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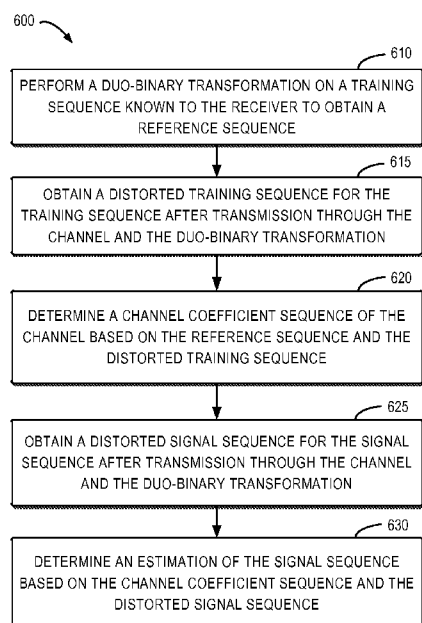


FIG. 6

(57) Abstract: The present disclosure presents a method and an apparatus for estimation of a received signal sequence. The method is implemented at a receiver configured to receive a signal sequence through a bandwidth-limited channel. The method includes performing a duo-binary transformation on a training sequence known to the receiver to obtain a reference sequence; obtaining a distorted training sequence for the training sequence after transmission through the channel and the duo-binary transformation; determining a channel coefficient sequence of the channel based on the reference sequence and the distorted training sequence; obtaining a distorted signal sequence for the signal sequence after transmission through the channel and the duo-binary transformation; and determining an estimation of the signal sequence based on the channel coefficient sequence and the distorted signal sequence.



METHOD AND APPARATUS FOR ESTIMATION OF RECEIVED SIGNAL SEQUENCE

FIELD

[0001] Embodiments of the present disclosure generally relate to the field of communications, and more specifically, to a method and an apparatus for an estimation of a received signal sequence.

BACKGROUND

[0002] Typically, with a good design of a bandwidth of a receiver, a binary signal can be transformed into a duo-binary signal for transmission. Due to such a signal transformation or shaping mechanism, it is possible to carry a data signal at a higher rate (for example, 25Gb/s or even 40Gb/s) on a regular narrow-bandwidth component (for example, an optical transmitter and receiver of 10G-bandwidth) for applicability to a future access system. However, as the narrow-bandwidth component has a low-pass filtering effect on the signal at the higher rate, a partial response of the signal is caused. Thus, a signal sequence with severe distortion is received at a receiver. This lowers performance of a communication system or even results in a communication failure.

SUMMARY

[0003] Embodiments of the present disclosure provide a method and an apparatus implemented at a receiver, a computer program product and a receiver.

[0004] In a first aspect of the present disclosure, there is provided a method implemented at a receiver. The receiver is configured to receive a signal sequence through a bandwidth-limited channel. The method comprises performing a duo-binary transformation on a training sequence known to the receiver to obtain a reference sequence; obtaining a distorted training sequence for the training sequence after transmission through the channel and the duo-binary transformation; determining a channel coefficient sequence of the channel based on the reference sequence and the distorted training sequence; obtaining a distorted signal sequence for the signal sequence after transmission through the channel and the duo-binary transformation; and determining an estimation of the signal sequence based on the channel coefficient sequence and the distorted signal sequence.

[0005] In some embodiments, performing the duo-binary transformation on the training

sequence to obtain the reference sequence comprises transforming a binary sequence into a duo-binary sequence; or transforming a four-level pulse amplitude modulation (PAM4) sequence into a duo-binary PAM4 sequence.

[0006] In some embodiments, determining the channel coefficient sequence of the channel comprises performing the following operations for at least one time: obtaining an intermediate training sequence based on a convolution of the distorted training sequence and a current channel coefficient sequence of the channel; comparing a difference between the intermediate training sequence and the reference sequence with a threshold; and in response to determining that the difference is greater than the threshold, adjusting the current channel coefficient sequence.

[0007] In some embodiments, determining the estimation of the signal sequence comprises determining the estimation of the signal sequence using a maximum likelihood sequence estimation algorithm.

[0008] In some embodiments, determining the estimation of the signal sequence using the maximum likelihood sequence estimation algorithm comprises determining the estimation of the signal sequence by using the channel coefficient sequence and the distorted signal sequence as an input to the maximum likelihood sequence estimation algorithm.

[0009] In some embodiments, determining the estimation of the signal sequence using the maximum likelihood sequence estimation algorithm comprises performing distortion compensation on the distorted signal sequence based on the channel coefficient sequence; determining an undistorted channel coefficient sequence of an undistorted duo-binary channel; and determining the estimation of the signal sequence by using the distorted signal sequence after the distortion compensation and the undistorted channel coefficient sequence as an input to the maximum likelihood sequence estimation algorithm.

[0010] In a second aspect of the present disclosure, there is provided a communication device. The communication device comprises a receiver configured to receive a signal sequence through a bandwidth-limited channel. The communication device comprises at least one processor and at least one memory including computer-executable instructions. The at least one memory and the computer-executable instructions are configured, with the at least one processor, to cause the communication device to perform a duo-binary transformation on a training sequence known to the receiver to obtain a reference sequence; obtain a distorted training sequence for the training sequence after transmission through the

channel and the duo-binary transformation; determine a channel coefficient sequence of the channel based on the reference sequence and the distorted training sequence; obtain a distorted signal sequence for the signal sequence after transmission through the channel and the duo-binary transformation; and determine an estimation of the signal sequence based on the channel coefficient sequence and the distorted signal sequence.

[0011] In a third aspect of the present disclosure, there is provided a computer program product. The computer product is tangibly stored on a non-volatile computer executable medium and comprises machine executable instructions. The machine executable instructions, when executed, cause a machine to perform steps of the method according to the first aspect.

[0012] In a fourth aspect of the present disclosure, there is provided a receiver for use in a communication device. The receiver comprises a duo-binary transformation module, a channel estimation module and a signal estimation module. The duo-binary transformation module is configured to perform a duo-binary transformation on a training sequence known to the receiver to obtain a reference sequence. The channel estimation module is configured to obtain a distorted training sequence for the training sequence after transmission through the channel and the duo-binary transformation, and determine a channel coefficient sequence of the channel based on the reference sequence and the distorted training sequence. The signal estimation module is configured to obtain a distorted signal sequence for the signal sequence after transmission through the channel and the duo-binary transformation, and determine an estimation of the signal sequence based on the channel coefficient sequence and the distorted signal sequence.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Through the following detailed description with reference to the accompanying drawings, the above and other objectives, features and advantages of embodiments of the present disclosure will become more apparent. Several embodiments of the present disclosure will be illustrated by way of example but not limitation in the drawings in which:

[0014] FIG. 1 illustrates an example scenario of transmitting a high speed signal using a bandwidth-limited channel.

[0015] FIG. 2 illustrates an example configuration of a conventional signal estimation module.

[0016] FIG. 3 illustrates simulated different eye diagrams for different channel responses.

[0017] FIG. 4 illustrates a schematic block diagram of receiving architecture according to embodiments of the present disclosure.

5 [0018] FIG. 5 illustrates a principle diagram of a spectral transformation according to embodiments of the present disclosure.

[0019] FIG. 6 illustrates a flowchart of a method implemented at a receiver according to embodiments of the present disclosure.

[0020] FIG. 7 illustrates an embodiment of determining an estimation of a signal sequence according to embodiments of the present disclosure.

10 [0021] FIG. 8 illustrates a further embodiment of determining an estimation of a signal sequence according to embodiments of the present disclosure.

