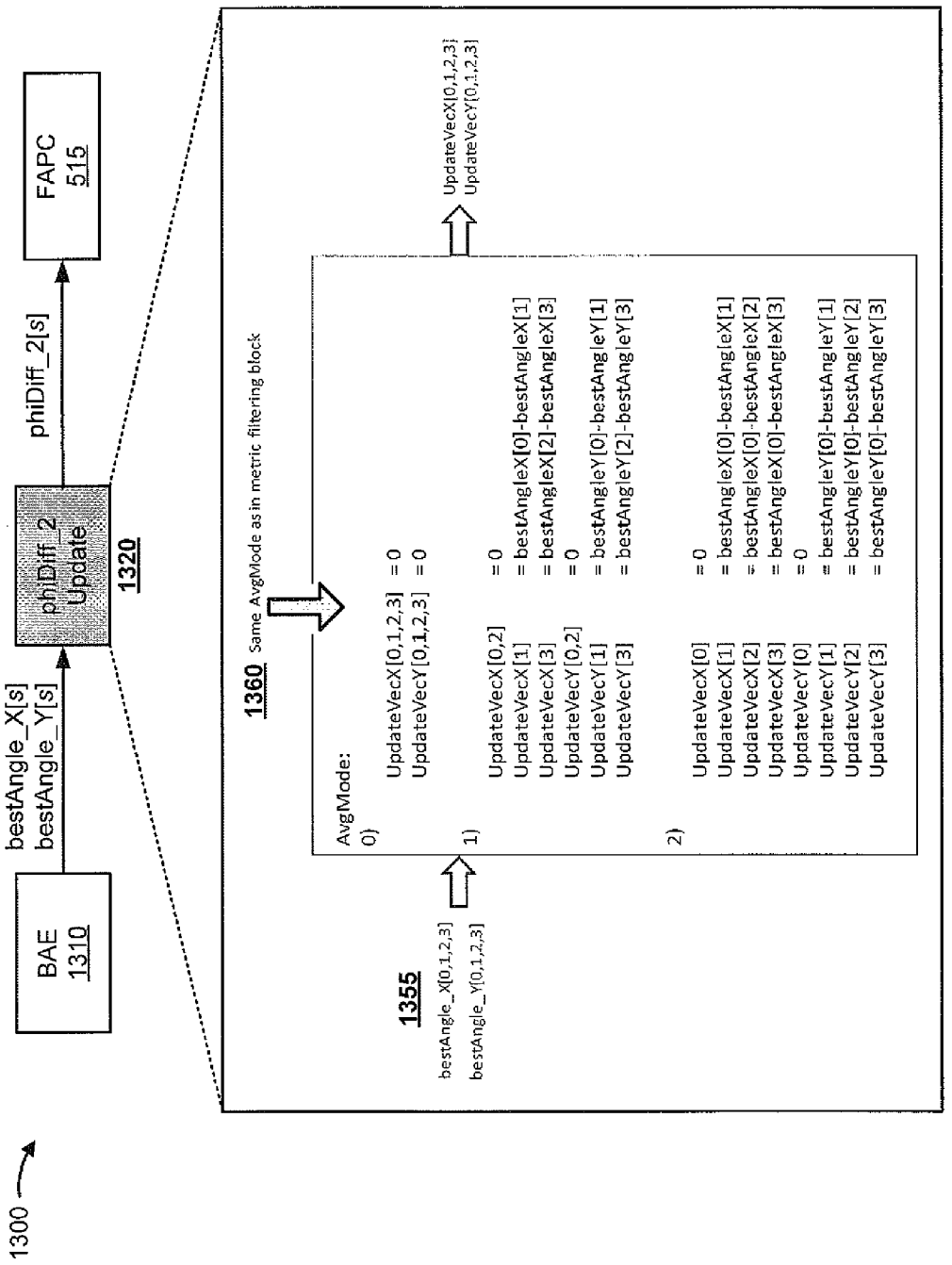
1300
BAE
1310
bestAngle_X[s]
bestAngle_Y[s]
phiDiff_2
Update
1320
phiDiff_2[s]
FAPC
515
1360 Same AvgMode as in metric filtering block
1355
bestAngle_X[0,1,2,3]
bestAngle_Y[0,1,2,3]
AvgMode:
0)
UpdateVecX[0,1,2,3] = 0
UpdateVecY[0,1,2,3] = 0
1)
UpdateVecX[0,2] = 0
UpdateVecX[1] = bestAngleX[0]-bestAngleX[1]
UpdateVecX[3] = bestAngleX[2]-bestAngleX[3]
UpdateVecY[0,2] = 0
UpdateVecY[1] = bestAngleY[0]-bestAngleY[1]
UpdateVecY[3] = bestAngleY[2]-bestAngleY[3]
2)
UpdateVecX[0] = 0
UpdateVecX[1] = bestAngleX[0]-bestAngleX[1]
UpdateVecX[2] = bestAngleX[0]-bestAngleX[2]
UpdateVecX[3] = bestAngleX[0]-bestAngleX[3]
UpdateVecY[0] = 0
UpdateVecY[1] = bestAngleY[0]-bestAngleY[1]
UpdateVecY[2] = bestAngleY[0]-bestAngleY[2]
UpdateVecY[3] = bestAngleY[0]-bestAngleY[3]
UpdateVecX[0,1,2,3]
UpdateVecY[0,1,2,3]

FIG. 13C

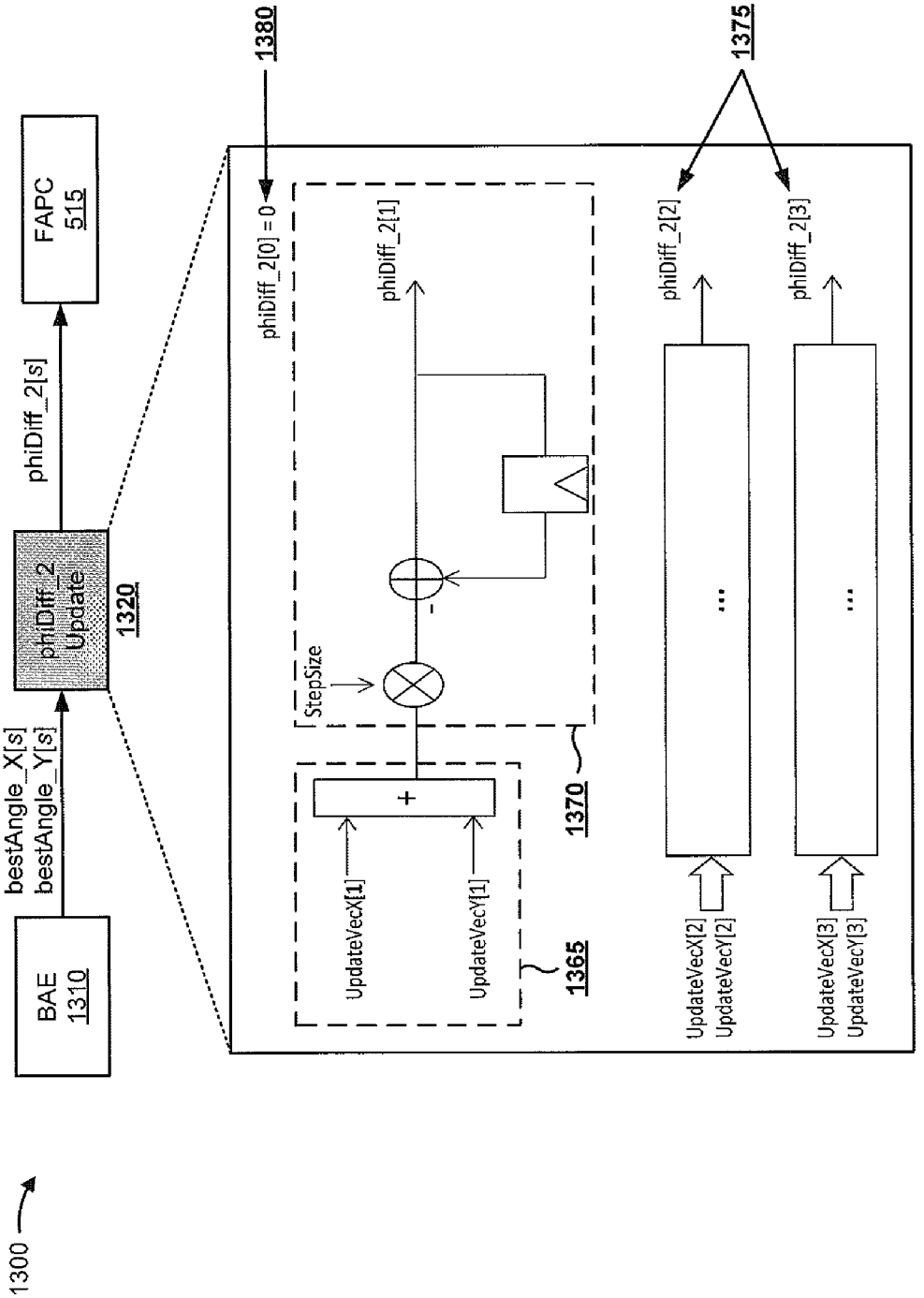
1300
BAE
1310
bestAngle_X[s]
bestAngle_Y[s]
phiDiff_2
Update
1320
phiDiff_2[s]
FAPC
515
1380
phiDiff_2[0] = 0
StepSize
phiDiff_2[1]
1370
UpdateVecX[1]
UpdateVecY[1]
1365
1375
phiDiff_2[2]
phiDiff_2[3]
UpdateVecX[2]
UpdateVecY[2]
UpdateVecX[3]
UpdateVecY[3]

FIG. 13D

FREQUENCY AND PHASE COMPENSATION FOR MODULATION FORMATS USING MULTIPLE SUB-CARRIERS

BACKGROUND

Wavelength division multiplexed (WDM) optical communication systems (referred to as "WDM systems") are systems in which multiple optical signals, each having a different wavelength, are combined onto a single optical fiber using an optical multiplexer circuit (referred to as a "multiplexer"). Such systems may include a transmitter circuit, such as a transmitter (Tx) photonic integrated circuit (PIC) having a transmitter component to provide a laser associated with each wavelength, a modulator configured to modulate the output of the laser, and a multiplexer to combine each of the modulated outputs (e.g., to form a combined output or WDM signal).

