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- (71) **Applicant (for all designated States except US):** **MON-ASH UNIVERSITY** [AU/AU]; Wellington Road, Clayton, Victoria 3168 (AU).
- (72) **Inventors; and**
- (75) **Inventors/Applicants (for US only):** **DU, Liang Bangyuan** [AU/AU]; PO Box 35, Monash University, Clayton, Victoria 3800 (AU). **LOWERY, Arthur James** [AU/AU]; 136 Derby Street, Kew, Victoria 3101 (AU).
- (74) **Agent:** **WATERMARK PATENT & TRADE MARKS ATTORNEYS**; Level 2, 302 Burwood Road, Hawthorn, Victoria 3122 (AU).

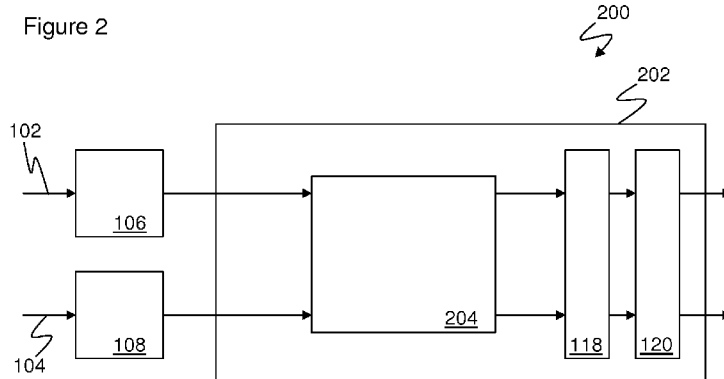
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(54) **Title:** SELF-TUNING RECEIVER FOR COHERENT OPTICAL OFDM



(57) **Abstract:** A method for use in receiving a selected subcarrier of a Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) signal employs an adaptive Fractionally-Spaced Time-Domain Equalizer (FS-TDE) (204). The FS-TDE (204) has a plurality of configurable tap coefficients, which are configured according to the method such that the FS-TDE is adapted to simultaneously demultiplex and equalize the selected subcarrier. The CO-OFDM signal (102, 104) is processed using the FS-TDE (204) to generate and output a demultiplexed and equalized selected subcarrier signal. The use of a suitable adaptive FS-TDE enables a number of previously distinct signal processing functions to be combined into a single, simplified, signal processing element. In particular, the functions of a mixer, a Discrete Fourier Transform (DFT), and an equalizer for linear distortions, such as chromatic dispersion and Polarization Mode Dispersion (PMD), may be combined into a single demultiplexing and equalizing FS-TDE.

SELF-TUNING RECEIVER FOR COHERENT OPTICAL OFDM**FIELD OF THE INVENTION**

The present invention relates generally to optical communications, and more particularly to receivers for use in coherent optical communications systems.

5 BACKGROUND OF THE INVENTION

Modern optical fiber communications systems employ Wavelength Division Multiplexing (WDM) for transmission of multiple channels on a single optical fiber. WDM systems generally employ a number of separate optical carriers, each having a distinct and well-defined optical frequency or wavelength, and each carrying a
10 separate information stream at data rates of, for example, 10 Gb/s or higher. Current generation systems are being deployed with bit rates of 40 Gb/s per WDM channel, while the next generation of systems are targeting 100 Gb/s per channel.

Conventional WDM systems employ optical filters and/or WDM multiplexers and demultiplexers for combination and separation of multiple wavelength channels
15 carried on a single optical fiber. As a practical matter, conventional WDM systems require that the optical frequency spacing of adjacent channels be sufficiently large to avoid interference resulting from overlap of optical signal spectra, as well as allowing for the transitions of optical filters and multiplexers between the passband and stop-band. As a result, greater spectral efficiency is obtained in conventional WDM
20 systems by employing the highest practical data rate on each WDM channel, in order to maximize the ratio between the usable signal bandwidth, and the frequency guard-bands between adjacent channels.

On the other hand, there are known benefits to transmitting signals having lower bandwidth in optical fiber links. For example, the total chromatic dispersion
25 experienced by a propagating optical signal (i.e. the differential delay between the fastest and slowest propagating frequency components) is proportional to the signal bandwidth. The complexity of certain forms of chromatic dispersion compensation, and particularly those performed wholly or partially within the electronic domain in coherent communications systems, is therefore reduced through the use of narrower
30 bandwidth channels. Similar considerations apply to higher-order Polarization Mode Dispersion (PMD). Additionally, it is well-known that the strength of nonlinear interactions, which can cause signal distortion in long-haul optical transmission systems, is greatest between signal components that are more-closely spaced in frequency. The greatest benefits in mitigating nonlinear distortion may therefore be

achieved by controlling peak power levels and/or applying nonlinear compensation techniques over a number of narrower bandwidth channels, rather than over a single corresponding wider bandwidth channel.

5 The desire to create more spectrally efficient multi-frequency optical transmission systems has led to proposals for so-called Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) transmission systems and techniques. The CO-OFDM proposals are based on theoretical analysis, and practical experience with electronic systems, from which it is known that signals in adjacent frequency channels may actually be permitted to overlap spectrally, with (in principle) no
10 resulting interference, so long as all channels have the property of orthogonality. Orthogonal Frequency Division Multiplexing (OFDM) has been developed within the electrical Radio Frequency (RF) domain, wherein the various multiplexed frequency channels satisfy the conditions that transmitted data symbols on all channels are aligned or synchronised, and that the frequency spacing of the channels is equal to
15 the symbol rate of each data channel. Under these conditions, all of the channels are mathematically orthogonal to one another, and may therefore, at least in principle, be separated without interference.

The practical development of CO-OFDM systems requires the development of receivers that are able to demultiplex the orthogonal channels. Two general classes
20 of CO-OFDM receivers have been proposed. One class of such receivers is based upon the use of electronic demultiplexing, whereby a high bandwidth detector and electronic front end operates at the full rate of the CO-OFDM channels. The combined optical signal is coherently detected, and processed within the electronic domain in order to demultiplex the individual orthogonal channels. Typically, this is
25 done within the digital domain, requiring the use of a high sampling rate and significant computational intensity (i.e. number of operations per output sample and/or per unit time). This translates into substantial practical requirements, such as hardware size, processing speed and/or power consumption, which in turn impact upon cost and reliability.

30 An alternative class of CO-OFDM receivers employs optical circuits, such as an array of couplers, or a suitably designed Arrayed Waveguide Grating (AWG), having similar characteristics to a Discrete Fourier Transform (DFT), as is commonly used to perform demultiplexing of OFDM channels within the digital domain. Optical demultiplexing methods reduce the electronic and digital processing complexity, but

require a separate coherent receiver for each CO-OFDM subcarrier channel. Additionally, it is anticipated that primarily passive optical demultiplexing circuits will require active trimming in order to optimize the received signal quality, due to variations in the transmitted channel properties, and manufacturing tolerances in the demultiplexing circuit elements.

There is therefore an ongoing need for improved methods and apparatus for receiving and demultiplexing CO-OFDM signals that enable reduction of the computational complexity of electronic-digital implementations, and the ability to provide suitable active trimming or tuning of optical demultiplexing circuits.

The present invention is directed to meeting this ongoing need.