[0022] FIG. 9 illustrates a block diagram of a device suitable for implementing embodiments of the present disclosure.

15 [0023] FIG. 10 illustrates a simulated performance-comparison graph of embodiments of the present disclosure against a conventional solution.

[0024] FIG. 11 illustrates another simulated performance-comparison graph of embodiments of the present disclosure against a conventional solution.

[0025] FIG. 12 illustrates a graph of an experimental test according to embodiments of the present disclosure.

20 [0026] FIG. 13 illustrates a graph of a further experimental test according to embodiments of the present disclosure.

[0027] Throughout the drawings, identical or similar reference numbers are used to represent identical or similar elements.

DETAILED DESCRIPTION OF EMBODIMENTS

25 [0028] Principles and spirits of the present disclosure will now be described with reference to several example embodiments illustrated in the drawings. It should be appreciated that description of those embodiments is merely to enable those skilled in the art to better understand and further implement the present disclosure and is not intended for limiting the scope disclosed herein in any manner.

[0029] As used herein, the term “includes” and its variants are to be read as open terms that mean “includes but is not limited to.” The term “based on” is to be read as “based at least in part on.” The term “one implementation” and “an implementation” are to be read as “at least one implementation.” The term “another implementation” is to be read as “at least one other
5 implementation.” The terms “first,” “second,” and the like may refer to different or same objects. Other definitions, either explicit or implicit, may be included below.

[0030] The term “terminal device” or “user equipment” (UE) used herein may refer to any terminal device capable of performing wireless communications with a base station or with another one. As an example, the terminal device may include a mobile terminal (MT), a
10 subscriber station (SS), a portable subscriber station (PSS), a mobile station (MS), or an access terminal (AT), and one of the above on a vehicle. The terminal device may be any type of mobile terminal, fixed terminal or portable terminal, such as mobile telephone, station, unit, device, multimedia computer, multimedia tablet, Internet node, communicator, desk-top computer, laptop computer, notebook computer, netbook computer, tablet computer, personal
15 communication system (PCS) device, personal navigation device, personal digital assistant (PDA), audio/video player, digital camera/video camera, positioning device, TV receiver, radio broadcast receiver, E-book device, gaming device, smart meter, meter or other smart appliances applicable to MTC communications, or any combination thereof. In the context of the present disclosure, terms “terminal device” and “user equipment” can be used
20 interchangeably for convenience of discussion.

[0031] The term “network devices” used herein refers to other entities or nodes having specified functions in the base station or communications network. “Base station (BS)” may indicate a node B (NodeB or NB), an evolved NodeB (eNodeB or eNB), a remote radio unit (RRU), a radio header (RH), a remote radio head (RRH), a relay, a low power node such as a
25 femto station and a pico station, and the like. Coverage of a base station, i.e., a geological region capable of providing service, is referred to as a cell. In the context of the present disclosure, the terms “network device” and “base station” can be used interchangeably for convenience of discussion, and eNB may mainly act as an example of the network device.

[0032] FIG. 1 illustrates an example scenario 100 of transmitting a high speed signal using a
30 bandwidth-limited channel. As illustrated in FIG. 1, there is shown architecture 190 which performs transmission/detection by transforming a conventional binary signal sequence (for example, an On-Off Keying (OOK) signal or a pulse amplitude modulation (PAM4) signal) into a duo-binary signal sequence (for example, a duo-binary signal or a duo-binary PAM4

signal), in which transmitting devices 130-133 and a receiver device 150 having a 10G bandwidth are used to transmit a signal with 25Gb/s per wavelength.

[0033] As shown, a binary signal sequence (for example, an OOK signal) generated by first through fourth processing boards 110-113 can be transmitted via 25G interfaces 120-123 to duo-binary transmitting-receiving architecture 190 denoted with a dotted box. The duo-binary transmitting-receiving architecture 190 may include four 10G transmitters 130-133 which convert signals from the first through fourth processing boards 110-113 into a 10G-bandwidth signal for transmitting through an optical link 140 to a 10G-bandwidth receiver 150.

[0034] Subsequently, the signal can pass through a direct detection module 160, a signal estimation module 161 and a forward error correction module 162 for physical decoding and error correction, so as to recover the 25G-bandwidth binary signals. Next, the 25G-bandwidth binary signals are transmitted via a 25G interface 170 to a fifth processing board 180 on the receiving end for further signal processing.

[0035] It can be seen that, in the conventional solution shown in FIG. 1, the binary signals from the transmitters 130-133 (in an optical network unit (ONU), for example) are transformed in the receiver 150 (in an optical line terminal (OLT), for example) into duo-binary signals, thereby leading to a poor bit error rate (BER) in the direct detection module 160. In order to compensate for a partial response caused by a low-pass filtering effect of the narrow-bandwidth (for example, 10G) components on the high speed signals (for example, 25G), an advanced intelligent algorithm can be used to improve correctness of an estimation performed on the received signal sequence with severe distortion. For example, the signal estimation module 161 may use a maximum likelihood sequence estimation (MLSE) algorithm to improve the correctness of the signal sequence estimation.

[0036] It should be appreciated that FIG. 1 only shows components or modules related with the embodiment of the present disclosure for the sake of simplicity, and in other embodiments, the example scenario 100 can include more or less components or modules. In addition, although FIG. 1 shows a particular number of components or modules, the number of these modules or components may be greater or smaller in other embodiments.

[0037] FIG. 2 illustrates an example configuration of a conventional signal estimation module 161. As shown in FIG. 2, the signal estimation module 161 can include an estimator initializing module 210 and an estimator module 220. The estimator initialization module

210 can provide a preset function 230 to set a preset condition for the estimator module 220 performing signal sequence estimation.

[0038] As shown, the estimator initialization module 210 can receive one or more pre-inputs. FIG. 2 for example depicts a first pre-input 211, a second pre-input 212 and a third pre-input 213. Typically, the first pre-input 211 can be a duo-binary channel coefficient sequence, which is set to an ideal value (for example, [1, 1]) in the conventional signal estimation module 161. The second pre-input 212 can be a constellation of a binary sequence (for example, an OOK or a PM4 sequence), which is set to [01] in the example of FIG. 2. The third pre-input 213 can be a traceback depth, which is set to 20 in the example of FIG. 2. Of course, the estimator initialization module 210 may also receive more or less pre-inputs. Based on these pre-inputs, the estimator initialization module 210 implements initialization of the estimator 220.

[0039] On one hand, the estimator 220 is initialized by the estimator initialization module 210, and the initialization is based on the first pre-input 211, the second pre-input 212 and the third pre-input 213. On the other hand, the estimator 220 receives a distorted signal sequence 214. Based on the initialization performed by the estimator initialization module 210 and the distorted signal sequence 214, the estimator 220 can determine an estimation 215 of the signal sequence for example via an estimation algorithm. In many instances, the estimator 220 may employ an MLSE algorithm to determine the estimation 215 of the signal sequence.

[0040] It should be appreciated that FIG. 2 only illustrates components or modules related with embodiments of the present disclosure, for the sake of simplicity. In other embodiments, the signal estimation module 161 may include more or less components or modules. Besides, although FIG. 2 shows a particular number of components or modules, the number of modules or components may be greater or smaller in other embodiments. In addition, although FIG. 2 shows specific sequence values of various inputs and outputs, those skilled in the art would appreciate that these sequence values are only provided illustratively and may have other different sequence values in other embodiments.