A WDM system may also include a receiver circuit having a receiver (Rx) PIC and an optical demultiplexer circuit (referred to as a "demultiplexer") configured to receive the combined output and demultiplex the combined output into individual optical signals. Additionally, the receiver circuit may include receiver components to convert the optical signals into electrical signals, and output the data carried by those electrical signals.

SUMMARY

According to some possible implementations, an optical receiver may include a digital signal processor. The digital signal processor may receive input signals carried by respective sub-carriers. The digital signal processor may determine, based on the input signals, a frequency compensation value and a phase compensation value to be used to modify an input signal. The digital signal processor may modify the input signal, to form a modified input signal, using the frequency compensation value and the phase compensation value. The frequency compensation value may be used to modify a frequency of the input signal, and the phase compensation value may be used to modify a phase of the input signal. The digital signal processor may determine, based on the modified input signal, a phase estimate value that represents an estimated phase for the input signal, may combine the frequency compensation value, the phase compensation value, and the phase estimate value to generate a phase adjustment signal, may combine the input signal and the phase adjustment signal to form an output signal, and may output the output signal.

According to some possible implementations, a system may include an optical receiver. The optical receiver may receive input signals carried by respective sub-carriers. The optical receiver may determine, based on the input signals, a frequency compensation value or a phase compensation value to be used to modify an input signal. The optical receiver may modify the input signal, to form a modified input signal, using the frequency compensation value or the phase compensation value. The frequency compensation value may be used to modify a frequency of the input signal, and the phase compensation value may be used to modify a phase of the input signal. The optical receiver may determine, based on the modified input signal, a phase estimate value that represents an estimated phase for the input signal. The optical receiver may combine the phase estimate value and the frequency compensation value or the phase compensation value to generate a phase adjustment signal, may combine the input signal and the phase adjustment signal to form an output signal, and may output the output signal.

According to some possible implementations, a method may include receiving, by an optical receiver, input signals carried by respective sub-carriers. The method may include determining, by the optical receiver and based on the input signals, a compensation value to be used to modify an input signal. The method may include adjusting, by the optical receiver and using the compensation value, the input signal to form a modified input signal. The compensation value may be used to modify a frequency or a phase of the input signal. The method may include determining, by the optical receiver and based on the modified input signal, a phase estimate value that represents an estimated phase associated with the input signal. The method may include combining, by the optical receiver, the compensation value and the phase estimate value to form a phase adjustment signal; combining, by the optical receiver, the input signal and the phase adjustment signal to form an output signal; and outputting, by the optical receiver, the output signal.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A-**1**C are diagrams of an overview of an example implementation described herein;

FIG. **2** is a diagram of an example network in which systems and/or methods, described herein, may be implemented;

FIG. **3** is a diagram of example components of an optical transmitter shown in FIG. **2**;

FIG. **4** is a diagram of example components of an optical receiver shown in FIG. **2**;

FIGS. **5**A and **5**B are diagrams of example components of a carrier recovery component shown in FIG. **4**; and

FIGS. **6-8**, **9**A, **9**B, **10-12**, and **13**A-**13**D are diagrams of example implementations relating to operations performed by components of the carrier recovery component shown in FIGS. **5**A and **5**B.

DETAILED DESCRIPTION

The following detailed description of example implementations refers to the accompanying drawings. The same reference numbers in different drawings may identify the same or similar elements.

In a WDM system, a transmitter may modulate an amplitude and/or a phase of a signal in order to convey data, via the signal, to a receiver where the signal may be demodulated to recover the data included in the signal. A particular modulation format (e.g., phase-shift keying (PSK), quadrature amplitude modulation (QAM), quadrature phase-shift keying (QPSK), binary phase-shift keying (BPSK), polarization-multiplexed quadrature phase-shift keying (PM-QPSK), etc.) may be used to modulate the signal. When the signal is transmitted or received over a link, random phase fluctuations in the signal may be introduced via the transmitter, the receiver, and/or the link. These random phase fluctuations may be compensated by the receiver during carrier phase recovery to correct a phase error introduced into the modulated signal, thus permitting the receiver to properly decode the modulated signal.

In a coherent receiver, the received signal is sampled by analog-to-digital converters (ADCs) for signal processing. Although 2 samples/symbol or less may be used for the CD compensation and PMD equalization, the subsequent carrier recovery uses 1 sample/symbol. During carrier phase recovery, the receiver may apply test phases to a received sample to determine the most-likely transmitted symbol. For example, the receiver may apply a maximum likelihood phase estimate technique by rotating a received sample using each test phase

to decode the received sample into a symbol. The receiver may determine which rotated sample is closest to (e.g., has the smallest Euclidean distance to) a constellation point (e.g., included in a constellation diagram for a particular modulation format), which corresponds to the decoded symbol. However, this technique may require a large number of test phases to generate an accurate estimate of the phase to be corrected for the received sample, which may be computationally expensive. Implementations described herein reduce the computational complexity of accurately estimating the phase error contained in a received sample. Furthermore, implementations described herein introduce a technique for performing carrier recovery when signals are transmitted using multiple digital sub-carriers, rather than a single carrier.

FIGS. **1**A-**1**C are diagrams of an overview of an example implementation **100** described herein. FIG. **1**A shows a constellation diagram that represents all possible symbols that may be transmitted via a signal modulated using a rectangular 16QAM modulation format. As shown by reference number **105**, some of the constellation points (e.g., symbols) in the constellation diagram are separated by a phase difference of 90 degrees (e.g., the constellation points represented by a white dot with a black outline). As shown by reference number **110**, when a receiver receives a sample corresponding to a symbol, the sample may include a phase error that, if not corrected, would be decoded to an incorrect symbol in the constellation diagram. For example, a phase error may have been introduced into the sample during transmission (e.g., due to random noise introduced into the sample/signal by the receiver, by a transmitter, during transmission via a fiber, etc.). The receiver may correct a phase error in the sample by rotating the sample using a set of test phases, and determining an error (e.g., a distance), for each test phase, between the rotated sample and the nearest constellation point in the constellation diagram. For example, the receiver may rotate the received sample using a set of test phases between −45 degrees and 45 degrees, as shown. As shown by reference number **115**, applying this carrier recovery technique to a constellation point with a 90 degree phase difference results in one minimum error value, which corresponds to the phase estimate for carrier recovery.

This carrier recovery technique cannot be used to easily correct a phase error associated with symbols in the constellation diagram that are separated by a phase difference of 36.87 degrees or 53.13 degrees (e.g., the symbols represented by a black dot with a black outline), which are shown by reference number **120**. The star in the constellation diagram represents a received sample. As shown, the receiver may scan+/−45 degrees from the received sample to identify a correct constellation point. Assume that the correct constellation point is found at a test phase of zero degrees, which corresponds to a first minimum error value. However, there is also a second minimum error value at a test phase of −36.87 degrees, which causes an ambiguity. These two minima associated with the error values (e.g., at 0 degrees and −36.87 degrees) are also shown by reference number **125**.

As shown in FIG. **1**B, and by reference number **130**, assume that the minimum error value for the received 90 degree phase difference symbol corresponds to a phase rotation of 20 degrees. Thus, to perform carrier recovery for the received sample, the receiver may rotate the phase of the received sample by 20 degrees to correct for the phase error so that the received sample may be properly decoded to the transmitted symbol, as shown by reference number **135**.

As shown by reference number **140**, assume that the two minimum error values for correspond to test phases of zero degrees and −36.87 degrees. Assume that the receiver properly performs carrier recovery by selecting the test phase of zero degrees. To perform carrier recovery for additional received samples, the receiver may use test phases that range from −22.5 degrees and 22.5 degrees around the selected test phase (e.g., a 45 degree sweep centered at 0 degrees), thereby eliminating the possibility of determining two minimum error values, as shown by reference number **150**. Thus, implementations described herein assist in accurately and efficiently correcting phase errors in received samples.

As shown in FIG. **1**C, implementations described herein may also assist in accurately and efficiently correcting phase errors in received samples when the samples are carried on signals transmitted via multiple digital sub-carriers. Note that by using digital subcarriers, the transmitter and the receiver may use one laser centered at the center of the overall signal spectrum. In an optical communication system, a certain bandwidth, or spectrum, may be allocated to an optical communications channel. As shown by reference number **155**, the channel may include a single carrier that carries data via the optical channel. In this case, implementations described herein may use a phase estimate of the single carrier for carrier recovery. As shown by reference number **160**, rather than including a single carrier, the channel may include multiple sub-carriers that carry data via the optical channel. In this case, implementations described herein may use an average phase estimate of multiple sub-carriers for carrier recovery. In this way, the receiver may accurately and efficiently determine phase estimates for received symbols, resulting in more accurate and efficient data transmission.

Implementations described herein may perform carrier recovery for different modulation formats, such as M-QAM modulation formats (e.g., 3QAM, 5QAM, 7QAM, 8QAM, 16QAM, etc.), BPSK modulation formats (e.g., Block-4D-BPSK, etc.), QPSK modulation formats (e.g., PM-QPSK, etc.), or the like.

FIG. **2** is a diagram of an example network **200** in which systems and/or methods, described herein, may be implemented. As shown in FIG. **2**, network **200** may include transmitter (Tx) module **210** (e.g., a Tx PIC), and/or receiver (Rx) module **220** (e.g., an Rx PIC). In some implementations, transmitter module **210** may be optically connected to receiver module **220** via link **230**. Additionally, link **230** may include one or more optical amplifiers **240** that amplify an optical signal as the optical signal is transmitted over link **230**.

Transmitter module **210** may include one or more optical transmitters **212**-**1** through **212**-M (M≥1), one or more waveguides **214**, and/or an optical multiplexer **216**. In some implementations, transmitter module **210** may include additional components, fewer components, different components, or differently arranged components than those shown in FIG. **2**.

Optical transmitter **212** may receive data for a data channel (shown as TxCh**1** through TxChM), may create multiple sub-carriers for the data channel, may map data, for the data channel, to the multiple sub-carriers, may modulate the data with an optical signal (e.g., a laser) to create a multiple sub-carrier output optical signal, and may transmit the multiple sub-carrier output optical signal. Optical transmitter **212** may be tuned to use an optical carrier of a designated wavelength. In some implementations, the grid of wavelengths emitted by optical transmitters **212** may conform to a known standard, such as a standard published by the Telecommunication Standardization Sector (ITU-T). Additionally, or alternatively the grid of wavelengths may be flexible and tightly packed to create a super channel.

Waveguide **214** may include an optical link or some other link to transmit output optical signals of optical transmitter

212. In some implementations, each optical transmitter **212** may include one waveguide **214**, or multiple waveguides **214**, to transmit output optical signals of optical transmitters **212** to optical multiplexer **216**.