SUMMARY OF THE INVENTION

In one aspect, the invention provides a method for use in receiving a selected subcarrier of a Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) signal, the method comprising:

providing an adaptive Fractionally-Spaced Time-Domain Equalizer (FS-TDE) having a plurality of configurable tap coefficients;

configuring the tap coefficients such that the FS-TDE is adapted to simultaneously demultiplex and equalize the selected subcarrier;

processing the CO-OFDM signal using the FS-TDE to generate a demultiplexed and equalized selected subcarrier signal; and outputting the selected subcarrier signal from the FS-TDE.

Advantageously, the use of a suitable adaptive FS-TDE, in accordance with embodiments of the present invention, enables a number of previously distinct signal processing functions to be combined into a single, simplified, signal processing element. In particular, the functions of a mixer, a Discrete Fourier Transform (DFT), and an equalizer for linear distortions, such as chromatic dispersion and Polarization Mode Dispersion (PMD), may be combined into a single demultiplexing and equalizing FS-TDE.

In preferred embodiments, the number of computations required to perform the combined demultiplexing and equalizing function is no greater than that of the equalizer function alone of receivers proposed in the prior art.

A further advantage of embodiments of the invention is that the signal processing required to adaptively configure the tap coefficients of the FS-TDE may be used in conjunction with a digital demultiplexing equalizer in an electronic

implementation, or to control, trim or tune adaptive elements of an optical demultiplexing circuit within an optical implementation.

Preferably, the step of configuring comprises presetting values of the tap coefficients such that a centre frequency of the FS-TDE initially corresponds substantially with a centre frequency of the selected subcarrier. Alternatively, the step of configuring comprises applying a training algorithm to adaptively set values of the tap coefficients during a training period within which the selected subcarrier is modulated with a predetermined training sequence. Preferably, the training algorithm comprises a Least Mean Squares (LMS) algorithm.

Preferably, the step of configuring further comprises applying a continuous algorithm to adapt values of the tap coefficients and maintain a lock of the FS-TDE on the selected subcarrier during ongoing operation. In some embodiments, the subcarrier is modulated with a signal having the Constant Modulus (CM) property, and the continuous algorithm is a Constant Modulus Algorithm (CMA).

In preferred embodiments, the selected subcarrier comprises two orthogonal polarization components, and the equalization performed by the FS-TDE comprises compensating for PMD. The equalization performed by FS-TDE may further comprise compensating for residual chromatic dispersion. The method may include a further step of at least partially compensating for chromatic dispersion of the CO-OFDM signal prior to the step of processing the optical OFDM signal using the FS-TDE. Advantageously, training algorithms and continuous adaptation algorithms, such as the LMS and CMA algorithms, will result in the automatic configuration of the FS-TDE to perform equalization of impairments such as PMD and CD.

In some embodiments, the method comprises the further step of performing coherent detection of the CO-OFDM signal to produce at least one corresponding electrical signal, wherein the FS-TDE is implemented electronically. Preferably, the method comprises the further step of digitizing the at least one corresponding electrical signal, wherein the FS-TDE is implemented digitally.

In alternative embodiments, the FS-TDE may be an optical filter comprising electronically controllable taps, wherein the step of configuring the tap coefficients comprises performing coherent detection of the selected subcarrier signal output from the FS-TDE to produce at least one corresponding electrical signal, processing the electrical signal to determine values of the tap coefficients, and applying

electronic control signals to the electronically controllable taps corresponding with the determined values of the tap coefficients.

In another aspect, the invention provides an optical receiver comprising:

an adaptive Fractionally-Spaced Time-Domain Equalizer (FS-TDE) having a
5 filter input port and a filter output port, and a plurality of configurable tap coefficients;

a receiver input port for receiving a Coherent Optical Orthogonal Frequency
Division Multiplexed (CO-OFDM) signal, the receiver input port being operatively
coupled to the filter input port;

a processor adapted to determine values of the configurable tap coefficients
10 such as the FS-TDE is adapted to simultaneously demultiplex and equalize a
selected subcarrier of the CO-OFDM signal, the processor being operatively coupled
to the FS-TDE to configure the tap coefficients in accordance with the determined
values; and

a receiver output port operatively coupled to the filter output port.

15 The coupling between the receiver input port and the filter input port may be
direct or indirect. For example, in some embodiments the FS-TDE may be
implemented electronically, and more-particularly digitally, such that the receiver
input port is operatively coupled to the filter input port via at least a coherent optical
detector and one or more Analogue-to-Digital Converters (ADCs).

20 Alternatively, the FS-TDE may be implemented as an optical circuit, whereby
the receiver input port may be directly coupled to the filter input port (e.g. via an
optical connection), and the receiver output port may be operatively coupled to the
filter output port via a coherent optical detector and, optionally, one or more ADCs.

Further features and advantages of the invention will be apparent from the
25 following description of preferred embodiments, which are offered by way of example
only, and which are not limiting of the scope of the invention as defined in any of the
preceding statements, or in the claims appended hereto.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments will now be described with reference to the
30 accompanying drawings, in which like reference numerals refer to like features,
and wherein:

Figure 1 is a block diagram of a prior art processor for use in a receiver of
a no-guard-interval coherent optical orthogonal frequency division multiplexing
transmission system;

Figure 2 is a block diagram of a processor for use in a receiver according to an embodiment of the invention;

Figure 3a is a graph showing the amplitude response of FS-TDE filters embodying the invention;

5 Figure 3b shows equalized constellations for back-to-back QPSK transmission according to an embodiment of the invention;

Figure 4 is a block diagram illustrating an experimental configuration according to an embodiment of the invention;

10 Figure 5 shows exemplary transmitted spectra of the experimental configuration of Figure 4;

Figures 6a and 6b show exemplary received constellations after transmission over 800 km in the configuration of Figure 4;

15 Figures 7a and 7b are graphs illustrating received Bit-Error-Ratio (BER) as a function of Optical Signal-to-Noise Ratio (OSNR) in the configuration of Figure 4; and

Figure 8 is a block diagram of a receiver in accordance with an alternative embodiment of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

20 Figure 1 shows a block diagram of a structure 100 for dual polarization (DP) No-Guard-Interval (No-GI) CO-OFDM receiver processing according to the prior art.

25 The structure 100 may be implemented as a digital signal processor, for example in software executing on a suitable central processing unit, or as custom, or semi-custom, hardware, such as an Application-Specific Integrated Circuit (ASIC). The input to the processor 100 comprises two complex-valued digital sequences 102, 104 corresponding with received orthogonal polarization components of a coherent optical signal. Chromatic dispersion compensators 106, 108 substantially reverse the chromatic dispersion accumulated during transmission, and the received and compensated samples are processed by a bank of demultiplexing and equalizing units 110, each of which is responsible for recovering a single subcarrier channel.

30 Within each unit 110, mixer 112 and a Discrete Fourier Transform (DFT) 114 are used to separate the subcarriers. The FS-TDE 116 is an adaptive multirate Finite Impulse Response (FIR) filter with N-taps and a downsampling factor S, where S is the number of samples per symbol.

Each FS-TDE 116 acts as a filter to select a desired subcarrier, and as an equalizer compensating for linear impairments, and in particular the effects of Polarization Mode Dispersion (PMD). The output of each FS-TDE 116 therefore corresponds with information transmitted on a single polarization state of a single selected subcarrier. Further processing includes recovery of the carrier 118, and demodulation of the data from the subcarrier 120.