[0041] In the case that the signal estimation module 161 employs the MLSE algorithm, accuracy of the MLSE-based duo-binary signal sequence estimation strongly relies on accuracy of the channel coefficient. In an ideal condition, the channel bandwidth is adapted to transform a binary signal into a duo-binary signal without distortion, and such a channel

coefficient for example is $[1, 1]$. Therefore, in the conventional signal estimation module 161, for example, at the first pre-input 211 of the estimator initialization module 221, the channel coefficient is preset to a value (for example, $[1, 1]$) under the ideal condition. However, it is obviously fails to represent the real channel accurately.

5 [0042] In fact, for example in a passive optical network (PON) system, real channel conditions for a plurality of optical network units (ONU) may be varied greatly. In order to intuitively demonstrate influences of the varied real channels on the receiving system. FIG. 3 illustrates simulated different eye diagrams for different channel responses (of channels from ONUs to OLTs, for example).

10 [0043] In FIG. 3, the horizontal axis represents a normalized frequency and the vertical axis represents a magnitude. The reference numbers 310-330 represent four types of channel responses. The reference numbers 311-341 respectively represent eye diagrams after passing through these different channels, and the reference number 350 at the upper right represents an eye diagram of a binary signal (for example, an OOK signal) prior to passing through the
15 channels. In the simulation, the preset channel coefficient in the signal estimation module 161 maintains unchanged at $[1, 1]$, while the channel response is made to be changed from 310 to 330, and then the BER is monitored.

[0044] It can be seen from FIG. 3 that different channel responses 310-330 generate different duo-binary waveforms in a direct detection manner. Additionally, in case of an inaccurate
20 channel coefficient not reflecting a real channel, the estimation algorithm (for example, MLSE) cannot ensure that it may improve correctness of signal sequence estimation, or it may lead to a worse detection result. In other words, the estimation algorithm (for example, MLSE) is unable to offer a stable efficiency due to inaccurate channel coefficient estimation.

[0045] In order to at least in part solve the above and other potential problems, the
25 embodiments of the present disclosure provide a method and an apparatus implemented at a receiver, to improve the estimation algorithm (for example, MLSE) and make the estimation algorithm more effective and powerful. With the embodiments of the present disclosure, in a future PON, signals in a duo-binary format can be employed and even duo-binary PAM4 signals can be employed, so as to double a capacity per wavelength. Therefore, signal
30 transmission of 50Gb/s can be implemented using a 10G-class device.

[0046] As discussed above, in a transmission system performing the duo-binary transformation, an undesirable recovery of a binary signal (for example, a PAM4 signal) at the

receiving end is mainly due to the inaccurate channel estimation of the duo-binary channel. Therefore, in the embodiments of the present disclosure, a duo-binary channel estimation model is introduced prior to using an estimation algorithm (for example, MLSE), and it is assigned with an accurate channel coefficient to improve estimation correctness of the binary signal (for example, the PAM4 signal).

[0047] In some embodiments, an “intermediate stage” is introduced to generate a standard duo-binary signal (for example, a duo-binary PAM4 signal) to increase accuracy of recovering the binary signal (for example, the PAM4 signal). Also, the noise enhancement effect is avoided. Basic ideas of the embodiments of the present disclosure will be described with reference to FIG. 4 and FIG. 5.

[0048] FIG. 4 illustrates a schematic block diagram 400 of receiving architecture according to embodiments of the present disclosure. As shown in FIG. 4, one or more transmitters 410-411 of 10G-bandwidth can transmit signal sequence (for example, an OOK or PAM4 sequence) 401 of a high rate (for example, 50Gb/s) to an optical link 420.

[0049] At a receiver 430, a direct detector 431 of 10G-bandwidth may detect the received signal directly. Then, the detected signal may be analog-to-digital converted via an analog-to-digital conversion (ADC) module. The resulting digital signal sequence subsequently passes through a channel estimation-assisted signal estimation module 440 according to embodiments of the present disclosure to determine an estimation 215 of the signal sequence. Thereafter, the determined estimation 215 of the signal sequence is input to a forward error correction module 436 to recover the transmitted high rate (for example, 50Gb/s) signal sequence 401.

[0050] According to embodiments of the present disclosure, the channel estimation-assisted signal estimation module 440 may include a channel estimation module 433, a duo-binary transformation module 434 and a signal estimation module 435. The “intermediate stage” as mentioned above may for example include the channel estimation module 433 and the duo-binary transformation module 434 of these modules. They are operated in cooperation with the signal estimation module 435, so as to achieve an improved estimation of the received signal sequence.

[0051] Specifically, the channel estimation module 433 may estimate a channel coefficient of a duo-binary channel, to learn and compensate for a “difference” between a real duo-binary channel and a standard duo-binary channel, rather than using an unchanged default channel

coefficient as in the conventional solution. The duo-binary conversion module 434 may provide a duo-binary transformed training sequence to perform learning on the channel coefficient, rather than using a direct binary training sequence as in the conventional estimation solution, thereby avoiding the noise enhancement effect. On the basis of these functions provided by the “intermediate stage,” the signal estimation module 435 may determine the estimation of the transmitted binary signal sequence (for example, an OOK or PAM4 sequence) using the learned channel coefficient.

[0052] As discussed above, in the embodiment shown in FIG. 4, the transmitters 410-411 may transmit a binary signal sequence, for example an OOK or PAM4 signal. At the receiver 430, prior to signal sequence estimation, a channel estimation is first implemented through the channel estimation module 433 and then fed to the signal estimation module 435 (for example, as a channel coefficient pre-input to the MLSE) to replace a default value (for example, [1, 1]) in the conventional solution. Based on the learned updated channel model, a distorted duo-binary signal is compensated to obtain a compensated duo-binary signal according to a standard duo-binary reference signal sequence (for example, a PAM4 reference signal). Next, the signal estimation module 435 determines the most likely estimation sequence 215 of the binary signal (for example, PAM4 or OOK) based on the fed channel coefficient.

[0053] Accordingly, the channel estimation-assisted signal estimation module 440 according to the embodiments of the present disclosure can learn a specific channel coefficient intelligently for each individual channel (for example, for each ONU), and can also update the channel coefficient adaptively in case of heating, aging or other fluctuations. In addition, it is transparent to different signal formats (for example, OOK or PAM4). A general principle of embodiments of the present disclosure will be described below with reference to a spectrum transformation diagram of FIG. 5.

[0054] FIG. 5 illustrates a principle diagram 500 of a spectrum transformation according to embodiments of the present disclosure. As shown in FIG. 5, the spectrum 510 represents a spectrum of an original signal before transmission. The spectrum 520 represents a bandwidth spectrum of a narrow-bandwidth transmission device, which has an insufficient bandwidth relative to the rate or baud rate of the signal. The spectrum 530 represents a spectrum of the signal received via the narrow-bandwidth transmission device, which shows a spectrum of a severely distorted signal after the signal passes through the narrow-bandwidth transmission device.

[0055] The spectrum 540 also represents a spectrum of the signal received through the narrow-bandwidth transmission device, and a spectrum 541 represents a supplemental spectral portion required for recovering the original signal on the basis of the spectrum 540. The spectrum 550 also represents a spectrum of the signal received through the narrow-bandwidth transmission device, and the spectrum 551 represents a spectrum of the signal after compensation using the “intermediate stage” of a standard duo-binary signal. The spectrum 560 represents a spectrum of a recovered signal after performing an MLSE estimation on the spectrum 551.

[0056] It is seen that, through such arrangement of an “intermediate stage” according to embodiments of the present disclosure, performance of the estimation algorithm (for example, the MLSE estimation) at a subsequent stage may be maximized and the influences of noise can be minimized. It should be appreciated that, although specific frequency values are given in FIG. 5, these frequency values are only examples and different frequency values may be used in other embodiments. Embodiments of the present disclosure are not limited by these specific frequency values.