Optical multiplexer **216** may include an arrayed waveguide grating (AWG) or some other type of multiplexer device. In some implementations, optical multiplexer **216** may combine multiple output optical signals, associated with optical transmitters **212**, into a single optical signal (e.g., a WDM signal). For example, optical multiplexer **216** may include an input (e.g., a first slab to receive input optical signals supplied by optical transmitters **212**) and an output (e.g., a second slab to supply a single WDM signal associated with the input optical signals). Additionally, optical multiplexer **216** may include waveguides connected to the input and the output. In some implementations, optical multiplexer **216** may combine multiple output optical signals, associated with optical transmitters **212**, in such a way as to produce a polarization diverse signal (e.g., also referred to herein as a WDM signal). As shown in FIG. **2**, optical multiplexer **216** may provide the WDM signal to receiver module **220** via an optical fiber, such as link **230**.

Optical multiplexer **216** may receive output optical signals outputted by optical transmitters **212**, and may output one or more WDM signals. Each WDM signal may include one or more optical signals, such that each optical signal includes one or more wavelengths. In some implementations, one WDM signal may have a first polarization (e.g., a transverse magnetic (TM) polarization), and another WDM signal may have a second, substantially orthogonal polarization (e.g., a transverse electric (TE) polarization). Alternatively, both WDM signals may have the same polarization.

Link **230** may include an optical fiber. Link **230** may transport one or more optical signals associated with multiple wavelengths. Amplifier **240** may include an amplification device, such as a doped fiber amplifier, a Raman amplifier, or the like. Amplifier **240** may amplify the optical signals as the optical signals are transmitted via link **230**.

Receiver module **220** may include an optical demultiplexer **222**, one or more waveguides **224**, and/or one or more optical receivers **226-1** through **226-N**($N \geq 1$). In some implementations, receiver module **220** may include additional components, fewer components, different components, or differently arranged components than those shown in FIG. **2**.

Optical demultiplexer **222** may include an AWG or some other type of demultiplexer device. In some implementations, optical demultiplexer **222** may supply multiple optical signals based on receiving one or more optical signals, such as WDM signals, or components associated with the one or more optical signals. For example, optical demultiplexer **222** may include an input (e.g., a first slab to receive a WDM signal and/or some other input signal), and an output (e.g., a second slab to supply multiple optical signals associated with the WDM signal). Additionally, optical demultiplexer **222** may include waveguides connected to the input and the output. As shown in FIG. **2**, optical demultiplexer **222** may supply optical signals to optical receivers **226** via waveguides **224**.

Waveguide **224** may include an optical link or some other link to transmit optical signals, output from optical demultiplexer **222**, to optical receivers **226**. In some implementations, each optical receiver **226** may receive optical signals via a single waveguide **224** or via multiple waveguides **224**.

Optical receiver **226** may include one or more photodetectors and/or similar devices to receive respective input optical signals outputted by optical demultiplexer **222**, to detect subcarriers associated with the input optical signals, to convert data within the sub-carriers to voltage signals, to convert the voltage signals to digital samples, and to process the digital samples to produce output data corresponding to the input optical signals. Optical receivers **226** may each operate to convert the input optical signal to an electrical signal that represents the transmitted data.

The number and arrangement of components shown in FIG. **2** is provided as an example. In practice, network **200** may include additional components, fewer components, different components, or differently arranged components than those shown in FIG. **2**. Additionally, or alternatively, a set of devices (e.g., one or more devices) shown in FIG. **2** may perform one or more functions described herein as being performed by another set of devices shown in FIG. **2**.

FIG. **3** is a diagram of example components of an optical transmitter **212**. As shown in FIG. **3**, optical transmitter **212** may include a TX DSP **310**, one or more DACs **320**, a laser **330**, and one or more modulators **340**. In some implementations, TX DSP **310**, DAC **320**, laser **330**, and/or modulator **340** may be implemented on one or more integrated circuits, such as one or more PICs, one or more application specific integrated circuits (ASICs), or the like. In some implementations, components of multiple optical transmitters **212** may be implemented on a single integrated circuit, such as a single PIC, to form a super-channel transmitter.

TX DSP **310** may include a digital signal processor. TX DSP **310** may receive input data from a data source, and may determine a signal to apply to modulator **340** to generate multiple sub-carriers. In some implementations, TX DSP **310** may receive streams of data, may map the streams of data onto each of the sub-carriers, may independently apply spectral shaping to each of the sub-carriers, and may obtain, based on the spectral shaping of each of the sub-carriers, a sequence of assigned integers to supply to DAC **320**. In some implementations, TX DSP **310** may generate the sub-carriers using time-domain or frequency-domain filtering and frequency shifting by a combination of reallocation of frequency bins and multiplication in the time domain.

DAC **320** may include a signal converting device or a collection of signal converting devices. In some implementations, DAC **320** may receive respective digital signals from TX DSP **310**, may convert the received digital signals to analog signals, and may provide the analog signals to modulator **340**. The analog signals may correspond to electrical signals (e.g., voltage signals) to drive modulator **340**. In some implementations, transmitter module **212** may include multiple DACs **320**, where a particular DAC **320** may correspond to a particular in-phase (I) or quadrature component (Q) of a particular polarization (e.g., an X polarization, a Y polarization) of a dual-pol signal.

Laser **330** may include a semiconductor laser, such as a distributed feedback (DFB) laser, or some other type of laser. Laser **330** may provide an output optical light beam to modulator **340**.

Modulator **340** may include a Mach-Zehnder modulator (MZM), such as a nested MZM, or another type of modulator. Modulator **340** may receive the optical light beam from laser **330** and the voltage signals from DAC **320**, and may modulate the optical light beam, based on the voltage signals, to generate a multiple digital sub-carrier output signal, which may be provided to multiplexer **216**.

In some implementations, optical transmitter **212** may include multiple modulators **340**, which may be used to modulate signals of different polarizations. For example, an optical splitter may receive an optical light beam from laser **330**, and may split the optical light beam into two branches: one for a first polarization and one for a second polarization.

The splitter may output one optical light beam to a first modulator **340**, which may be used to modulate signals of the first polarization, and another optical light beam to a second modulator **340**, which may be used to modulate signals of the second polarization. In some implementations, two DACs **320** may be associated with each polarization. In these implementations, two DACs **320** may supply voltage signals to the first modulator **340** (e.g., for an in-phase component of an X polarization and a quadrature component of the X polarization), and two DACs **320** may supply voltage signals to the second modulator **340** (e.g., for an in-phase component of a Y polarization and a quadrature component of the Y polarization). The outputs of modulators **340** may be combined back together using combiners (e.g., optical multiplexer **216**) and polarization multiplexing.

The number and arrangement of components shown in FIG. **3** is provided as an example. In practice, optical transmitter **212** may include additional components, fewer components, different components, or differently arranged components than those shown in FIG. **3**. For example, the quantity of DACs **320**, lasers **330**, and/or modulators **340** may be selected to implement an optical transmitter **212** that is capable of generating polarization diverse signals for transmission on an optical fiber, such as link **230**. Additionally, or alternatively, a set of components shown in FIG. **3** may perform one or more functions described herein as being performed by another set of components shown in FIG. **3**.

FIG. **4** is a diagram of example components of optical receiver **226**. As shown in FIG. **4**, optical receiver **226** may include a local oscillator **410**, one or more hybrid mixers **420**, one or more detectors **430**, one or more ADCs **440**, and an RX DSP **450**, which may include a carrier recovery component (CRC) **460**. In some implementations, local oscillator **410**, hybrid mixer **420**, detector **430**, ADC **440**, and/or RX DSP **450** may be implemented on one or more integrated circuits, such as one or more PICs, one or more ASICs, or the like. In some implementations, components of multiple optical receivers **226** may be implemented on a single integrated circuit, such as a single PIC plus one or more ASICs, to form a super-channel receiver.

Local oscillator **410** may include a laser, or a similar device. In some implementations, local oscillator **410** may include a laser to provide an optical signal to hybrid mixer **420**. In some implementations, local oscillator **410** may include a single-sided laser to provide an optical signal to hybrid mixer **420**. In some implementations, local oscillator **410** may include a double-sided laser to provide multiple optical signals to multiple hybrid mixers **420**.

Hybrid mixer **420** may include a combiner that receives a first optical signal (e.g., an input signal from optical demultiplexer **222**) and a second optical signal (e.g., from local oscillator **410**) and combines the first and second optical signals to generate a combined optical signal. In some implementations, hybrid mixer **420** may include a polarization beam splitter (PBS) which splits the first optical signal into two orthogonal signals. The two orthogonal signals may be combined with respective second optical signals (from a laser) with 90 degree phase with respect to each other. Hybrid mixer **420** may provide the combined optical signal to detector **430**.

Detector **430** may include a photodetector, such as a photodiode, to receive the output optical signal, from hybrid mixer **420**, and to convert the output optical signal to corresponding voltage signals. In some implementations, detector **430** may detect the entire spectrum of the output optical signal (e.g., containing all of the sub-carriers).

In some implementations, optical receiver **226** may include multiple detectors **430**, which may be used to detect signals of respective I and Q components of the two orthogonal polarizations. For example, a polarization splitter may receive an input signal, and may split the input signal into two substantially orthogonal polarizations, such as the first polarization and the second polarization. Hybrid mixers **420** may combine the polarization signals with optical signals from local oscillator **410**. For example, a first hybrid mixer **420** may combine a first polarization signal with the optical signal from local oscillator **410**, and a second hybrid mixer **420** may combine a second polarization signal with the optical signal from local oscillator **410** with 90 degree phase with respect to the first signal of the local oscillator.

Detectors **430** may detect the polarization signals to form corresponding voltage signals, and ADCs **440** may convert the voltage signals to digital samples. For example, two detectors **430** (e.g., balanced PIN diodes) may detect the first polarization signals to form the corresponding voltage signals, and a corresponding two ADCs **440** (e.g., that correspond to an I component and a Q component) may convert the voltage signals to digital samples for the first polarization signals. Similarly, two detectors **430** may detect the second polarization signals to form the corresponding voltage signals, and a corresponding two ADCs **440** (e.g., that correspond to an I component and a Q component) may convert the voltage signals to digital samples for the second polarization signals. RX DSP **450** may process the digital samples for the first and second polarization signals to generate resultant data, which may be outputted as output data.

ADC **440** may include four analog-to-digital converters that convert the voltage signals from detector **430** to digital samples. ADC **440** may provide the digital samples to RX DSP **450**.