Figure 2 shows a block diagram of a structure 200 for DP No-GI CO-OFDM receiver processing according to an embodiment of the present invention. In accordance with the principles of the invention, processing is simplified and a reduction in computational complexity is achieved. A single FS-TDE block 204 simultaneously performs the functions of the mixers 112, DFTs 114 and equalizing FS-TDEs 116 of the prior art processor 100. As will now be explained, this may be achieved with little or no increase in computational complexity over the processing performed by the prior art FS-TDEs 116 alone.

In particular, the FIR filters comprising the FS-TDE 204 may be configured to provide any desired impulse response up to a maximum length of N_{taps} , where N_{taps} is the number of taps used in the filters. A DFT of size N_{DFT} has an impulse response length N_{DFT} . Therefore, in any case for which $N_{\text{taps}} > N_{\text{DFT}}$, the DFT response may be incorporated into the FIR filter with no increase in computational requirements.

Furthermore, in accordance with embodiments of the invention the FIR filters comprising the FS-TDE 204, in combination with downsampling, eliminate the requirement for the mixers 112 of the prior art process 100. The impulse response of a band-pass filter differs from that of an equivalent low-pass filter by a factor corresponding with the filter centre frequency in each sample of the impulse response (i.e. tap coefficient value). The downsampling process aliases the passband of a band-pass filter back to baseband.

Overall, therefore, no additional computations on the high-rate signal samples are required in the FS-TDE 204 in any CO-OFDM system requiring more equalizer taps than the number of subcarriers. This will commonly be the case, since CO-OFDM systems of the type to which the invention applies generally employ a relatively small number of subcarriers. At the same time, the prior-art mixers and DFTs are eliminated, resulting in an overall reduction in computational requirements. Further inherent advantages of adaptive equalization are maintained, including automatic mitigation of other (linear) impairments of the channel, such as the finite

and non-ideal frequency response of the analog electronic and opto-electronic components in the transmitter and receiver.

The filter tap coefficients for a FS-TDE that receives multiple subcarriers cannot reliably be identified and configured using blind techniques such as the
5 Constant-Modulus-Algorithm (CMA). For each subcarrier, there will be a local minimum in the error vector of the CMA, corresponding with the low-pass and band-pass characteristics, as discussed above. The CMA cannot differentiate between these minima, and it is therefore possible that multiple FS-TDE's will converge (tune) to the same subcarrier.

10 According to embodiments of the invention, therefore, a short unique training sequence is initially transmitted on each subcarrier. A training-based algorithm, such as the Least-Mean-Squares (LMS) algorithm, is used to select a subcarrier according to its unique training sequence. Preferably, the training sequences are orthogonal, or approximately orthogonal, to one another and may be, for example, pseudo-random
15 bit sequences generated using suitable seed values. Training is only required once on system startup. Once the FS-TDE filter response has converged on the selected subcarrier, the CMA takes over, and the error vector will lock to the local minimum. Time-varying effects such as PMD can then be tracked with the CMA, which will make adjustments to the filter tap coefficients to keep the FS-TDE locked.

20 In an alternative embodiment, initial values of the filter tap coefficients may be configured directly such that each FS-TDE is initially centred on a different selected subcarrier.

By way of example, Figure 3(a) is a graph 300 showing the amplitude response of a set of converged FS-TDE filters for a single polarization, three-
25 subcarrier, back-to-back system employing QPSK modulation on each subcarrier. The horizontal axis 302 shows frequency relative to the central subcarrier of the CO-OFDM signal, while the vertical axis 304 shows relative magnitude. Each FS-TDE was trained using the LMS algorithm on a 512-symbol training sequence to converge the filters around the three subcarriers before switching to CMA for another 2048
30 symbols. It can be seen that the final responses 306, 308, 310 of the filters are substantially similar to sinc functions, with characteristically-strong sidelobes and overlapping passbands. It will therefore be appreciated that, in the back-to-back case, each FS-TDE behaves as one output of a DFT once trained.

Figure 3(b) shows the received constellations 312, 314, 316 of the three-subcarrier optical back-to-back system. The relatively small spread of each point in the constellations demonstrates that the crosstalk between subcarriers is very low, further confirming that the FS-TDE filters are acting like a DFT in that they maximize the orthogonality of the subcarriers.

A preferred embodiment of the invention has been further verified through transmission experiments.

Figure 4 shows schematically an experimental setup 400 for an 800-km system. The OFDM signal was generated using offline DSP 402 in MATLAB®. QPSK modulation was used on each subcarrier. A Tektronix AWG7102 Arbitrary Waveform Generator (AWG) 404, with two outputs operating at 10 Gsample/s, was used to generate in-phase and quadrature components of the signal. Two 5-GHz electrical low pass filters (LPF) 506, 508 were used to remove the image from the generated electrical signals. Minicircuits® 14-GHz microwave amplifiers 410, 412 were used to drive a Sumitomo 40-Gbps complex Mach-Zehnder Modulator (C-MZM) 414. An Agilent External Cavity Laser (ECL) with a linewidth of ~100 kHz was used as an optical carrier source 416. The modulated optical signal was split with a polarization beam splitter (PBS) 418 with its input polarization aligned so that the power was split evenly between two outputs. A one-meter long polarization maintaining fiber patch lead 420 was used as a delay line to decorrelate the two signals before they were recombined with another PBS 422 to generate a polarization multiplexed signal.

For purposes of the experiment, combined OFDM subcarriers were generated digitally by the offline DSP 402 and AWG 404 in order to avoid the need to provide three or five C-MZM's. In practical embodiments the orthogonal subcarriers may alternatively be generated using separate optical modulators, which may enable higher bit-rates per channel to be achieved.

The optical link 424 consisted of 10×80-km spans of standard single-mode fiber (S-SMF) 426. The loss of each span 426 was compensated by an erbium-doped fiber amplifier (EDFA) 428. The optical launch power into each span was maintained below -4 dBm. The primary sources of signal degradation during transmission were therefore chromatic dispersion, PMD, and amplifier noise. The received Optical Signal-to-Noise Ratio (OSNR) was controlled by changing the launch powers of the EDFAs and the attenuation of variable optical attenuator (VOA)

430, and measured using an Agilent 86142B Optical Spectrum Analyzer (OSA) with a resolution bandwidth of 0.1 nm (not shown). A Finisar *WaveShaper* (programmed to have a 50-GHz passband no guard interval coherent optical orthogonal frequency division multiplexing transmission system centered on the laser wavelength) was used as an optical filter 432 to remove the out-of-band amplified spontaneous emission (ASE) noise prior to the receiver, which comprised a Kyria dual-polarization 1×8 optical hybrid 434 and four pairs of u²t Photonics balanced photodiodes 436 to detect the optical signal.

The optical local oscillator (LO) for coherent detection was taken from the transmitter laser 416 with a 3-dB optical coupler 438. Since the propagation delay through 800 km of fiber is well in excess of the coherence time of the laser, the LO was uncorrelated with the transmitter laser. A Tektronix DSA72004 real-time digital sampling oscilloscope (DSO) 440, sampling at 50 Gsample/s on each of its four inputs, was used for analog-to-digital conversion, equivalent to four parallel ADC's.

Offline DSP based on MATLAB[®] was used to implement a processor 200 embodying the invention, as described previously with reference to Figure 2. Firstly, the digital signal was downsampled to 10 Gsample/s to match the sampling rate of the transmitter DAC's. The bulk of the chromatic dispersion was compensated across all subcarriers with a frequency domain equalizer using the overlap-add algorithm. Residual chromatic dispersion having a maximum differential delay of less than the length of the impulse response of the FS-TDE filters is automatically compensated as part of the adaptive equalization process.