[0057] Reference will be made to FIG. 6 in combination with FIG. 7 below to describe a method implemented at the receiver 430 according to embodiments of the present disclosure. FIG. 6 illustrates a flowchart of the method 600 implemented at the receiver 430 according to embodiments of the present disclosure. FIG. 7 illustrates an embodiment of determining an estimation of a signal sequence according to embodiments of the present disclosure.

[0058] As shown in FIG. 7, the channel estimation-assisted signal estimation module 440 in the embodiment of FIG. 7 has a structure similar to that of the signal estimation module 161 depicted in FIG. 2. A difference with D2 lies in that the estimator initialization module 210 and the estimator module 220 are improved according to ideas of embodiments of the present disclosure. In the embodiment as shown in FIG. 7, various functions of the “intermediate stage” as mentioned above are implemented collectively by the estimator initialization module 210. However, it should be appreciated that, in other embodiments, these functions of the “intermediate stage” may also be implemented by a different module or component in the channel estimation-assisted signal estimation module 440 (or even in the receiver 430).

[0059] It is noted that FIG. 7 only illustrates the components or modules related with embodiments of the present disclosure, and the channel estimation-assisted signal estimation module 440 can include more or less components or modules in other embodiments.

Besides, although FIG. 7 shows a particular number of components or modules, the number of these modules or components may be greater or smaller in other embodiments. In addition, although FIG. 7 shows specific sequence values of various inputs and outputs, those skilled in the art would appreciate that these sequence values are only provided illustratively and can have other different sequence values in other embodiments.

[0060] Referring back to FIG. 6, in some embodiments, the method 600 in FIG. 6 may be performed by the estimator initialization module 210 and the estimator module 220 of the channel estimation-assisted signal estimation module 440 implemented at the receiver 430. In other embodiments, the method 600 may also be performed by any one or more suitable modules or components in the receiver 430.

[0061] At block 610, the estimator initialization module 210 performs a duo-binary transformation on a training sequence 701 known to the receiver 340 to obtain a reference sequence 702. In some embodiments, this duo-binary transformation may include transforming a binary sequence (for example, an OOK sequence) into a duo-binary sequence (for example, a DB sequence), or transforming a four-level pulse amplitude modulation (PAM4) sequence into a duo-binary PAM4 sequence.

[0062] At block 615, the estimator initialization module 210 obtains a distorted training sequence 703 of the training sequence 701 after transmission through a channel and the duo-binary transformation. Specifically, in some embodiments, the transmitters 410 and 411 in FIG. 4 may transmit the known training sequence 701 on the optical link 420, such that the estimator initialization module 210 may receive, at the receiver 430, the distorted training sequence 703 after transmission through the channel and the duo-binary transformation. In other embodiments, the training sequence 701 may also be transmitted by other modules or components onto the channel and thus transmitted to the receiver 430.

[0063] At block 620, the estimator initialization module 210 determines a channel coefficient sequence 704 of the channel based on the reference sequence 702 and the distorted training sequence 703. In some embodiments, the estimator initialization module 210 may learn the channel coefficient sequence 704 of the channel through an iterative procedure.

[0064] In particular, as shown in FIG. 7, the estimator initialization module 210 may obtain an intermediate training sequence (not shown) by multiplying via a multiplier 720 the distorted training sequence 703 after processing of a delay module 710 by a current channel coefficient sequence ($a_0, a_1, a_2 \dots$) and adding together via a summer 730. Then, the

intermediate training sequence is compared with the reference sequence 702 in an error function module 740. Specifically, the error function module 740 compares a difference between the intermediate training sequence and the reference sequence 702 to a threshold. It should be appreciated that the threshold may be preset according to an implementation environment and/or a design objective.

[0065] Further, a decision module 750 may determine whether the difference between the intermediate training sequence and the reference sequence 702 is less than the threshold. If the difference is less than or equal to the threshold, which indicates convergence of the learning procedure for the channel coefficient, the decision module 750 may output the current channel coefficient sequence ($a_0, a_1, a_2 \dots$) to the estimator module 220 as the channel coefficient sequence 704.

[0066] If the difference is greater than the threshold, this indicates that the learning procedure of the channel coefficient has not converged. In this event, the estimator initialization module 210 may adjust the current channel coefficient sequence ($a_0, a_1, a_2 \dots$). For example, such adjustment may be performed with an equation given in FIG. 7, where ' μ ' represents a preset constant value, ' ϵ ' represents a preset threshold, and ' i ' represents the number of iterations. It should be noted that the estimator initialization module 210 adjusting the current channel coefficient sequence ($a_0, a_1, a_2 \dots$) through the specific equation is only a specific example. It will be appreciated by those skilled in the art that, in other embodiments, the current channel coefficient sequence ($a_0, a_1, a_2 \dots$) may be adjusted in any appropriate way such that the learning procedure of the channel coefficient converges.

[0067] Referring back to FIG. 6, at block 625, the estimator module 220 obtains a distorted signal sequence 214 of the signal sequence 401 after transmission through the channel and the duo-binary transformation. Specifically, the transmitters 410 and 411 in FIG. 4 may transmit the signal sequence 401 on the optical link 420, such that the estimator module 220 may receive in the receiver 430 the distorted signal sequence 214 after transmission through the channel and the duo-binary transformation.

[0068] At block 630, the estimator module 220 determines an estimation 215 of the signal sequence 401 based on the channel coefficient sequence 704 and the distorted signal sequence 214. For example, in the case of using the MLSE algorithm, the estimator module 220 may determine the estimation 215 of the signal sequence 401 by using the channel coefficient sequence 704 and the distorted signal sequence 214 as an input to the MLSE algorithm.

[0069] It should be appreciated that the estimator module 220 may determine the estimation 215 of the signal sequence 401 in other manners. A further embodiment in which the estimator module 220 determines the estimation 215 of the signal sequence 401 will be described below with reference to FIG. 8. Most modules or components in FIG. 8 are the same or similar to those in FIG. 7 and thus the description thereof is omitted.

[0070] As shown, a difference between FIG. 8 and FIG. 7 mainly lies in that, when the current channel coefficient sequence ($a_0, a_1, a_2 \dots$) is determined by the decision module 750 to be converged, the estimator initialization module 210 performs the distortion compensation on the distorted signal sequence 214 in the estimator initialization module 210 based on the channel coefficient sequence 704, i.e., the current channel coefficient sequence ($a_0, a_1, a_2 \dots$), and then inputs a distortion compensated signal sequence 801 to the estimator module 220, rather than providing, via the decision module 750, to the estimator module 220 the current channel coefficient sequence ($a_0, a_1, a_2 \dots$) as the channel coefficient sequence 704.

[0071] To this end, unlike in FIG. 7, the distorted signal sequence 214 is input to the estimator initialization module 210. In addition, a fourth pre-set input 802 is added to the estimator module 220, which is a default duo-binary channel coefficient. In other words, in the embodiment as shown in FIG. 8, the estimator module 220 can operate similarly to a conventional estimator. This is because the signal sequence 801 input to the estimator module 220 is already compensated based on the learned channel coefficient 704.

[0072] Therefore, in the case that the estimator module 220 uses the MLSE algorithm, the estimator module 220 may determine an undistorted channel coefficient sequence 802 of an undistorted duo-binary channel (for example, as a fourth pre-input), and determines the estimation 215 of the signal sequence 401 by using the distorted signal sequence 801 after the distortion compensation and the undistorted channel coefficient sequence 802 as an input of the MLSE algorithm.