RX DSP **450** may include a digital signal processor. RX DSP **450** may receive the digital samples from ADC **440**, may demultiplex the samples according to the subcarriers, may independently process the samples for each of the subcarriers, may map the processed samples to produce output data, and may output the output data. RX DSP **450** may include CRC **460**, which may include one or more components for performing carrier recovery, as described in more detail elsewhere herein.

The number and arrangement of components shown in FIG. **4** is provided as an example. In practice, optical receiver **226** may include additional components, fewer components, different components, or differently arranged components than those shown in FIG. **4**. For example, the quantity of hybrid mixers **420**, detectors **430**, and/or ADCs **440** may be selected to implement an optical receiver **226** that is capable of receiving and processing a polarization diverse signal. Additionally, or alternatively, a set of components shown in FIG. **4** may perform one or more functions described herein as being performed by another set of components shown in FIG. **4**.

FIGS. **5**A and **5**B are diagrams of example components of carrier recovery component **460** shown in FIG. **4**. As shown in FIG. **5**A, carrier recovery component **460** may include a first-in first-out delay component (FIFO Delay) **505**, a multiplier component **510**, a frequency and phase compensation component (FAPC) **515**, a phase test component **520**, a metric filtering component **525**, a phase estimate component **530**, a phase unwrap component **535**, another FIFO Delay component **540**, an adder component **545**, a lookup table component (LUT) **550**, a frequency estimate component **555**, and a phase difference estimate component **560**.

Carrier recovery component (CRC) **460** may receive an input signal (e.g. from the output of an equalizer), and may pass the input signal to FIFO Delay **505**, which may delay the input signal to compensate for delay introduced by operations performed by other components of CRC **460** (e.g., components **515-550**) prior to an adjustment signal being received by multiplier component **510**. Multiplier component **510** may receive the input signal from FIFO Delay **505**, and may adjust the input signal (e.g., via multiplication, rotation, etc.) using an adjustment signal received from LUT **550**. For example, multiplier component **510** may adjust a phase of the input signal using an output phase value received from LUT **550**. Multiplier component **510** may output the adjusted signal as an output signal from CRC **460**, and may further output the adjusted signal to a feedback loop that includes phase difference estimate component **560**.

CRC **460** may also pass the input signal to FAPC **515**. Components **515-550** may operate on the input signal to determine the output phase value to be provided to multiplier **510**. Components **555** and **560** may be included in a feedback loop that determines feedback signals to be used to adjust operations of components **515-550** (e.g., FAPC **515**).

As shown in FIG. **5**B, FAPC **515** may provide a phase and/or frequency compensated signal to phase test component **520**. Phase test component **520** may apply test phases to the signal, and may determine error values based on applying the test phases. Metric filtering component **525** may receive the error values, and may average the error values over time and/or over multiple sub-carriers. Phase estimate component **530** may receive the averaged error values, and may determine one or more phase estimates for the input signals based on the averaged error values. Phase unwrap component **535** may unwrap the phase estimate values across a full phase cycle (e.g., 360 degrees), and may provide the unwrapped phase estimate as shown in FIG. **5**A. Components of CRC **460** will be described in more detail elsewhere herein.

The number of components shown in FIGS. **5**A and **5**B is provided as an example. In practice, CRC **460** may include additional components, fewer components, different components, or differently arranged components than those shown in FIGS. **5**A and **5**B. Additionally, or alternatively, a set of components of CRC **460** may perform one or more functions described as being performed by another set of components of CRC **460**.

FIG. **6** is a diagram of an example implementation **600** relating to operations performed by frequency and phase compensation component (FAPC) **515**. As shown in FIG. **6**, FAPC **515** may receive an input signal (e.g., a digital sample, a digital signal, etc.). In example implementation **600**, FAPC **515** is shown as receiving 16 samples, on each of 4 sub-carriers that each have two polarizations (e.g., Xpol and Ypol), per clock cycle. Thus, FAPC **515** receives 64 samples on the X polarization (e.g., 16 samples×4 sub-carriers carrying data on the X polarization) and 64 samples on the Y polarization (e.g., 16 samples×4 sub-carriers carrying data on the Y polarization), for a total of 128 samples per clock cycle. Each sample may include a symbol (e.g., with a phase value and an amplitude value).

In some implementations, FAPC **515** may compensate the frequency of the input signal(s) using a frequency estimate value (FreqEstVal) received from frequency estimate component (FE) **555**, determined as described elsewhere herein.

Additionally, or alternatively, FAPC **515** may compensate a phase difference between the X polarization and the Y polarization for each sub-carrier using a first phase difference value (phiDiff_1, or Φ_{diff1}) received from PDE **560**, determined as described elsewhere herein. In some implementations, the quantity of phiDiff_1 values received from PDE **560** may correspond to the quantity of sub-carriers. For example, PDE **560** is shown as providing four phiDiff_1 values to FAPC **515** (e.g., phiDiff_1[0], phiDiff_1[1], phiDiff_1[2], and phiDiff_1[3]), where the values of 0-3 correspond to the 4 sub-carriers of example implementation **600**.

Additionally, or alternatively, FAPC **515** may compensate a phase difference between different sub-carriers using a second phase difference value (phiDiff_2, or Φ_{diff2}) received from PDE **560**, determined as described elsewhere herein. In some implementations, the quantity of phiDiff_2 values received from PDE **560** may correspond to the quantity of sub-carriers. For example, PDE **560** is shown as providing four phiDiff_2 values to FAPC **515** (e.g., phiDiff_2[0], phiDiff_2[1], phiDiff_2[2], and phiDiff_2[3]), where the values of 0-3 correspond to the 4 sub-carriers of example implementation **600**.

For each sub-carrier s, FAPC **515** may compensate a sample received via the sub-carrier, based on input received from FE **555** and PDE **560**, as follows:

$$x'_s[n]=x_s[n]\times e^{-j[XCompvalues_s[n]]}$$

$$y'_s[n]=y_s[n]\times e^{-j[YCompvalues_s[n]]}$$

In the above equations, $x'_s[n]$ and $y'_s[n]$ may represent the frequency and phase compensated symbols, for the n^{th} sample (or at time n) of sub-carrier s, calculated by FAPC **515** for the X polarization and the Y polarization, respectively. Furthermore, $x_s[n]$ and $y_s[n]$ may represent the input symbols before adjustment, e may represent Euler's number (e.g., the mathematical constant e≈2.71828), j may represent the imaginary component of the sample (e.g., the square root of −1), and $XCompValue_s[n]$ and $YCompValue_s[n]$ may represent X polarization and Y polarization compensation values, respectively, to be applied to the input symbols by FAPC **515**. In some implementations, $XCompValue_s[n]$ and $YCompValue_s[n]$ may be represented as follows:

$$XCompValue_s[n]=\left(\int_{-\infty}^{n} FreqEstVal\right)+\frac{\phi_{diff1}[s]}{2}+\phi_{diff2}[s]$$

$$YCompValue_s[n]=\left(\int_{-\infty}^{n} FreqEstVal\right)-\frac{\phi_{diff1}[s]}{2}+\phi_{diff2}[s]$$

In the above equations, FreqEstVal may represent the frequency estimate value received from FE **555**, Φ_{diff1} may represent the first phase difference value received from PDE **560**, and Φ_{diff1} may represent the second phase difference value received from PDE **560**. As used herein, a frequency compensation value may refer to the frequency estimate value (FreqEstVal), an integral of the frequency estimate value (e.g., from $n_{initial}$ to n_{final}, such as from negative infinity to n), or the like. As used herein, a phase compensation value may refer to the first phase difference value (e.g., Φ_{diff1}), the second phase difference value (e.g., Φ_{diff2}), a mathematical combination of the first phase difference value and the second phase difference value

$$\left(\text{e.g., } \frac{\phi_{diff1}[s]}{2}+\phi_{diff2}[s]\right),$$

or the like.

As shown in FIG. **6**, FAPC **515** may provide $x'_s[n]$ and $y'_s[n]$ to phase test component **520**. FAPC **515** may calculate these symbols for every sub-carrier s, and for every input

sample n. As further shown in FIG. **6**, FAPC **515** may provide $XCompValue_s[n]$ and $YCompValue_s[n]$ to phase ramp component **540**.

As indicated above, FIG. **6** is provided merely as an example. Other examples are possible and may differ from what was described with regard to FIG. **6**. For example, FAPC **515** may perform additional operations, fewer operations, or different operations than those described in connection with FIG. **6**.

FIG. **7** is a diagram of an example implementation **700** relating to operations performed by phase test component (PT) **520**. As described herein in connection with FIG. **6**, PT **520** may receive phase and frequency compensated symbols $x'_s[n]$ and $y'_s[n]$ from FAPC **515**. PT **520** may apply test phases to each received symbol (sample), and may calculate an error value associated with each test phase. The quantity of test phases and the span of the test phases may be configurable. As an example, assume that PT **520** uses 8 test phases. When performing carrier recovery for modulation formats that have 90 degree phase symmetry, PT **520** may use test phases that span 90 degrees. For example, when using 8 test phases that span 90 degrees, PT **520** may evenly space the test phases by using values of 0° (or 90°), 11.25°, 22.5°, 33.75°, 45°, 56.25°, 67.5°, and 78.75°. As another example, when using 8 test phases that span 180 degrees, PT **520** may evenly space the test phases by using values of 0° (or 180°), 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, and 157.5°.

PT **520** may apply a test phase to a received sample as follows:

$$x''_s[i,n] = x'_s[n] \times e^{-j\times\left(\frac{i}{i_{total}}\right)\times(span)}$$

$$y''_s[i,n] = y'_s[n] \times e^{-j\times\left(\frac{i}{i_{total}}\right)\times(span)}$$

In the above equations, $x''_s[i,n]$ and $y''_s[i,n]$ may represent the test phase compensated symbols, for the n^{th} sample (or at time n) of sub-carrier s when test phase i is applied, calculated by PT **520** for the X polarization and the Y polarization, respectively. Furthermore, $x'_s[n]$ and $y'_s[n]$ may represent the phase and frequency compensated symbols received from FAPC **515**, e may represent Euler's number, j may represent the imaginary component of the sample, i_{total} may represent the total quantity of test phases, and span may represent the span of the test phases. As an example, using 8 test phases that span 90 degrees, PT **520** may set span equal to $\pi/2$ radians (e.g., 90 degrees), and may set i/i_{total} equal to 0/8 for the first test phase (e.g., test phase 0), to ⅛ for the second test phase (e.g., test phase 1), etc., and to ⅞ for the last test phase (e.g., test phase 7, where the 8 test phases are identified as test phases 0 through 7). Thus, every input sample, for a particular sub-carrier and polarization, will result in eight output samples (e.g., one for each test phase).