Values of the tap coefficients of the FIR filters of each FS-TDE, corresponding with each subcarrier, were configured initially with an LMS algorithm, with the first 512 data symbols from each subcarrier being used for training. The step size used for LMS was 0.02. Fine tuning and continuous adaptation of the FS-TDE filters was then performed using CMA with a step size of 0.001. Finally, the phase noise from each subcarrier was compensated independently using the Viterbi-Viterbi algorithm.

Two different systems were experimentally verified, having three and five subcarriers respectively. The three-subcarrier signal was generated with a four-point IFFT and the five-subcarrier signal was generated with a six-point DFT. In each case, the carrier at the Nyquist frequency was zeroed, with all other subcarriers carrying data. The three-subcarrier system had a bit rate of 30 Gb/s and 97436 randomly generated symbols were transmitted, which contained 1.17 million bits. The bit rate

for the five-subcarrier system was 33.33 Gb/s and 64957 symbols were transmitted, corresponding with 1.3 million bits. The sampling rate of the DAC's of the AWG 404 limited the maximum transmission rates that could be used.

The optical spectra of the two systems were measured with an Agilent High-Resolution Spectrometer (HRS), and are shown in Figure 5. The optical spectrum 502 for the three-subcarrier system is shown with frequency relative to 193.4 THz on the horizontal axis 504, and amplitude on the vertical axis 506. The resolution of the spectrum 508 is limited by that of the spectrometer, however for illustrative purposes the locations of the three subcarriers 510, 512, 514 are shown. Similarly, the spectrum 516 for the five-subcarrier system is shown, again with frequency on the horizontal axis 518 and amplitude on the vertical axis 520. The measured spectrum 522 is shown, along with the locations of the five subcarriers 524, 526, 528, 530, 532.

The received QPSK constellations after transmission over 800 km of S-SMF are shown for the three-subcarrier system in Figure 6(a), and for the five-subcarrier system in Figure 6(b). A 12-tap FS-TDE was used for the three-subcarrier system. The received OSNR, measured with the OSA set to a resolution bandwidth of 0.1 nm, was 15.3 dB. The five-subcarrier system used a 16-tap FS-TDE and the received OSNR was 15.2 dB. Error-free transmission was achieved in all subcarriers of both systems. After receiving all of the symbols, the filter response of the adaptive FS-TDE remained centered on the subcarrier selected by LMS during training.

More particularly, Figure 6(a) shows received constellations 602, 604, 606 for the three subcarriers, along with corresponding signal quality factors Q_{const} . Similarly, Figure 6(b) shows received constellations 608, 610, 612, 614, 616 for the five subcarriers, along with their corresponding values of Q_{const} . In each case, Q_{const} is calculated from the spread in the equalized constellations in a conventional manner. The signal qualities were similar for all subcarriers, with the outermost subcarriers having slightly lower Q_{const} values. Degradation from linear crosstalk would be most significant on the middle subcarrier because it has the maximum number of neighbours. This suggests that linear crosstalk is not a significant source of degradation and the proposed equalizer is effective in subcarrier demultiplexing after 800 km of transmission. The degradation of the outer channels is believed to be due to the truncation of their sinc responses, due to the DAC's response, the subsequent image rejecting electrical LPFs and other bandwidth limitations.

Figure 7 shows graphs 702, 704 of received Q_{BER} on the vertical axes 706, calculated from the average bit-error-ratio (BER) count of all subcarriers assuming a Gaussian distribution, as a function of the OSNR on the horizontal axes 708. Figure 7(a) shows the graph 702 for the three-subcarrier system, while Figure 7(b) shows the graph 704 for the five-subcarrier system.

Results are shown for both systems after 80 km ($\diamond$ - 710, 712) and 800 km ($\circ$ - 714, 716). The 80-km baseline was used instead of back-to-back to decorrelate the phases of the transmitter laser and LO. ASE-limited Q curves 718 are calculated from the OSNR assuming that the only source of degradation is additive white Gaussian noise, generated by ASE. The ASE-limited Q is 0.5 dB higher for the five-subcarrier system because of the higher bit rate. An FEC limit 720 is shown at a Q of 9.8 dB which corresponds with a BER of 10^{-3} .

The graphs 702, 704 show that the degradation in Q_{BER} after the 800-km link, compared to the 80-km link was very small for both systems, indicating that the fiber impairments were almost fully compensated by the digital equalizer. For the three-subcarrier 30 Gb/s system, the required OSNR for a BER of 10^{-3} was 8.5 dB after 80 km and 8.6 dB after 800 km, around 1 dB higher than the ASE-limited Q of 7.6 dB. For the five-subcarrier 33.33 Gb/s system, OSNRs of 9.5 dB and 9.3 dB were required after 80 km and 800 km respectively, which is less than 1.5-dB above the ASE-limited Q of 8.1 dB. This suggests that the OSNR penalty from linear crosstalk is negligible for a BER of 10^{-3} .

A block diagram of a receiver 800 according to an alternative embodiment of the invention is shown in Figure 8. In the embodiment 800 the FS-TDE is implemented in the optical domain. A received CO-OFDM signal first passes through a chromatic dispersion compensator 802, which may be, for example, a length of dispersion-compensating fiber.

The compensator 802 is configured to substantially compensate accumulated chromatic dispersion, however some residual chromatic dispersion may be equalized by the FS-TDE.

An optical splitter 804 divides the dispersion-compensated optical signal into a plurality of optical paths, corresponding with the number of individual subcarriers. Each signal is coupled to the input of an optical FS-TDE 806, which comprises a splitter 808, which is coupled to a corresponding recombiner 810 via an array of delay lines 812. Each delay line 812 includes a variable optical element 814, which

enables the amplitude and/or phase of the signal passing therethrough to be controlled, via a set of corresponding electronic control inputs 816. The FS-TDE 806 may be implemented, for example, as a planar waveguide device in a suitable electro-optic material, such as lithium niobate. In general, the splitter 108, combiner 810, and parallel delay lines 812 act as an optical FIR filter, wherein each delay line 812 corresponds with a filter tap, and the variable optical elements 814 may be controlled to vary the tap coefficients.

In the embodiment 800, an optical gate 818 is used to sample the output of the optical FIR filter at time intervals corresponding with the tap delays. It will be appreciated that sampling may alternatively be performed in the electronic domain, following detection. However, performing optical sampling may enable the use of lower bandwidth detectors and front-end electronics.

A coherent optical receiver 820, such as the hybrid 434 and balanced detectors 436 shown in Figure 4, receives the de-multiplexed optical subcarrier and generates four outputs, corresponding with the in-phase and quadrature components of the two polarization states of the detected signal. A processor 822, which is preferably a digital signal processor, implements adaptive algorithms, such as the LMS and/or CMA algorithms described above in relation to the first embodiment of the invention, in order to generate the adaptive control signals 816 that are applied to the optical FS-TDE 806. The processor 822 also demodulates the transmitted information from the received optical subcarrier. The processor 822 may also perform further signal processing functions, such as the implementation of Forward Error Correction (FEC).