[0073] FIG. 9 illustrates a block diagram of a device 900 suitable for implementing embodiments of the present disclosure. In some embodiments, the device 900 may be used to implement the method 600 implemented at the receiver 430 according to the embodiments of the present disclosure. In other embodiments, the device 900 may be used to implement the channel estimation-assisted signal estimation module 440 as shown in FIG. 4 or FIG. 7 or a part thereof.

[0074] As shown in FIG. 9, the device includes a controller 910. The controller 910

controls operations and functionalities of the device 900. For example, in some embodiments, the controller 910 can execute various operations by means of instructions 930 stored in a memory 920 coupled thereto. The memory 920 can be of any appropriate type applicable to the local technical environment, and can be implemented using any appropriate data storage technique, including but not limited to a storage device of a semiconductor, a magnetic storage device and system, and an optical storage device and system. Although only a memory module is shown in FIG. 9, there may be a plurality of physically different memory modules in the device 900.

[0075] The controller 910 can be of any appropriate type applicable to the local technical environment, and can include, but are not limited to, a general purpose computer, a special purpose computer, a microcontroller, a digital signal processor (DSP) and one or more in controller-based multi-core controller architecture. The device 900 may also include a plurality of controllers 910. The controller 910 is coupled to a transceiver 940, and the transceiver 940 can implement receiving and transmission of information via one or more antennas 950 and/or other components.

[0076] When the device 900 acts as the channel estimation-assisted signal estimation module 440 depicted in FIG. 4, 7 or 8, the controller 910 and the transceiver 940 can operate in cooperation to implement the method 600 as described above with reference to FIG. 6. All features as described with reference to FIG. 4 through FIG. 8 are applicable to the device 900, which is omitted herein.

[0077] FIG. 10 illustrates a simulated performance-comparison graph of embodiments of the present disclosure against a conventional solution. As shown in FIG. 10, the horizontal axis represents signal-to-noise ratio (SNR) in decibel (dB) and the vertical axis represents bit error ratio (BER). The curve 1001 in the inset at the lower left of FIG. 10 represents a channel pulse response under a given channel coefficient, while the curve 1002 represents an ideal duo-binary pulse response.

[0078] Furthermore, the curve 1003 represents a curve of the BER varying with the SNR in a direct detection solution without any processing. The curve 1004 represents a curve of the BER varying with the SNR in a solution using a feed forward equalizer (FFE) (which has an 8-tap finite impulse response (FIR) filter based on the Least Mean Square (LMS) algorithm). The curve 1005 represents a curve of the BER varying with the SNR in an MLSE solution using a default duo-binary channel coefficient. The curve 1006 represents a curve of the

BER varying with the SNR in an MLSE solution using a channel coefficient obtained by learning according to embodiments of the present disclosure.

[0079] It can be seen from FIG. 10 that the solution according to embodiments of the present disclosure can achieve a lower bit error ratio under the same signal-to-noise ratio, particularly when the SNR is high. As such, the solution according to embodiments of the present disclosure can achieve better performance than other simulated solutions.

[0080] FIG. 11 illustrates another simulated performance-comparison graph of embodiments of the present disclosure against a conventional solution. As shown in FIG. 11, the horizontal axis represents received signal power in dBm and the vertical axis represents bit error ratio (BER).

[0081] In FIG. 11, the curve 1101 and the curve 1102 represent curves of the BER varying with the received signal power in a direct detection solution with 20km optical transmission and without optical transmission, respectively, without any processing. The curve 1103 and the curve 1104 represent curves of the BER varying with the received signal power in a solution using a feed forward equalizer (FFE) (which has an 8-tap finite impulse response (FIR) filter based on the Least Mean Square (LMS) algorithm) with 20km optical transmission and without optical transmission, respectively. The curve 1105 and the curve 1106 represent curves of the BER varying with the received signal power in an MLSE solution using a default duo-binary channel coefficient with 20km optical transmission and without optical transmission, respectively. The curve 1107 and the curve 1108 represent curves of the BER varying with the received signal power in an MLSE solution using a channel coefficient obtained by learning according to embodiments of the present disclosure, with 20km optical transmission and without optical transmission, respectively.

[0082] It can be seen from FIG. 11 that, due to strong bandwidth filtering, the signals are distorted severely and can hardly be recognized even using the direct MLSE. However, by utilizing appropriate channel compensation and an improved MLSE according to embodiments of the present disclosure, a significant improvement may be achieved. That is, the solution according to embodiments of the present disclosure can achieve a lower bit error ratio under the same received signal power, particularly when the received signal power is high.

[0083] FIG. 12 illustrates a graph of an experimental test according to embodiments of the present disclosure. As shown in FIG. 12, the horizontal axis represents frequency in GHz

and the vertical axis represents normalized magnitude in decibel (dB). The reference number 1201 illustrates a directly received eye diagram, the reference number 1202 illustrates an eye diagram after channel learning, and the reference number 1203 illustrates a channel pulse response obtained by learning.

5 [0084] In the experimental test, a 10G-B/s PAM4 (i.e., at 20Gb/s bit rate) signal is transmitted to a direct modulation laser (DML) having a 2.7Ghz@3dB bandwidth. As illustrated by the reference number 1201, the eye diagram of the duo-binary PAM4 directly received shows poor performance. However, as illustrated by the reference number 1202, the eye diagram after the channel learning may be improved. Specifically, the BER is
10 increased from $1.2\text{E-}1$ (i.e., 1.2×10^{-3}) to $5.2\text{E-}3$. Thereafter, the MLSE is implemented and the BER is further reduced below $3\text{E-}3$ to satisfy requirements of a particular forward error correction (FEC) threshold. This demonstrates that a signal rate of 20Gb/s can be reached using merely 2.5G-class transmitters and receivers, which achieves 8 times of spectrum efficiency.

15 [0085] FIG. 13 illustrates a graph of a further experimental test according to embodiments of the present disclosure. As shown in FIG. 13, the horizontal axis represents frequency in GHz and the vertical axis represents normalized magnitude in decibel (dB). The reference number 1301 illustrates a directly received eye diagram, the reference number 1302 illustrates an eye diagram after channel learning, and the reference number 1303 illustrates a channel
20 pulse response obtained by learning.

[0086] In the experimental test, a 25G-B/s PAM4 (i.e., at a 50Gb/s bit rate) signal is squeezed to an end-to-end 4.6GHz@3dB bandwidth-limited channel. As illustrated by the reference number 1301, the eye diagram of the duo-binary PAM4 directly received shows poor performance. However, as illustrated by the reference number 1302, the eye diagram
25 after the channel learning can be improved. Specifically, the BER is increased from $1\text{E-}1$ to $2\text{E-}3$. Thereafter, the MLSE is implemented and the BER is further reduced below $6\text{E-}4$. In contrast, the typical MLSE using a default channel coefficient only reduces the BER to $5\text{E-}2$.

[0087] The above-mentioned simulations and experiments demonstrate that the
30 embodiments of the present disclosure can significantly improve accuracy of an estimation of a signal sequence after a duo-binary transformation, by implementing an adaptive channel learning prior to signal sequence estimation. Through the embodiments of the present

disclosure, data transmission with a peak rate of 20Gb/s can be achieved for duo-binary PAM4 signals using a 2.7G-3db bandwidth DML laser in a condition that the BER is $3.8E-3$, and 50Gb/s data transmission can be achieved with a 4.6G-3dB bandwidth using a typical 10GHz-bandwidth device. Furthermore, under a varying channel coefficient, the
5 embodiments of the present disclosure are also effective to improve the correctness. In other words, the embodiments of the present disclosure are adaptive and intelligent for different communication devices (for example, ONUs in a PON system), particularly in the uplink direction.