As further shown in FIG. **7**, one or more test phase compensated symbols for each polarization may be provided to a decision device **710**. Decision device **710** may determine, for each input symbol, a symbol in the constellation diagram with which the input symbol is most likely to correspond. For example, decision device **710** may use a maximum likelihood estimation (e.g., by determining the minimum Euclidean distance between the input symbol and a symbol in the constellation diagram). Decision device **710** may be configured based on a modulation format of the signal (e.g., QPSK, Block-4D-BPSK, 3QAM, 16QAM, etc.).

In some implementations, decision device **710** may use two or more consecutive samples (e.g., n, n+1) to determine a most likely symbol (e.g., when the modulation format is Block-4D-BPSK). PT **520** may input the test phase compensated symbol and the most likely symbol into a subtractor **720**. Subtractor **720** may determine a difference between the test phase compensated symbol and the most likely symbol, and may provide the difference to a metric calculator **730**.

Metric calculator **730** may calculate an error value based on the difference. For example, metric calculator **730** may calculate a power of the error (e.g., a power of the difference), such as by squaring a difference of an in-phase component of the symbol (e.g., I), by squaring a difference of a quadrature component of the symbol (Q), and by summing the squares (e.g., I^2+Q^2). Metric calculator **730** may calculate a first error value for the X polarization and a second error value for the Y polarization. The error values calculated by metric calculator **730** for sub-carrier s and sample n using test phase i may be represented as MetricX_s[i,n] for the X polarization, and MetricY_s[i,n] for the Y polarization.

As further shown in FIG. **7**, PT **520** may provide the X and Y error values to an adder **740**. Adder **740** may combine the X and Y error values, for a particular sub-carrier s, test phase i, and sample n, to generate a combined error value for the particular sub-carrier s, test phase i, and sample n. The combined error value may be represented as Metric_s[i,n] (e.g., which may represent a sum of MetricX_s[i,n] and MetricY_s[i,n]). By combining the X and Y error values, adder **740** may reduce noise on the combined metric value. PT **520** may provide Metric_s[i,n] to metric filtering component **525**.

As indicated above, FIG. **7** is provided merely as an example. Other examples are possible and may differ from what was described with regard to FIG. **7**. For example, PT **520** may perform additional operations, fewer operations, or different operations than those described in connection with FIG. **7**.

FIG. **8** is a diagram of an example implementation **800** relating to operations performed by phase metric filtering component (MF) **525**. As described herein in connection with FIG. **7**, MF **525** may receive combined metric values (e.g., Metric_s[i,n]) from PT **520**. MF **525** may average combined metric values across multiple sub-carriers to generate a sub-carrier-averaged metric value for a particular sub-carrier s, test phase i, and sample n. Additionally, or alternatively, MF **525** may average combined metric values over time to generate a time-averaged metric value for a particular sub-carrier s, test phase i, and sample n. MF **525** may calculate the sub-carrier-averaged metric value and/or the time-averaged metric value to reduce an amount of noise in the metric value.

As an example, and as shown in FIG. **8**, assume that an optical channel is divided into four subcarriers, labeled **0**, **1**, **2**, and **3**. As shown by reference number **810**, assume that MF **525** receives a combined metric value Metric_s[i,n] for each of the four sub-carriers (e.g., Metric_0[i,n], Metric_1[i,n], Metric_2[i,n], and Metric_3[i,n]). As shown by reference number **820**, MF **525** may use an Avg_Mode indicator value to determine whether to calculate a sub-carrier-averaged metric value using multiple metric values for multiple respective sub-carriers (e.g., for a particular test phase and sample). For example, if the Avg_Mode value is equal to a first value (e.g., 0), then MF **525** may not calculate a sub-carrier-averaged metric value.

As another example, if the Avg_Mode value is equal to a second value (e.g., 1), then MF **525** may calculate a sub-carrier-averaged metric value (e.g., SCAverage) using metric values from two different sub-carriers. For example, MF **525** may calculate SCAverage_0[i, n] and SCAverage_1[i,n] by averaging Metric_0[i,n] and Metric_1[i,n]. Similarly, MF **525** may calculate SCAverage_2[i,n] and SCAverage_3[i,n]

by averaging Metric_2[i,n] and Metric_3[i,n]. In some implementations, MF **525** may average other combinations of metric values (e.g., by averaging Metric_0 and Metric_2, Metric_0 and Metric_3, etc.)

As another example, if the Avg_Mode value is equal to a third value (e.g., 2), then MF **525** may calculate the sub-carrier-averaged metric value using metric values from four different sub-carriers. For example, MF **525** may calculate SCAverage_0[i,n], SCAverage_1[i,n], SCAverage_2[i,n], and SCAverage_3[i,n] by averaging Metric_0[i,n], Metric_1[i,n], Metric_2[i,n], and Metric_3[i,n].

In some implementations, Avg_Mode may be a different value than described above, and MF **525** may calculate the sub-carrier-averaged metric value using metric values for different quantities (e.g., **3**, **5**, etc.) of sub-carriers and/or may combine metric values for different combinations of sub-carriers. In some implementations, the value of Avg_Mode may be configurable (e.g., based on user input, based on a modulation format, based on a quantity of sub-carriers, etc.).

As shown by reference number **830**, MF **525** may use an FFCR_Coeff[n_{start}, n_{end}] value to calculate a time-averaged metric value (e.g., TimeAverage_s[i,n]) using multiple metric values for multiple respective samples (e.g., for a particular test phase and sub-carrier). For example, MF **525** may calculate a time-averaged metric value over a particular quantity of samples (e.g., from n_{start} to n_{end}). Additionally, or alternatively, MF **525** may calculate a time-weighted average (e.g., with more recent samples being weighted more heavily than less recent samples), or may use another averaging technique to calculate the time-averaged metric value.

As shown by reference number **840**, MF **525** may generate and provide a final metric value, FinalMetric_s[i,n], to phase estimate component **530**. In some implementations, the final metric value may be equal to the combined metric value (e.g., Metric_s[i,n]) received from PT **520**. In some implementations, the final metric value may include a sub-carrier-averaged metric value (e.g., SCAverage_s[i,n]). In some implementations, the final metric value may include a time-averaged metric value (e.g., TimeAverage_s[i,n]). In some implementations, the final metric value may include a combination of sub-carrier-averaged metric values and time-averaged metric values. In this case, the time averaging and the sub-carrier averaging may be performed in any order.

As an example, MF **525** may calculate multiple sub-carrier-averaged metric values, for a particular sample, by averaging metric values for the particular sample over multiple sub-carriers. MF **525** may then calculate a time-averaged metric value, for the particular sample, by averaging multiple sub-carrier-averaged metric values over multiple samples.

As indicated above, FIG. **8** is provided merely as an example. Other examples are possible and may differ from what was described with regard to FIG. **8**. For example, MF **525** may perform additional operations, fewer operations, or different operations than those described in connection with FIG. **8**.

FIGS. **9**A and **9**B are diagrams of an example implementation **900** relating to operations performed by phase estimate component (PE) **530**. As described herein in connection with FIG. **8**, PE **530** may receive final metric values (e.g., FinalMetric_s[i,n]) from MF **525**. PE **530** may determine a phase estimate (e.g., a most likely phase for a received symbol), for a particular sub-carrier s and sample n, using all of the final metric values FinalMetric_s[i,n] for each test phase i.

PE **530** may calculate a phase estimate PhiEst[s,n] for a first symbol (e.g., a first received symbol) by determining a minimum final metric value among all final metric values for different test phases applied to the first symbol. PE **530** may set the value of PhiEst[s,n] equal to the test phase value associated with the minimum final metric value. For example, PE **530** may determine the phase estimate PhiEst[s,0] for a first symbol n=0, where there are 8 test phases, by calculating the following:

$$\min_{i:0\rightarrow 7}\{\text{FinalMetric_s}[i,0]\}$$

PE **530** may then set the value of PhiEst[s,0] equal to the phase value of test phase i associated with the minimum final metric value. For example, when using 8 test phases that span 90 degrees, i={0, 1, 2, 3, 4, 5, 6, 7} may correspond to test phase values of {0°, 11.25°, 22.5°, 33.75°, 45°, 56.25°, 67.5°, 78.75° }. Thus, if i=2 generated the minimum metric value (e.g., FinalMetric_s[2,0]), then PE **530** may set PhiEst[s,0] equal to 22.5°.

For the second symbol (e.g., n=1), PE **530** may determine a minimum of fewer than all of the final metric values for the different test phases applied to the second symbol. For example, to calculate PhiEst[s,1], PE **530** may determine a minimum of four final metric values that center around PhiEst[s,0] (e.g., half of the eight total final metric values corresponding to the eight test phases). This avoids the issue of two minimum values discussed above in connection with FIGS. **1**A and **1**B. PE **530** may continue to determine phase estimate values in this manner, by calculating PhiEst[s,n+1] by determining a minimum of final metric values centered around PhiEst[s,n].

In some implementations, PE **530** may determine an interpolated phase estimate value to update PhiEst[s,n]. For example, PE **530** may interpolate PhiEst[s,n] using a quantity of final metric values centered around PhiEst[s,n].

As shown in FIG. **9**A, and by reference number **910**, assume that PE **530** receives eight final metric values associated with eight test phase values for a first symbol on a first sub-carrier. As shown by reference number **920**, PE **530** may determine a minimum final metric value of four final metric values associated with four consecutive test phases, such as a minimum final metric value associated with test phase 0, 1, 2, or 3 (e.g., Min[0,1,2,3]), a minimum final metric value associated with test phase 2, 3, 4, or 5 (e.g., Min[2,3,4,5]), a minimum final metric value associated with test phase 4, 5, 6, or 7 (e.g., Min[4,5,6,7]), and a minimum final metric value associated with test phase 6, 7, 0, or 1 (e.g., Min[6,7,0,1]). Note that each of these calculations is centered around a different pair of test phases (e.g., 1-2, 3-4, 5-6, and 7-0).