In conclusion, embodiments of the present invention provide improved methods and apparatus for receiving and demultiplexing CO-OFDM signals. A single FS-TDE performs simultaneous demultiplexing and equalizing, and eliminates the requirement for additional mixers and demultiplexers, such as DFTs, required in the prior art. Embodiments of the invention employ either electronic/digital FS-TDEs, or may employ optical devices or circuits to implement FS-TDEs within the optical domain. Configuration of an FS-TDE to lock onto a specific selected subcarrier may be achieved by a training sequence, or by setting an appropriate initial configuration of the tap coefficients.

It will be appreciated that the embodiments of the invention described herein are offered by way of example only, and a number of modifications and variations are

possible, such as would be apparent to persons skilled in the art of optical communications. The described embodiments are therefore not limiting of the scope of the invention, which is as defined in the claims appended hereto.

CLAIMS:

1. A method for use in receiving a selected subcarrier of a Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) signal, the method comprising:
 - 5 providing an adaptive Fractionally-Spaced Time-Domain Equalizer (FS-TDE) having a plurality of configurable tap coefficients;
configuring the tap coefficients such that the FS-TDE is adapted to simultaneously demultiplex and equalize the selected subcarrier;
processing the CO-OFDM signal using the FS-TDE to generate a
10 demultiplexed and equalized selected subcarrier signal; and
outputting the selected subcarrier signal from the FS-TDE.
2. The method of claim 1 wherein the step of configuring comprises presetting values of the tap coefficients such that a centre frequency of the FS-TDE initially corresponds substantially with a centre frequency of the selected
15 subcarrier.
3. The method of claim 1 wherein the step of configuring comprises applying a training algorithm to adaptively set values of the tap coefficients during a training period within which the selected subcarrier is modulated with a predetermined training sequence.
- 20 4. The method of claim 3 wherein the training algorithm comprises a Least Mean Squares (LMS) algorithm.
5. The method of claim 1 wherein the step of configuring further comprises applying a continuous algorithm to adapt values of the tap coefficients and maintain a lock of the FS-TDE on the selected subcarrier during ongoing
25 operation.
6. The method of claim 5 wherein the subcarrier is modulated with a signal having the Constant Modulus (CM) property, and the continuous algorithm is a Constant Modulus Algorithm (CMA).

7. The method of claim 1 wherein the selected subcarrier comprises two orthogonal polarization components, and the equalization performed by the FS-TDE comprises compensating for PMD.

8. The method of claim 1 wherein the equalization performed by FS-TDE
5 comprises compensating for residual chromatic dispersion.

9. The method of claim 1 comprising a further step of at least partially compensating for chromatic dispersion of the CO-OFDM signal prior to the step of processing the optical OFDM signal using the FS-TDE.

10. The method of claim 1 comprising the further step of performing coherent
10 detection of the CO-OFDM signal to produce at least one corresponding electrical signal, wherein the FS-TDE is implemented electronically.

11. The method of claim 10 comprising the further step of digitizing the at least one corresponding electrical signal, wherein the FS-TDE is implemented digitally.

12. The method of claims 1 wherein the FS-TDE is an optical filter comprising
15 electronically controllable taps, wherein the step of configuring the tap coefficients comprises performing coherent detection of the selected subcarrier signal output from the FS-TDE to produce at least one corresponding electrical signal, processing the electrical signal to determine values of the tap coefficients, and applying electronic control signals to the electronically controllable taps
20 corresponding with the determined valued of the tap coefficients.

13. An optical receiver comprising:

an adaptive Fractionally-Spaced Time-Domain Equalizer (FS-TDE) having a filter input port and a filter output port, and a plurality of configurable tap coefficients;

a receiver input port for receiving a Coherent Optical Orthogonal Frequency
25 Division Multiplexed (CO-OFDM) signal, the receiver input port being operatively coupled to the filter input port;

a processor adapted to determine values of the configurable tap coefficients such as the FS-TDE is adapted to simultaneously demultiplex and equalize a

selected subcarrier of the CO-OFDM signal, the processor being operatively coupled to the FS-TDE to configure the tap coefficients in accordance with the determined values; and

a receiver output port operatively coupled to the filter output port.