[0088] As used herein, the term “determining” covers various acts. For example,
10 “determining” may include operation, calculation, process, derivation, investigation, search (for example, search through a table, a database or a further data structure), identification and the like. In addition, “determining” may include receiving (for example, receiving information), accessing (for example, accessing data in the memory) and the like. Further, “determining” may include resolving, selecting, choosing, establishing and the like.

[0089] It will be noted that the embodiments of the present disclosure can be implemented
15 in software, hardware, or a combination thereof. The hardware part can be implemented by a special logic; the software part can be stored in a memory and executed by a suitable instruction execution system such as a microprocessor or a special purpose hardware. Those skilled in the art would appreciate that the above device and method may be implemented
20 with computer executable instructions and/or in processor-controlled code, and for example, such code is provided on a carrier medium such as a programmable memory or an optical or electronic signal bearer.

[0090] Further, although operations of the method according to the present disclosure are described in a particular order in the drawings, it does not require or imply that these
25 operations are necessarily performed according to this particular sequence, or a desired outcome can only be achieved by performing all shown operations. On the contrary, the execution order for the steps as depicted in the flowcharts may be varied. Alternatively, or in addition, some steps may be omitted, a plurality of steps may be merged into one step, or a step may be divided into a plurality of steps for execution. It will also be noted that the
30 features and functions of two or more units of the present disclosure may be embodied in one apparatus. In turn, the features and functions of one unit described above may be further embodied in more units.

[0091] Although the present disclosure has been described with reference to various embodiments, it should be understood that the present disclosure is not limited to the disclosed embodiments. The present disclosure is intended to cover various modifications and equivalent arrangements included in the spirit and scope of the appended claims.

I/We Claim:

1. A method implemented at a receiver, the receiver configured to receive a signal sequence through a bandwidth-limited channel, the method comprising:

performing a duo-binary transformation on a training sequence known to the receiver
5 to obtain a reference sequence;

obtaining a distorted training sequence for the training sequence after transmission through the channel and the duo-binary transformation;

determining a channel coefficient sequence of the channel based on the reference sequence and the distorted training sequence;

10 obtaining a distorted signal sequence for the signal sequence after transmission through the channel and the duo-binary transformation; and

determining an estimation of the signal sequence based on the channel coefficient sequence and the distorted signal sequence.

15 2. The method of claim 1, wherein performing the duo-binary transformation on the training sequence to obtain the reference sequence comprises:

transforming a binary sequence into a duo-binary sequence; or

transforming a four-level pulse amplitude modulation (PAM4) sequence into a duo-binary PAM4 sequence.

20 3. The method of claim 1, wherein determining the channel coefficient sequence of the channel comprises performing the following operations for at least one time:

obtaining an intermediate training sequence based on a convolution of the distorted training sequence and a current channel coefficient sequence of the channel;

25 comparing a difference between the intermediate training sequence and the reference sequence with a threshold; and

in response to determining that the difference is greater than the threshold, adjusting the current channel coefficient sequence.

30 4. The method of claim 1, wherein determining the estimation of the signal sequence comprises:

determining the estimation of the signal sequence using a maximum likelihood sequence estimation algorithm.

5. The method of claim 4, wherein determining the estimation of the signal sequence using the maximum likelihood sequence estimation algorithm comprises:

determining the estimation of the signal sequence by using the channel coefficient sequence and the distorted signal sequence as an input to the maximum likelihood sequence estimation algorithm.

6. The method of claim 4, wherein determining the estimation of the signal sequence using the maximum likelihood sequence estimation algorithm comprises:

performing distortion compensation on the distorted signal sequence based on the channel coefficient sequence;

determining an undistorted channel coefficient sequence of an undistorted duo-binary channel; and

determining the estimation of the signal sequence by using the distorted signal sequence after the distortion compensation and the undistorted channel coefficient sequence as an input to the maximum likelihood sequence estimation algorithm.

7. A communication device comprising a receiver configured to receive a signal sequence through a bandwidth-limited channel, the communication device comprising:

at least one processor; and

at least one memory including computer-executable instructions, the at least one memory and the computer-executable instructions configured, with the at least one processor, to cause the communication device to:

perform a duo-binary transformation on a training sequence known to the receiver to obtain a reference sequence;

obtain a distorted training sequence for the training sequence after transmission through the channel and the duo-binary transformation;

determine a channel coefficient sequence of the channel based on the reference sequence and the distorted training sequence;

obtain a distorted signal sequence for the signal sequence after transmission through the channel and the duo-binary transformation; and

determine an estimation of the signal sequence based on the channel coefficient sequence and the distorted signal sequence.

8. The communication device of claim 7, wherein the at least one memory and the computer executable instructions are further configured, with the at least one processor, to cause the communication device to:

transform a binary sequence into a duo-binary sequence; or

5 transform a four-level pulse amplitude modulation (PAM4) sequence into a duo-binary PAM4 sequence.

9. The communication device of claim 7, wherein the at least one memory and the computer executable instructions are further configured, with the at least one processor, to
10 cause the communication device to perform the following operations for at least one time:

obtaining an intermediate training sequence based on a convolution of the distorted training sequence and a current channel coefficient sequence of the channel;

comparing a difference between the intermediate training sequence and the reference sequence with a threshold; and

15 in response to determining that the difference is greater than the threshold, adjusting the current channel coefficient sequence.

10. The communication device of claim 7, wherein the at least one memory and the computer executable instructions are further configured, with the at least one processor, to
20 cause the communication device to:

determine the estimation of the signal sequence using a maximum likelihood sequence estimation algorithm.

11. The communication device of claim 10, wherein the at least one memory and the
25 computer executable instructions are further configured, with the at least one processor, to cause the communication device to:

determine the estimation of the signal sequence by using the channel coefficient sequence and the distorted signal sequence as an input to the maximum likelihood sequence estimation algorithm.

30

12. The communication device of claim 10, wherein the at least one memory and the computer executable instructions are further configured, with the at least one processor, to cause the communication device to:

perform distortion compensation on the distorted signal sequence based on the channel

coefficient sequence;

determine an undistorted channel coefficient sequence of an undistorted duo-binary channel; and

5 determine the estimation of the signal sequence by using the distorted signal sequence after the distortion compensation and the undistorted channel coefficient sequence as an input to the maximum likelihood sequence estimation algorithm.

10 13. A computer program product tangibly stored on a non-volatile computer executable medium and comprising machine executable instructions, the machine executable instructions, when executed, causing a machine to perform steps of the method of any of claims 1-6.

14. A receiver for use in a communication device, comprising:

15 a duo-binary transformation module configured to perform a duo-binary transformation on a training sequence known to the receiver to obtain a reference sequence;

a channel estimation module configured to:

obtain a distorted training sequence for the training sequence after transmission through the channel and the duo-binary transformation, and

20 determine a channel coefficient sequence of the channel based on the reference sequence and the distorted training sequence; and

a signal estimation module configured to:

obtain a distorted signal sequence for the signal sequence after transmission through the channel and the duo-binary transformation, and

25 determine an estimation of the signal sequence based on the channel coefficient sequence and the distorted signal sequence.

15. The receiver of claim 14, wherein the duo-binary transformation module is further configured to:

transform a binary sequence into a duo-binary sequence; or

30 transform a four-level pulse amplitude modulation (PAM4) sequence into a duo-binary PAM4 sequence.