As shown by reference number **930**, once PE **530** determines a minimum final metric value from each group of four test phases, PE **530** may perform an interpolation (e.g., a parabolic interpolation) to estimate an interpolated phase value that corresponds to an actual minimum final metric value, as described in more detail in connection with FIG. **9**B. PE **530** may compare the four interpolated phase values (e.g., one from each group of four test phases) to determine which one corresponds to a minimum final metric value, and may select the interpolated phase value that corresponds to the minimum final metric value as PhiEst[s,0]. PE **530** may provide PhiEst[s,n] to phase unwrap component **535**.

Additionally, or alternatively, PE **530** may calculate a group indicator value (e.g., a two bit value of 0, 1, 2, or 3) to be used to select an interpolated phase value for the next symbol (e.g., to select a value for PhiEst[s,1]). For example, the output of the interpolation may be a six bit value, and PE **530** may provide the four most significant bits (MSBs) to an

adder that combines the four MSBs with a value of 15 to produce a group indicator value of 0, 1, 2, or 3. When selecting PhiEst[s,n+1], PE **530** may use the group indicator value to select from the four interpolated phase values. For example, PE **530** may select the interpolated phase value determined from Min[0,1,2,3] when the group indicator value is equal to 0, may select the interpolated phase value determined from Min[2,3,4,5] when the group indicator value is equal to 1, may select the interpolated phase value determined from Min[4,5,6,7] when the group indicator value is equal to 2, and may select the interpolated phase value determined from Min[6,7,0,1] when the group indicator value is equal to 3. In this way, PE **530** may avoid the issue of selecting between two minimum values, as discussed above in connection with FIGS. **1**A and **1**B.

As shown in FIG. **9**B, PE **530** may perform an interpolation (e.g., a parabolic interpolation) to estimate an interpolated phase value that corresponds to an actual minimum final metric value. FIG. **9**B shows a plot of test phases 0, 1, 2, and 3, shown as Φ_0, Φ_1, Φ_2, and Φ_3 (e.g., corresponding to 0°, 11.25°, 22.5°, and 33.75°, respectively), and a corresponding final metric value associated with each test phase. This plot may correspond to an interpolation performed after determining Min[0,1,2,3], shown in FIG. **9**A.

As shown by reference number **940**, assume that test phase 1 corresponds to a minimum final metric value, as compared to test phases 0, 2, and 3. However, as shown by reference number **950**, the actual minimum final metric value is associated with a phase value somewhere between the phase values of test phases 1 and 2 (e.g., between 11.25° and 22.5°). PE **530** may use multiple test phase values and the corresponding final metric values to interpolate a function that relates a phase value to a final metric value, as shown by reference number **960**. As an example, PE **530** may use the test phase associated with the minimum final metric value (e.g., Φ_1) and the two test phases on either side of that test phase (e.g., Φ_0 and Φ_2), to interpolate the function. As another example, PE **530** may use all four test phase values and the corresponding final metric values to interpolate the function. PE **530** may use the function to determine an interpolated phase value that corresponds to the minimum final metric value of the function.

As indicated above, FIGS. **9**A and **9**B are provided merely as an example. Other examples are possible and may differ from what was described with regard to FIGS. **9**A and **9**B. For example, PE **530** may perform additional operations, fewer operations, or different operations than those described in connection with FIGS. **9**A and **9**B.

FIG. **10** is a diagram of an example implementation **1000** relating to operations performed by phase unwrap component (PU) **535**. As described herein in connection with FIGS. **9**A and **9**B, PU **535** may receive a phase estimate value PhiEst[s,n] from PE **530**. The value of PhiEst[s,n] may include a value between 0° and 90° for a modulation format with 90 degree symmetry, a value between 0° and 180° for a modulation format with 180 degree symmetry, etc. However, the actual phase value of a symbol may include a value between 0° and 360°. PU **535** may convert a received phase estimate value (e.g., PhiEst[s,n]) to an unwrapped phase estimate value (e.g., PhiEst_{unwrap}[s,n]) between 0° and 360°.

PU **535** may determine the actual phase value by calculating a phase difference between consecutively-received phase estimate values, such as a first phase estimate value PhiEst[s,n] and a second phase estimate value PhiEst[s,n+1]). PU **535** may subtract the first phase estimate value from the second phase estimate value. If the result is less than a first threshold value, then PU **535** may add a value equal to the span of the test phases (e.g., 90 degrees, 180 degrees, etc.) to the second phase estimate value. If the result is greater than a second threshold value, then PU **535** may subtract a value equal to the span of the test phases from the second phase estimate value. PU **535** may provide the resulting unwrapped phase estimate value PhiEst_{unwrap}[s,n] to adder **545** and frequency estimate component **555**.

As an example, and as shown in FIG. **10**, assume that PhiEst[s,0], shown in FIG. **10** as Φ_{in}[0], is equal to 0°, and that PhiEst[s,1], shown in FIG. **10** as Φ_{in}[1], is equal to 85°. Assume that PU **535** determines that Φ_{in}[1]-Φ_{in}[0] is equal to a result of 85°, which is greater than a threshold value of 45° (e.g., half the distance between 0° and a positive span of 90°). Thus, PU **535** calculates PhiEst_{unwrap}[s,1], shown in FIG. **10** as Φ_{out}[1], as Φ_{in}[1]-90°=−5°.

As another example, assume that Φ_{in}[0] is equal to 90°, and that Φ_{in}[1] is equal to 5°. Assume that PU **535** determines that Φ_{in}[1]-Φ_{in}[0] is equal to a result of −85°, which is less than a threshold value of −45° (e.g., half the distance between 0° and a negative span of −90°). Thus, PU **535** calculates Φ_{out}[1] =Φ_{in}[1]+90°=95°. In this way, PU **535** may unwrap received phase values along a full phase cycle of 360°.

As indicated above, FIG. **10** is provided merely as an example. Other examples are possible and may differ from what was described with regard to FIG. **10**. For example, PU **535** may perform additional operations, fewer operations, or different operations than those described in connection with FIG. **10**.

FIG. **11** is a diagram of an example implementation **1100** relating to operations performed by adder **545**, lookup table component (LUT) **550**, and multiplier **510**. As described herein in connection with FIG. **10**, and as shown by reference number **1110**, adder **545** may receive an unwrapped phase estimate value PhiEst_{unwrap}[s,n] from PU **535**. The unwrapped phase estimate value may be a value that combines information determined based on the X polarization and the Y polarization. In example implementation **1100**, assume that CRC **460** processes 16 samples per clock cycle, and that an optical channel that provides input to CRC **460** includes 4 sub-carriers.

As shown by reference number **1120**, adder **545** may also receive a phase and frequency compensation value from FIFO Delay **540**. For example, adder **545** may receive a phase and frequency compensation value for the X polarization (e.g., XCompValue_s[n]) and a phase and frequency compensation value for the Y polarization (e.g., YCompValue_s[n]). FIFO Delay **540** may delay providing the compensation values to adder **545** to coincide with the unwrapped phase estimate value being provided to adder **545**. In this way, adder **545** may properly combine the compensation values and the unwrapped phase estimate value (e.g., with appropriate timing). As shown by reference number **1130**, adder **545** may combine (e.g., may sum) each phase and frequency compensation value with the phase estimate value to determine an output phase for each polarization (e.g., XCompValue_s[n]+ PhiEst_{unwrap}[s,n] for the X polarization, and YCompValue_s [n]+PhiEst_{unwrap}[s,n] for the Y polarization). The output phases may be represented using a real number.

As shown by reference number **1140**, LUT **550** may receive the real number output phases, and may convert the real number output phases to complex number output phases. For example, LUT **550** may use a lookup table to perform the conversion. As shown by reference number **1150**, LUT **550** may provide the complex number output phases to multiplier **510**. As shown by reference number **1160**, multiplier **510** may also receive an input signal from FIFO Delay **505**. For example, multiplier **510** may receive an input signal for the X

polarization and an input signal for the Y polarization. FIFO Delay **540** may delay providing the input signal(s) to multiplier **510** to coincide with the complex number output phase value being provided to multiplier **510**. In this way, multiplier **510** may properly combine the input signals and the complex number output phase values (e.g., with appropriate timing). Multiplier **510** may combine (e.g., may multiply, rotate, etc.) each input signal value with a corresponding complex number output phase to determine a carrier-recovered output signal for each polarization.

As shown by reference number **1170**, multiplier **510** may output the output signal (e.g., to a symbol decoder). Additionally, or alternatively, as shown by reference number **1180**, multiplier **510** may provide a feedback signal via a feedback loop to another component of CRC **460** (e.g., PDE **560**). The feedback signal may be the same as the output signal, in some implementations. In some implementations, multiplier **510** may provide the feedback signal at a different rate than the output signal. For example, multiplier **510** may generate 16 output signals per sub-carrier per clock cycle, and may generate 2 feedback signals per sub-carrier per clock cycle, as shown.

As indicated above, FIG. **11** is provided merely as an example. Other examples are possible and may differ from what was described with regard to FIG. **11**. For example, adder **545**, LUT **550**, and/or multiplier **510** may perform additional operations, fewer operations, or different operations than those described in connection with FIG. **11**.

FIG. **12** is a diagram of an example implementation **1200** relating to operations performed by frequency estimate component (FE) **555**. As described herein in connection with FIG. **10**, FE **555** may receive a set of unwrapped phase estimate values $PhiEst_{unwrap}[s,n]$ from PU **535**. FE **555** may use the set of unwrapped phase estimate values to calculate a frequency estimate value FreqEstVal (e.g., to be used by FAPC **515** to compensate a frequency value of an input signal).

As an example, and as shown by reference number **1210**, assume that FE **555** receives 16 samples (e.g., per clock cycle), labeled **0** through **15**, on the first sub-carrier (e.g., s=0). As shown by reference number **1220**, FE **555** may calculate a difference between each pair of adjacent samples (e.g., samples n={0,1}, n={1,2}, n={2,3}, . . . , n={14,15}). As shown by reference number **1230**, FE **555** may sum all of these difference values to calculate a frequency compensation error introduced by processing performed by components **515**-**535**.

As shown by reference number **1240**, FE **555** may optionally average the frequency compensation error across multiple sub-carriers. As shown by reference number **1250**, FE **555** may be configured to include or exclude a sub-carrier from the averaging operation. FE **555** may perform processing similar to that shown by reference numbers **1210**-**1230** for each sub-carrier, and may average the frequency compensation error across two or more sub-carriers.

As shown by reference number **1260**, FE **555** may input the frequency compensation error (or the average frequency compensation error) into a digital integrator to form a first order feedback loop to control the error. FE **555** may control the feedback loop (e.g., an amount of bandwidth used by the feedback loop) using a step size value. FE **555** may output the frequency compensation error (or the average frequency compensation error) to FAPC **515** as the frequency estimate value FreqEstVal.