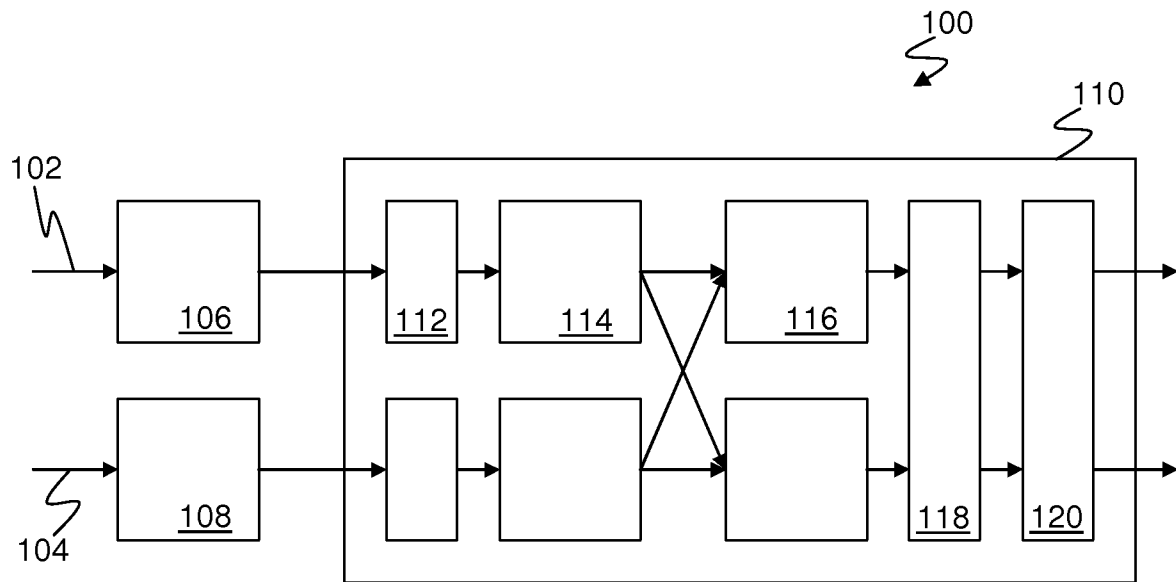


Figure 1

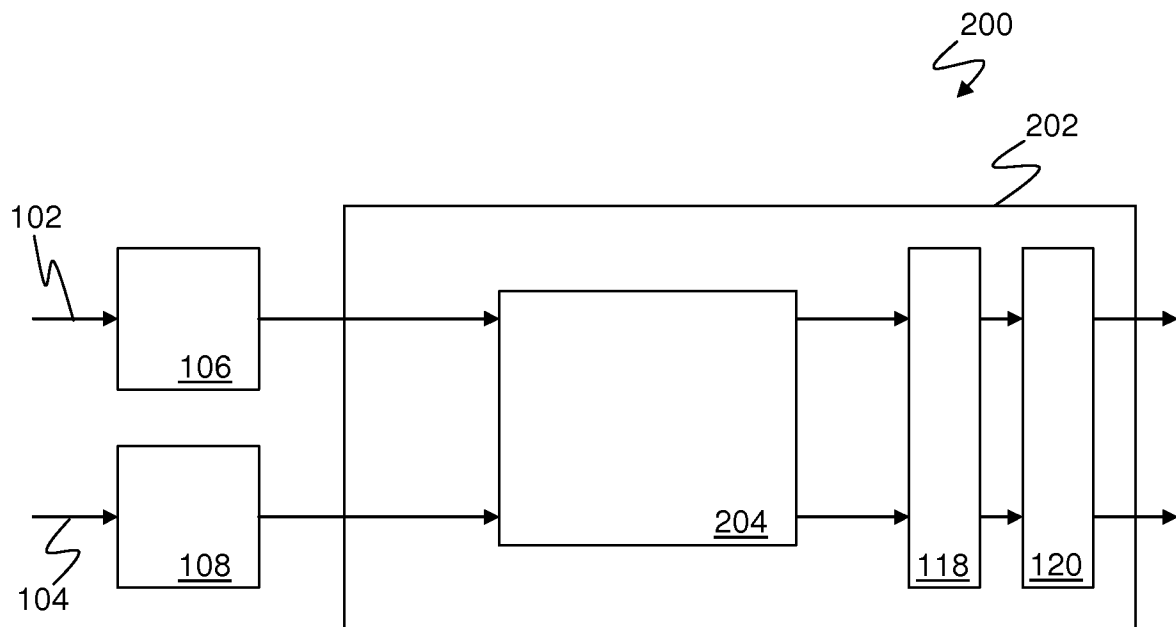


Figure 2

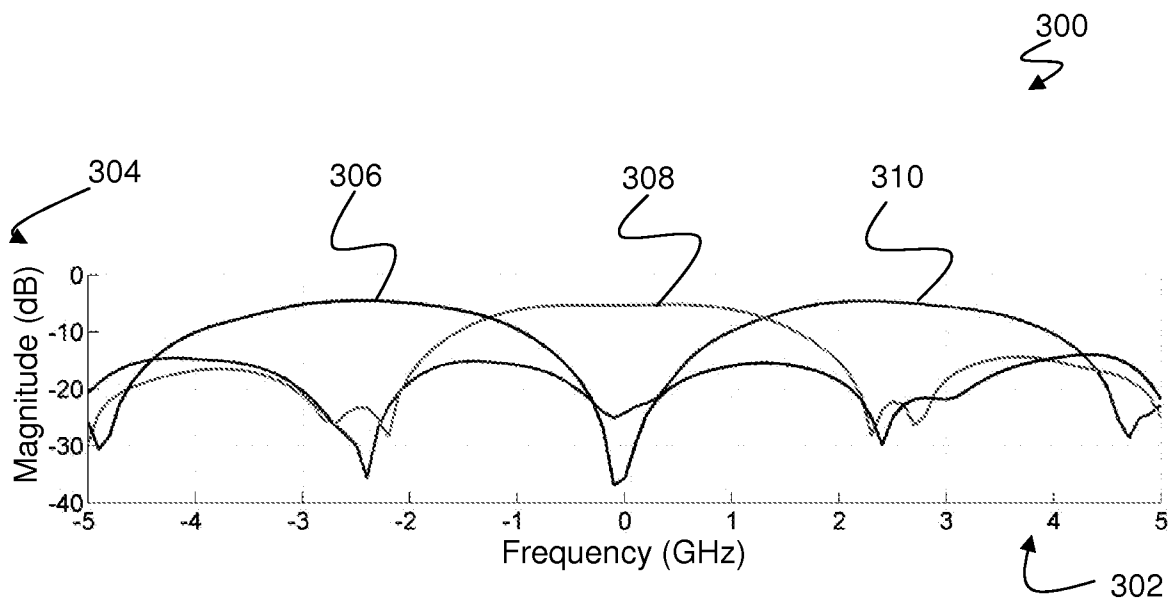


Figure 3(a)

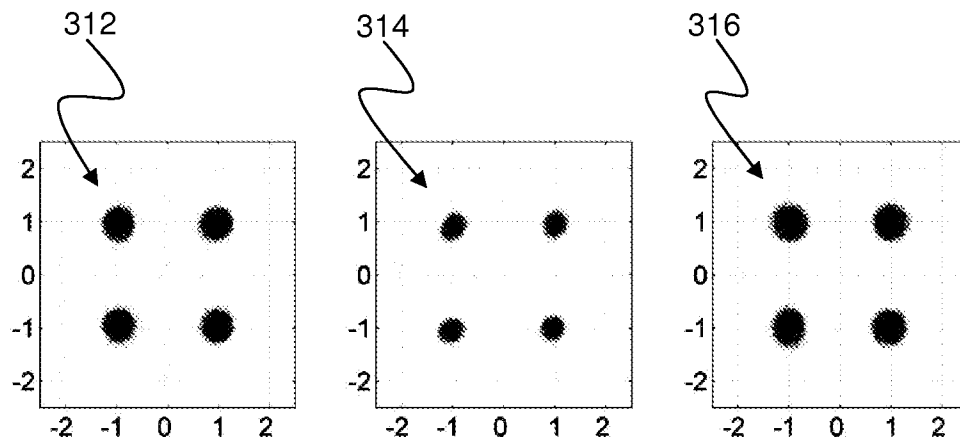


Figure 3(b)

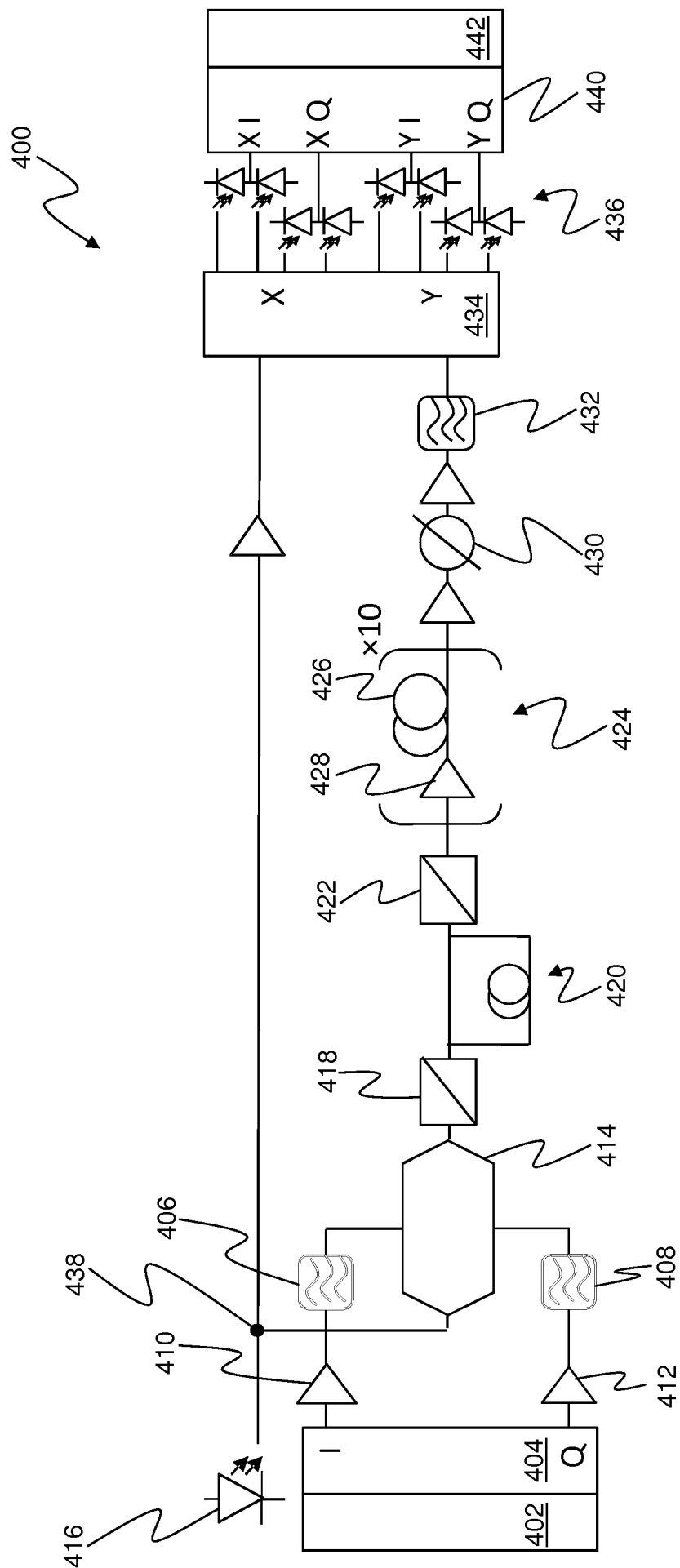


Figure 4

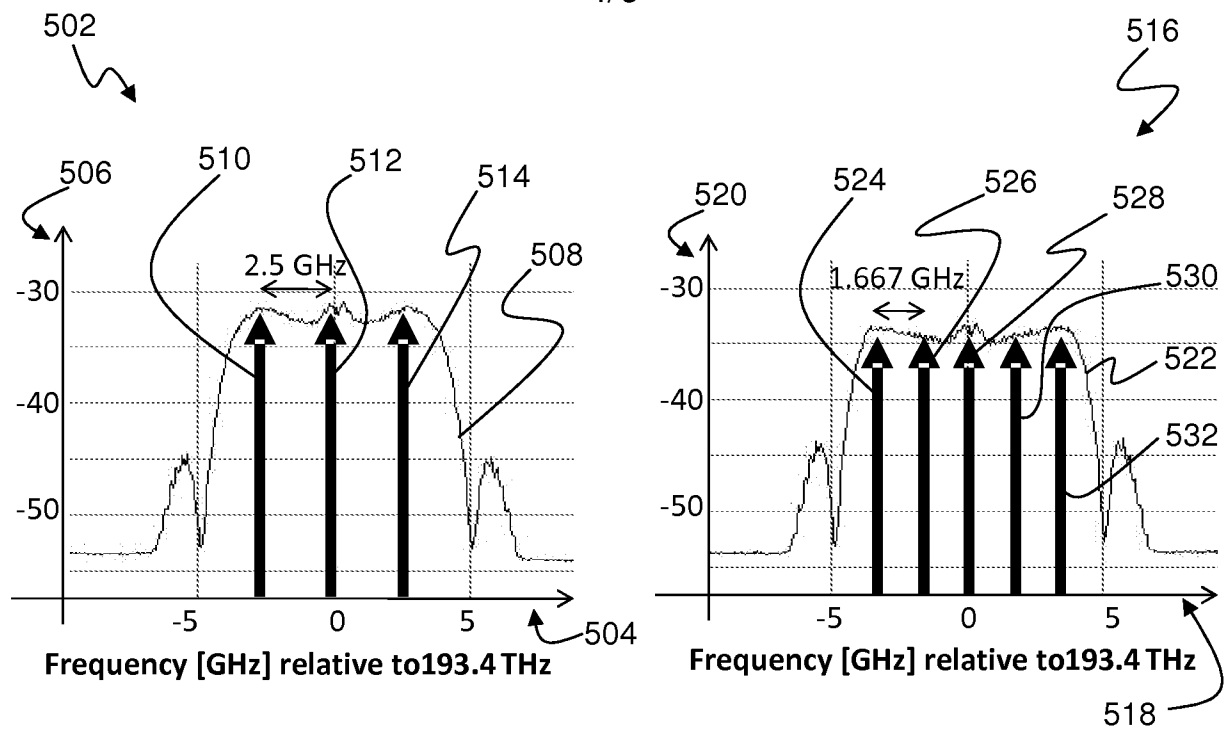


Figure 5

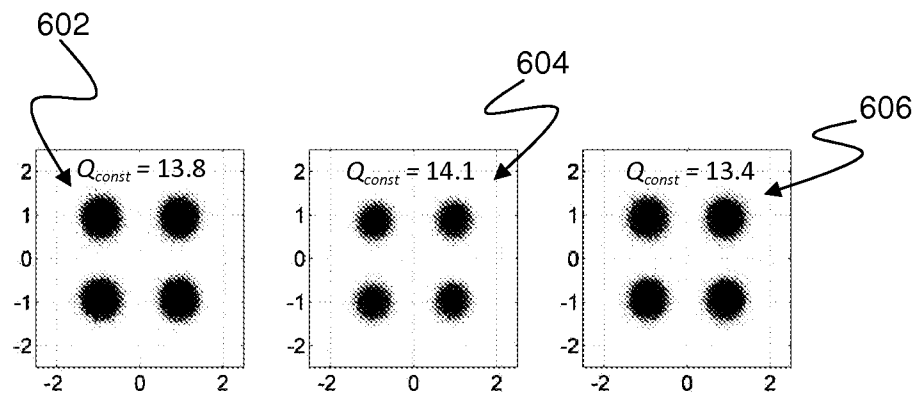


Figure 6(a)

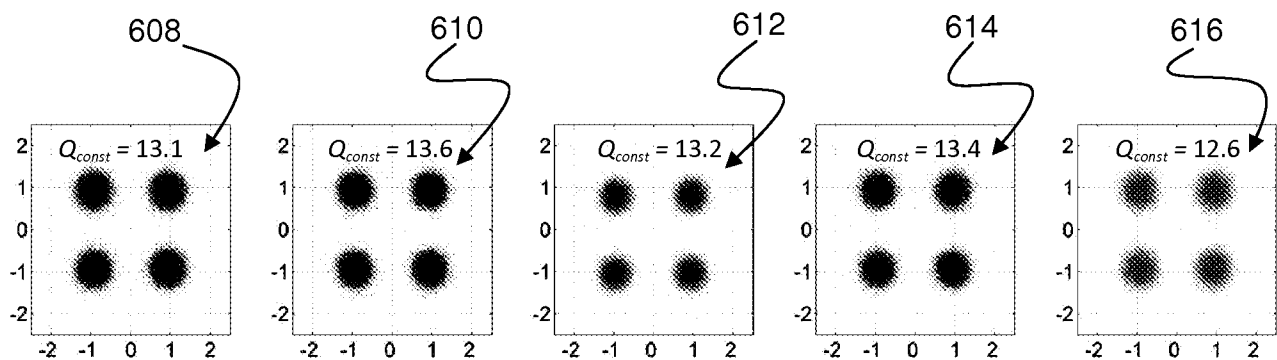


Figure 6(b)