As indicated above, FIG. **12** is provided merely as an example. Other examples are possible and may differ from what was described with regard to FIG. **12**. For example, FE **555** may perform additional operations, fewer operations, or different operations than those described in connection with FIG. **12**.

FIGS. **13**A-**13**D are diagrams of an example implementation **1300** relating to operations performed by phase difference estimate component (PDE) **560**. As described herein in connection with FIG. **11**, PDE **560** may receive a set of feedback signals from multiplier **510**. PDE **560** may use the set of feedback signals to calculate a set of first phase difference values, phiDiff_1[s], that represent a phase difference between the X polarization and the Y polarization for each sub-carrier s. Additionally, or alternatively, PDE **560** may use the set of feedback signals to calculate a set of second phase difference values, phiDiff_2[s], that represent a phase difference between different sub-carriers. As shown in FIG. **13**A, PDE **560** may include a DiffPhi metric accumulate component (DMA) **1305**, a best angle estimate component (BAE) **1310**, a phiDiff_1 update component (PhiDiff1 Update) **1315**, and a phiDiff_2 update component (PhiDiff2 Update) **1320**.

As an example, and as shown by reference number **1325**, assume that DMA **1305** receives, from multiplier **510**, a feedback signal on the X polarization and a feedback signal on the Y polarization for each sub-carrier. Multiplier **510** may be configured to provide a particular quantity of signals per clock cycle (e.g., 2 samples per clock cycle). DMA **1305** may apply test phases to each received symbol on each polarization, and may calculate a metric value associated with each test phase. DMA **1305** may calculate the metric value in a similar manner as PT **520**, as described elsewhere herein, except that DMA **1305** may prevent the metric value for the X polarization and the metric value for the Y polarization from being combined (e.g., DMA **1305** may perform the steps shown by reference numbers **710**-**730** of FIG. **7**, and may not perform the step shown by reference number **740**).

The outputs from DMA **1305** for the X polarization may be represented as $phiDiffMetricX_s[i_{initial}:i_{final}]$, where s represents a sub-carrier and $i_{initial}:i_{final}$ represents each test phase from the first test phase $i_{initial}$ to the last test phase i_{final}. Similarly, the outputs from DMA **1305** for the Y polarization may be represented as $phiDiffMetricY_s[i_{initial}:i_{final}]$. As an example, and as shown by reference number **1330**, when there are 8 test phases, DMA **1305** may output **64** metric values, with eight for each of the two polarizations on each of the four sub-carriers. As shown by reference number **1335**, DMA **1305** may average each of these metric values over a particular quantity of clock cycles (e.g., 32 clock cycles). DMA **1305** may provide the metric values (or the averaged metric values) to BAE **1310**.

BAE **1310** may determine the test phase that results in the minimum metric value (e.g., a most likely test phase) for a particular polarization and a particular sub-carrier. Additionally, or alternatively, BAE **1310** may perform an interpolation to determine a more accurate phase estimate value that results in a minimum metric value for the particular polarization and the particular sub-carrier. As an example, BAE **1310** may determine the minimum metric value and the interpolated phase estimate value in a manner similar to that described elsewhere herein in connection with PE **530**.

The outputs from BAE **1310** for the X polarization (e.g., an interpolated phase estimate value that corresponds to a minimum metric value) may be represented as bestAngleX[s], where s represents a sub-carrier. Similarly, the outputs from BAE **1310** for the Y polarization may be represented as bestAngleY[s]. As shown by reference number **1340**, when there are four sub-carriers, BAE **1310** may output **8** interpolated phase estimates, with one for each of the two polariza-

tions and the four sub-carriers (e.g., bestAngleX[0,1,2,3] and bestAngleY[0,1,2,3]). BAE **1310** may provide the interpolated phase estimate values to PhiDiff1 Update **1315** and PhiDiff2 Update **1320** to update the values of phiDiff_1[s] and phiDiff_2[s], as described in more detail below.

As shown in FIG. **13**B, and by reference number **1345**, PhiDiff1 Update **1315** may receive, for each sub-carrier, a first interpolated phase estimate value for the X polarization and a second interpolated phase estimate value for the Y polarization. As further shown, a subtractor component may determine a difference between the first and second interpolated phase estimate values for a particular sub-carrier. As shown by reference number **1350**, PhiDiff1 Update **1315** may input the difference into a digital integrator to form a first order feedback loop to drive the difference toward zero. PhiDiff1 Update **1315** may control the feedback loop (e.g., an update speed, a tracking speed, etc.) using a step size value. Additionally, or alternatively, PhiDiff1 Update **1315** may be configured to perform the steps shown by reference numbers **1345** and **1350** at a particular clock cycle interval (e.g., every 32 clock cycles, where DMA **1305** averages error values over 32 clock cycles).

The output from the integrator for sub-carrier s may be represented as phiDiff_1[s], which may represent a phase difference between the X polarization and the Y polarization of sub-carrier s. As shown, PhiDiff1 Update **1315** may provide this value to FAPC **515**, which may use the value to compensate a phase of an input signal.

As shown in FIG. **13**C, and by reference number **1355**, PhiDiff2 Update **1320** may receive, for each sub-carrier, a first interpolated phase estimate value for the X polarization and a second interpolated phase estimate value for the Y polarization. As shown by reference number **1360**, PhiDiff2 Update **1320** may determine an AvgMode indicator value, which may be the same as the Avg_Mode indicator value discussed herein in connection with MF **525**. PhiDiff2 Update **1320** may determine a manner in which to update interpolated phase estimates, for a particular polarization and across multiple sub-carriers, based on the AvgMode value.

As an example, when AvgMode is equal to a first value (e.g., 0), then each sub-carrier may be treated independently, and PhiDiff2 Update **1320** may not update the interpolated phase estimate values. In this case, PhiDiff2 Update **1320** may set an update value for the X polarization (e.g., UpdateVecX[s]) to zero, and may set an update value for the Y polarization (e.g., UpdateVecY[s]) to zero.

As another example, when AvgMode is equal to a second value (e.g., 1), then PhiDiff2 Update **1320** may update the interpolated phase estimate values by averaging across two sub-carriers. For example, when there are four sub-carriers, PhiDiff2 Update **1320** may set two update values, for a particular polarization, to zero as a reference value. PhiDiff2 Update **1320** may set two other update values, for the particular polarization, as a difference between two interpolated phase estimate values for different sub-carriers (e.g., one of the reference phase estimate values and another phase estimate value). For example, on the X polarization, PhiDiff2 Update **1320** may set the following update values:

$$UpdateVec_X[0]=0$$

$$UpdateVec_X[1]=bestAngle_X[0]-bestAngle_X[1]$$

$$UpdateVec_X[2]=0$$

$$UpdateVec_X[3]=bestAngle_X[2]-bestAngle_X[3]$$

As another example, when AvgMode is equal to a third value (e.g., 2), then PhiDiff2 Update **1320** may update the interpolated phase estimate values by averaging across all sub-carriers. For example, when there are four sub-carriers, PhiDiff2 Update **1320** may set one update value, for a particular polarization, to zero as a reference value. PhiDiff2 Update **1320** may set three other update values, for the particular polarization, as a difference between a reference phase estimate value and each other phase estimate value. For example, on the X polarization, PhiDiff2 Update **1320** may set the following update values:

$$UpdateVec_X[0]=0$$

$$UpdateVec_X[1]=bestAngle_X[0]-bestAngle_X[1]$$

$$UpdateVec_X[2]=bestAngle_X[0]-bestAngle_X[2]$$

$$UpdateVec_X[3]=bestAngle_X[0]-bestAngle_X[3]$$

In some implementations, AvgMode may be a different value than described above, and PhiDiff2 Update **1320** may calculate the update values using combined interpolated phase estimate values in a different manner, and/or for a different quantity of sub-carriers.

As shown in FIG. **13**D, and by reference number **1365**, PhiDiff2 Update **1320** may sum a first update value for the X polarization and a second update value for the Y polarization on a particular sub-carrier, such as the second sub-carrier (e.g., s=1). As shown by reference number **1370**, PhiDiff2 Update **1320** may input the summed update value into a digital integrator to form a first order feedback loop to drive the difference between the update values toward zero. PhiDiff2 Update **1320** may control the feedback loop using a step size value. The output from the integrator for sub-carrier s may be represented as phiDiff_2[s], which may represent a phase difference between multiple sub-carriers, and which may be used to compensate a phase of an input signal carried by sub-carrier s. PhiDiff2 Update **1320** may provide phiDiff_2[s] to FAPC **515**, which may use the value to compensate the phase of the input signal.

As shown by reference number **1375**, PhiDiff2 Update **1320** may calculate the phase differences for the other sub-carriers in a similar manner. As shown by reference number **1380**, such a calculation may result in a phiDiff_2 value of zero for a reference value.

As indicated above, FIGS. **13**A-**13**D are provided merely as an example. Other examples are possible and may differ from what was described with regard to FIGS. **13**A-**13**D. For example, PDE **560** may perform additional operations, fewer operations, or different operations than those described in connection with FIGS. **13**A-**13**D.

The foregoing disclosure provides illustration and description, but is not intended to be exhaustive or to limit the implementations to the precise form disclosed. Modifications and variations are possible in light of the above disclosure or may be acquired from practice of the implementations.

Implementations described herein reduce the computational complexity of accurately estimating the phase of a received symbol, and provide accurate and efficient carrier recovery when signals are transmitted using multiple sub-carriers, rather than a single carrier.

Some implementations are described herein in connection with thresholds. As used herein, satisfying a threshold may refer to a value being greater than the threshold, more than the threshold, higher than the threshold, greater than or equal to the threshold, less than the threshold, fewer than the thresh-

old, lower than the threshold, less than or equal to the threshold, equal to the threshold, etc.

It will be apparent that systems and/or methods, described herein, may be implemented in different forms of hardware, firmware, or a combination of hardware and software. The actual specialized control hardware or software code used to implement these systems and/or methods is not limiting of the implementations. Thus, the operation and behavior of the systems and/or methods were described herein without reference to the specific software code—it being understood that software and hardware can be designed to implement the systems and/or methods based on the description herein.

Even though particular combinations of features are recited in the claims and/or disclosed in the specification, these combinations are not intended to limit the disclosure of possible implementations. In fact, many of these features may be combined in ways not specifically recited in the claims and/or disclosed in the specification. Although each dependent claim listed below may directly depend on only one claim, the disclosure of possible implementations includes each dependent claim in combination with every other claim in the claim set.