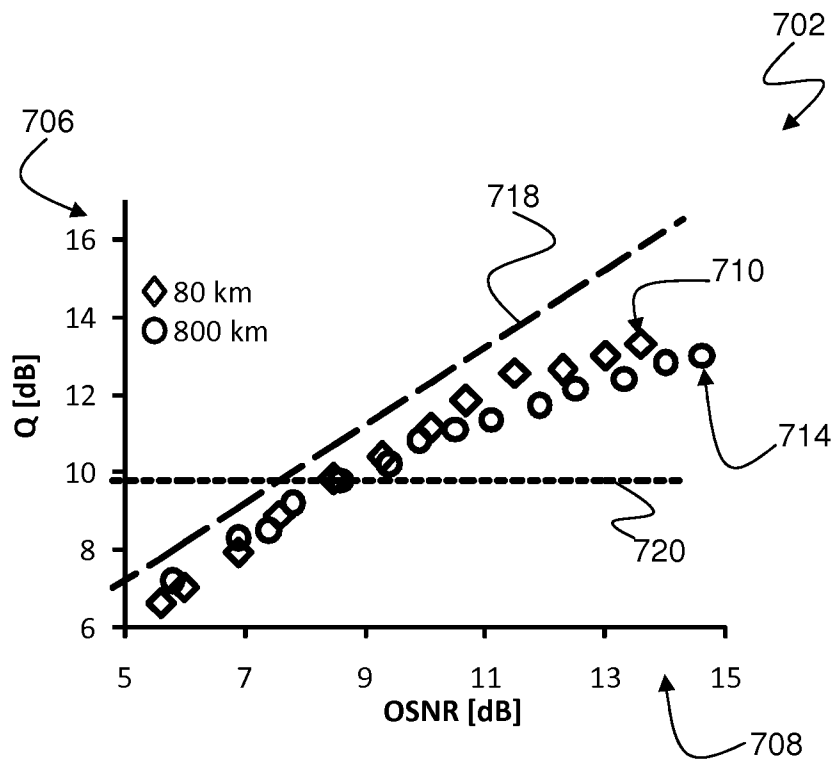


Figure 7(a)

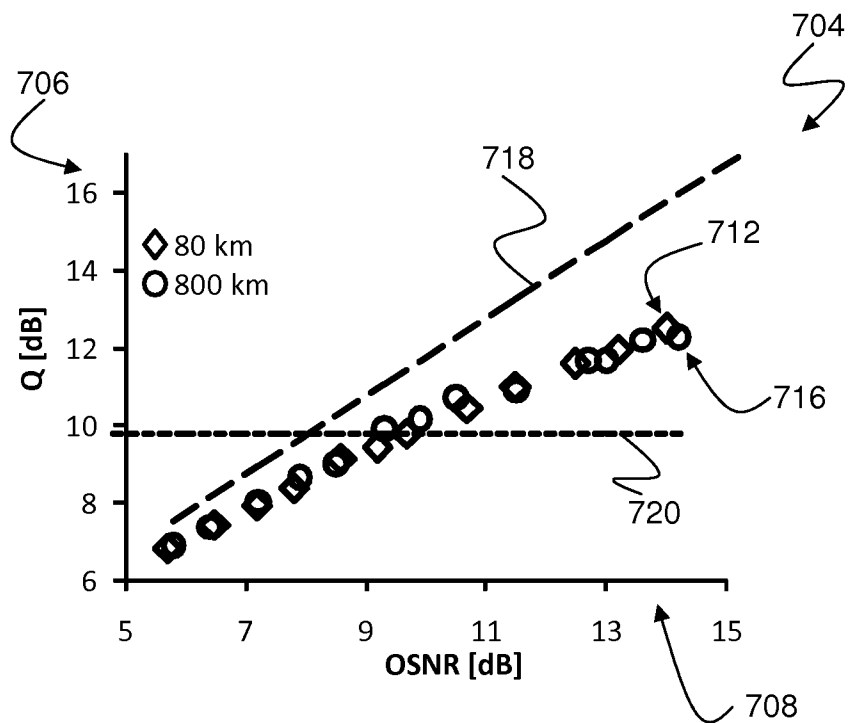


Figure 7(b)

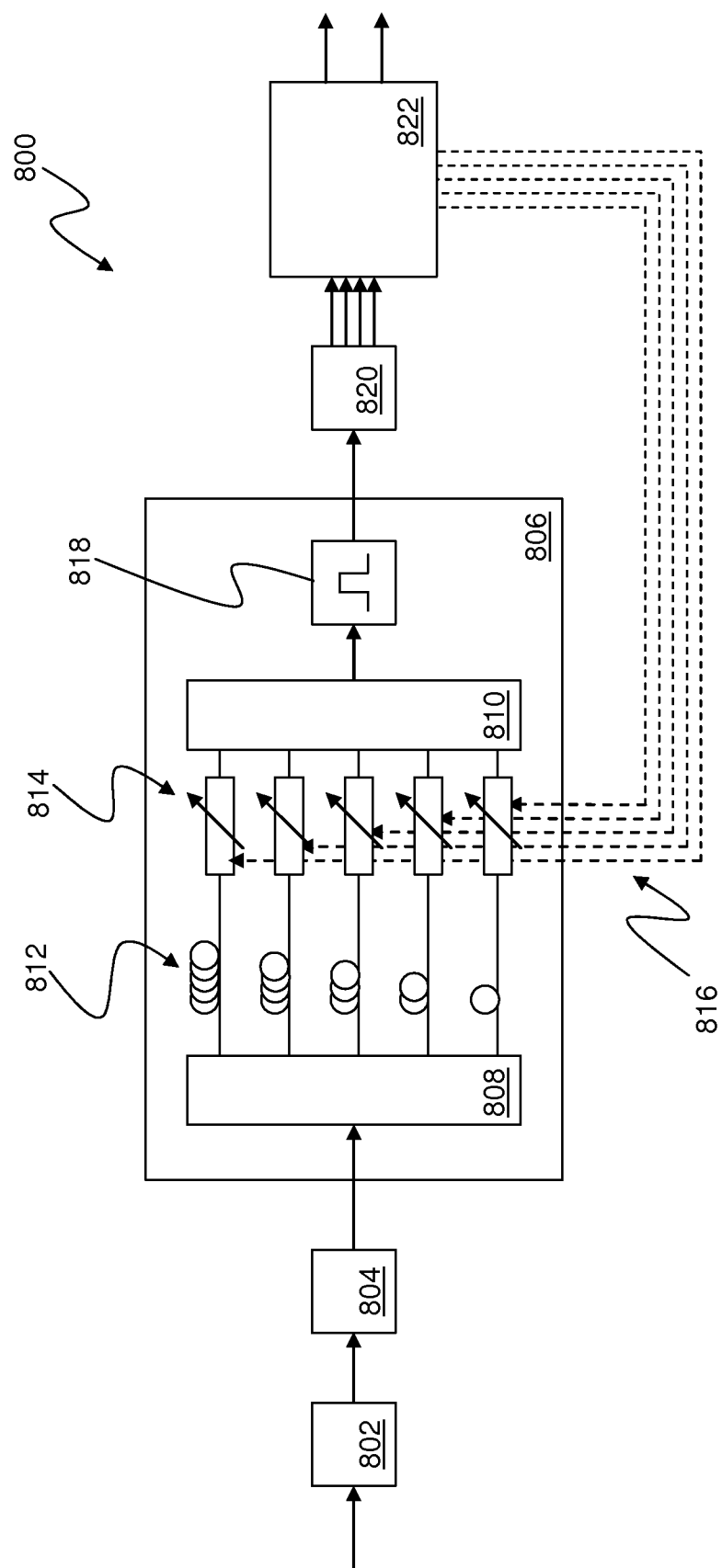


Figure 8