No element, act, or instruction used herein should be construed as critical or essential unless explicitly described as such. Also, as used herein, the articles "a" and "an" are intended to include one or more items, and may be used interchangeably with "one or more." Furthermore, as used herein, the term "set" is intended to include one or more items, and may be used interchangeably with "one or more." Where only one item is intended, the term "one" or similar language is used. Also, as used herein, the terms "has," "have," "having," or the like are intended to be open-ended terms. Further, the phrase "based on" is intended to mean "based, at least in part, on" unless explicitly stated otherwise.

What is claimed is:

1. An optical receiver, comprising:

a digital signal processor configured to:

receive a plurality of input signals carried by a respective plurality of sub-carriers;

determine, based on the plurality of input signals, a frequency compensation value and a phase compensation value to be used to modify an input signal of the plurality of input signals;

modify the input signal, to form a modified input signal, using the frequency compensation value and the phase compensation value,

the frequency compensation value being used to modify a frequency of the input signal,

the phase compensation value being used to modify a phase of the input signal;

determine, based on the modified input signal, a phase estimate value that represents an estimated phase for the input signal;

combine the frequency compensation value, the phase compensation value, and the phase estimate value to generate a phase adjustment signal;

combine the input signal and the phase adjustment signal to form an output signal; and

output the output signal.

2. The optical receiver of claim **1**, where the digital signal processor, when determining the frequency compensation value, is further configured to:

determine a plurality of frequency compensation error values corresponding to the plurality of sub-carriers; and

determine the frequency compensation value based on the plurality of frequency compensation error values.

3. The optical receiver of claim **2**, where the digital signal processor, when determining the plurality of frequency compensation error values, is further configured to:

receive a plurality of samples, associated with the input signal, carried by a particular sub-carrier of the plurality of sub-carriers; and

determine a frequency compensation error value, of the plurality of frequency compensation error values, based on the plurality of samples.

4. The optical receiver of claim **1**, where the input signal has a first polarization and a second polarization; and

where the digital signal processor, when determining the phase compensation value, is further configured to:

determine a first phase estimate value for the input signal,

the first phase estimate value being associated with the first polarization of the input signal;

determine a second phase estimate value for the input signal,

the second phase estimate value being associated with the second polarization of the input signal,

the second polarization being different than the first polarization;

calculate a difference between the first phase estimate value and the second phase estimate value; and

determine the phase compensation value based on the difference between the first phase estimate value and the second phase estimate value.

5. The optical receiver of claim **4**, where the digital signal processor, when determining the first phase estimate value, is further configured to:

apply a plurality of test phases to the input signal on the first polarization;

calculate a plurality of error values that each corresponds to one of the plurality of test phases;

select a test phase, of the plurality of test phases, that corresponds to a lowest error value, of the plurality of error values, as compared to other error values included in the plurality of error values; and

interpolate the first phase estimate value based on the selected test phase.

6. The optical receiver of claim **1**, where the digital signal processor, when determining the phase compensation value, is further configured to:

determine a plurality of first phase estimate values, corresponding to the plurality of sub-carriers, associated with a first polarization of the plurality of input signals;

determine a plurality of second phase estimate values, corresponding to the plurality of sub-carriers, associated with a second polarization of the plurality of input signals,

the second polarization being different than the first polarization;

calculate a first difference between at least one first phase estimate value, of the plurality of first phase estimate values, and at least one other first phase estimate value of the plurality of first phase estimate values;

calculate a second difference between at least one second phase estimate value, of the plurality of second phase estimate values, and at least one other second phase estimate value of the plurality of second phase estimate values; and

determine the phase compensation value based on the first difference and the second difference.

7. The optical receiver of claim **1**, where the digital signal processor, when determining the phase compensation value, is further configured to:

determine a first phase difference between a first signal of a first polarization and a second signal of a second polarization,

the first signal and the second signal being included in the modified input signal;

determine a second phase difference between a third signal, included in the modified input signal and carried via a first sub-carrier of the plurality of sub-carriers, and a fourth signal carried via a second sub-carrier of the plurality of sub-carriers; and

determine the phase compensation value based on the first phase difference and the second phase difference.

8. The optical receiver of claim **1**, where the digital signal processor is further configured to:

provide the output signal as a feedback signal;

determine, based on the feedback signal, another phase compensation value to be used to modify another input signal; and

modify the other input signal using the other phase compensation value.

9. A system, comprising:

an optical receiver configured to:

receive a plurality of input signals carried by a respective plurality of sub-carriers;

determine, based on the plurality of input signals, a frequency compensation value or a phase compensation value to be used to modify an input signal of the plurality of input signals;

modify the input signal, to form a modified input signal, using the frequency compensation value or the phase compensation value,

the frequency compensation value being used to modify a frequency of the input signal,

the phase compensation value being used to modify a phase of the input signal;

determine, based on the modified input signal, a phase estimate value that represents an estimated phase for the input signal;

combine the phase estimate value and the frequency compensation value or the phase compensation value to generate a phase adjustment signal;

combine the input signal and the phase adjustment signal to form an output signal; and

output the output signal.

10. The system of claim **9**, where the optical receiver, when determining the frequency compensation value, is further configured to:

determine a plurality of frequency compensation error values corresponding to the plurality of sub-carriers; and

determine the frequency compensation value based on the plurality of frequency compensation error values.

11. The system of claim **9**, where the optical receiver, when determining the frequency compensation value, is further configured to:

determine a mode indicator value that indicates whether to combine a plurality of frequency compensation error values, corresponding to the plurality of sub-carriers, to determine the frequency compensation value; and

selectively perform a first action or a second action based on the mode indicator value,

the first action including using a single frequency compensation error value, corresponding to a single sub-carrier of the plurality of sub-carriers, to determine the frequency compensation value when the mode indicator value is equal to a first value, and

the second action including using at least two frequency compensation error values, corresponding to at least two sub-carriers of the plurality of sub-carriers, to determine the frequency compensation value when the mode indicator value is equal to a second value,

the second value being different than the first value.

12. The system of claim **9**, where the optical receiver, when determining the phase compensation value, is further configured to:

determine a first phase estimate value for the input signal,

the first phase estimate value being associated with a first polarization of the input signal;

determine a second phase estimate value for the input signal,

the second phase estimate value being associated with a second polarization of the input signal,

the second polarization being different than the first polarization;

calculate a difference between the first phase estimate value and the second phase estimate value; and

determine the phase compensation value based on the difference between the first phase estimate value and the second phase estimate value.

13. The system of claim **9**, where the optical receiver, when determining the phase compensation value, is further configured to:

determine a plurality of first phase estimate values, corresponding to the plurality of sub-carriers, associated with a first polarization of the plurality of input signals;

determine a plurality of second phase estimate values, corresponding to the plurality of sub-carriers, associated with a second polarization of the plurality of input signals,

the second polarization being different than the first polarization;

calculate a first difference between at least one first phase estimate value, of the plurality of first phase estimate values, and at least one other first phase estimate value of the plurality of first phase estimate values;

calculate a second difference between at least one second phase estimate value, of the plurality of second phase estimate values, and at least one other second phase estimate value of the plurality of second phase estimate values; and

determine the phase compensation value based on the first difference and the second difference.

14. The system of claim **9**, where the optical receiver, when determining the phase compensation value, is further configured to:

determine a mode indicator value that indicates whether to combine a plurality of phase estimate values, corresponding to the plurality of sub-carriers, to determine the phase compensation value; and

selectively perform a first action or a second action based on the mode indicator value,

the first action including using a single phase estimate value, corresponding to a single sub-carrier of the plurality of sub-carriers, to determine the phase compensation value when the mode indicator value is equal to a first value, and

the second action including using at least two phase estimate values, corresponding to at least two sub-carriers of the plurality of sub-carriers, to determine the phase compensation value when the mode indicator value is equal to a second value,

the second value being different than the first value.

15. A method, comprising:

receiving, by an optical receiver, a plurality of input signals carried by a respective plurality of sub-carriers;

determining, by the optical receiver and based on the plurality of input signals, a compensation value to be used to modify an input signal of the plurality of input signals;

adjusting, by the optical receiver and using the compensation value, the input signal to form a modified input signal,

the compensation value being used to modify a frequency or a phase of the input signal;

determining, by the optical receiver and based on the modified input signal, a phase estimate value that represents an estimated phase associated with the input signal;

combining, by the optical receiver, the compensation value and the phase estimate value to form a phase adjustment signal;

combining, by the optical receiver, the input signal and the phase adjustment signal to form an output signal; and

outputting, by the optical receiver, the output signal.

16. The method of claim **15**, where determining the compensation value further comprises:

determining a plurality of frequency compensation error values corresponding to the plurality of sub-carriers; and

determining the compensation value based on the plurality of frequency compensation error values.

17. The method of claim **15**, where determining the compensation value further comprises:

determining a first phase estimate value associated with the input signal,

the first phase estimate value representing a first estimated phase associated with a first polarization of the input signal;

determining a second phase estimate value associated with the input signal,

the second phase estimate value representing a second estimated phase associated with a second polarization of the input signal,

the second polarization being different than the first polarization;

calculating a difference between the first phase estimate value and the second phase estimate value; and

determining the compensation value based on the difference between the first phase estimate value and the second phase estimate value.

18. The method of claim **15**, where determining the compensation value further comprises:

determining a plurality of first phase estimate values, corresponding to the plurality of input signals, that represent a first estimated phase associated with a first polarization;

determining a plurality of second phase estimate values, corresponding to the plurality of input signals, that represent a second estimated phase associated with a second polarization;

the second polarization being different than the first polarization;

calculating a first difference between at least one first phase estimate value, of the plurality of first phase estimate values, and at least one other first phase estimate value of the plurality of first phase estimate values;

calculating a second difference between at least one second phase estimate value, of the plurality of second phase estimate values, and at least one other second phase estimate value of the plurality of second phase estimate values; and

determining the compensation value based on the first difference and the second difference.

19. The method of claim **15**, where determining the compensation value further comprises:

determining the compensation value based on at least one of:

a plurality of frequency compensation error values associated with different sub-carriers of the plurality of sub-carriers, or

a plurality of phase estimate values associated with the different sub-carriers.

20. The method of claim **15**, further comprising:

determining a feedback signal based on the output signal;

determining, based on the feedback signal, another compensation value to be used to modify another input signal; and

modifying the other input signal using the other compensation value.

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