16. The receiver of claim 14, wherein the channel estimation module is configured to perform the following operations for at least one time:

obtaining an intermediate training sequence based on a convolution of the distorted training sequence and a current channel coefficient sequence of the channel;

comparing a difference between the intermediate training sequence and the reference sequence with a threshold; and

5 in response to determining that the difference is greater than the threshold, adjusting the current channel coefficient sequence.

17. The receiver of claim 14, wherein the signal estimation module is further configured to:

10 determine the estimation of the signal sequence using a maximum likelihood sequence estimation algorithm.

18. The receiver of claim 17, wherein the signal estimation module is further configured to:

15 determine the estimation of the signal sequence by using the channel coefficient sequence and the distorted signal sequence as an input to the maximum likelihood sequence estimation algorithm.

19. The receiver of claim 17, wherein the signal estimation module is further configured to:

20 perform distortion compensation on the distorted signal sequence based on the channel coefficient sequence;

determine an undistorted channel coefficient sequence of an undistorted duo-binary channel; and

25 determine the estimation of the signal sequence by using the distorted signal sequence after the distortion compensation and the undistorted channel coefficient sequence as an input to the maximum likelihood sequence estimation algorithm.

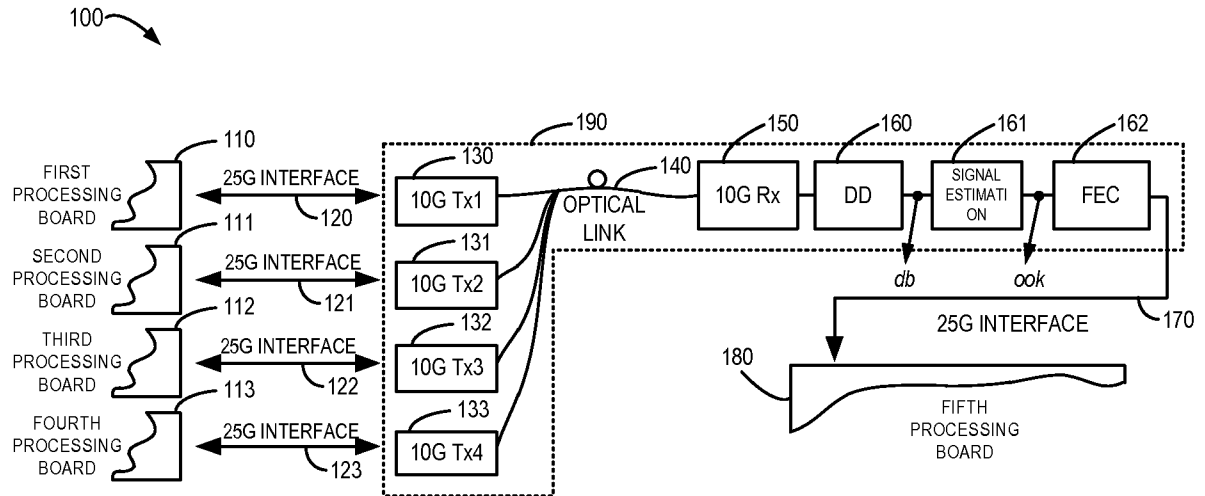


FIG. 1

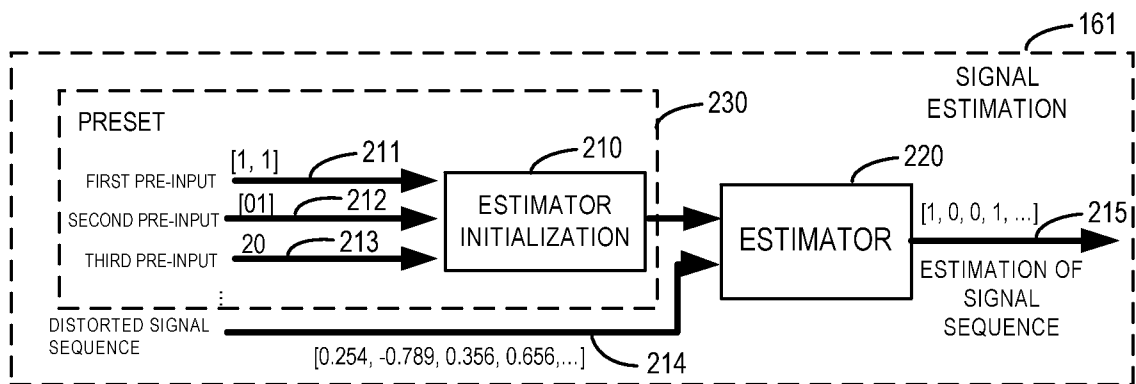


FIG. 2

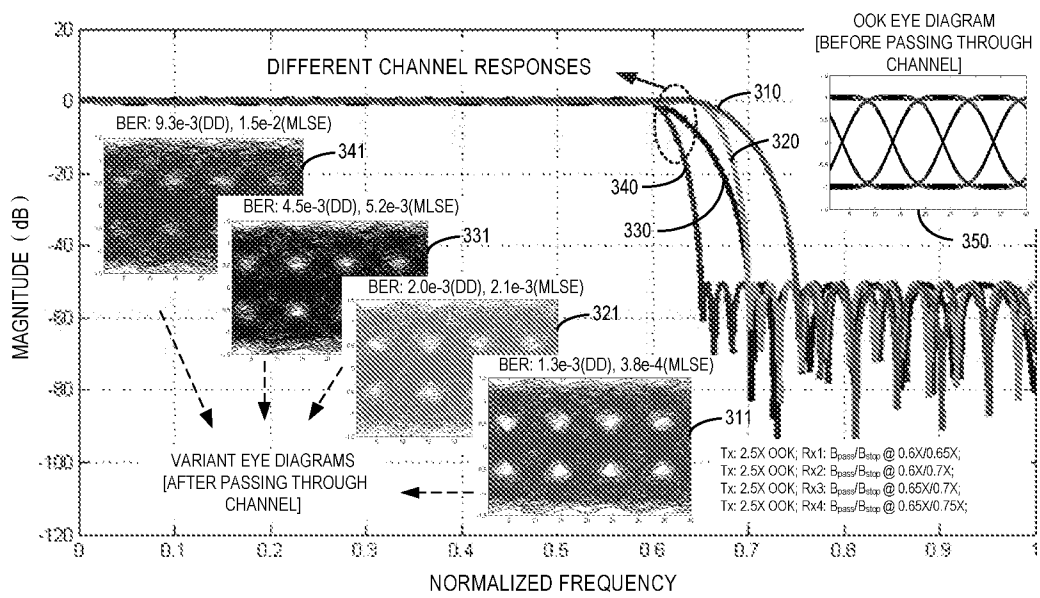


FIG. 3

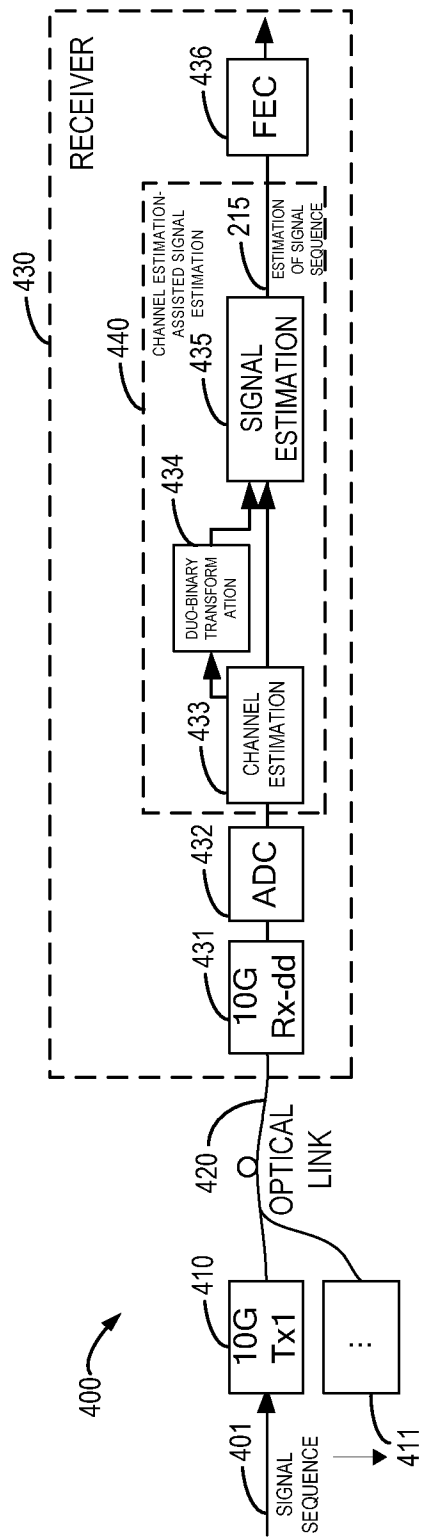


FIG. 4

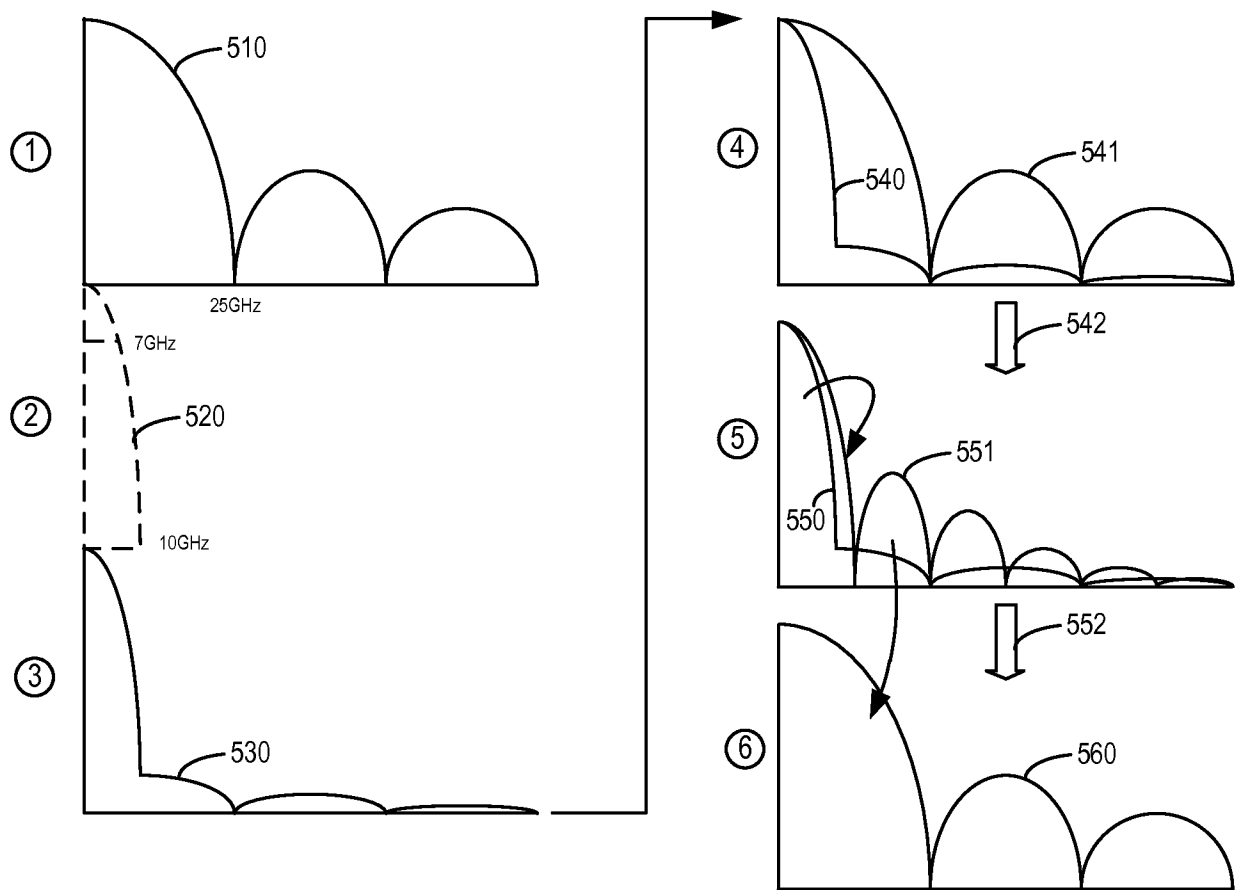
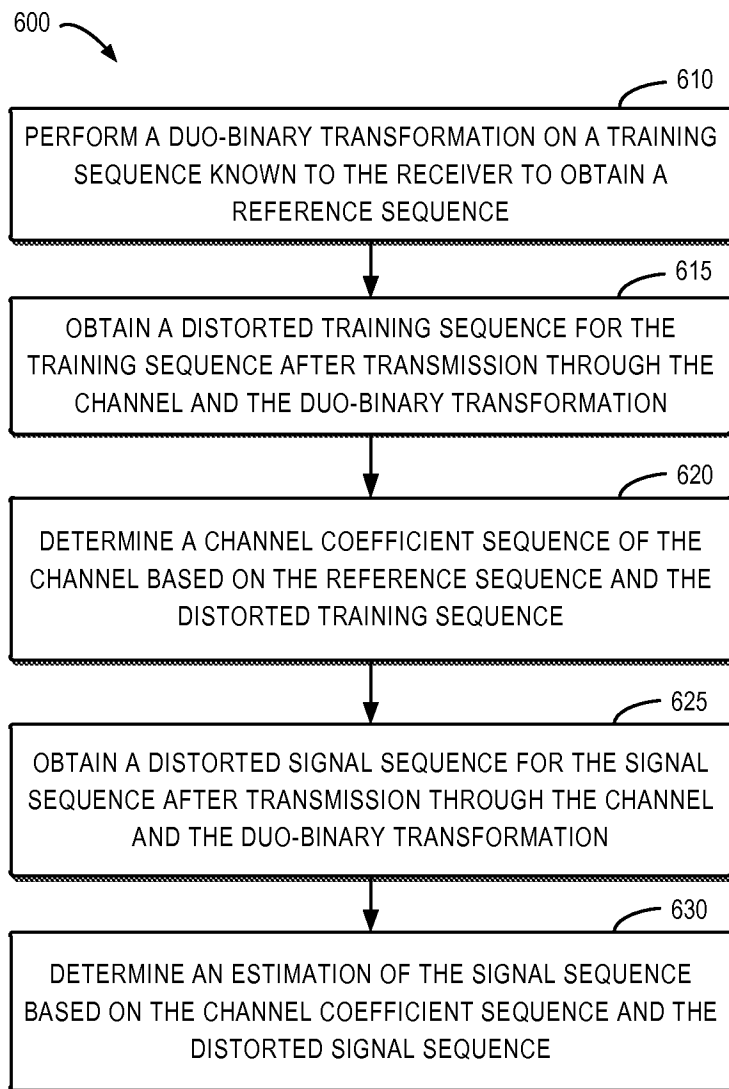


FIG. 5

**FIG. 6**

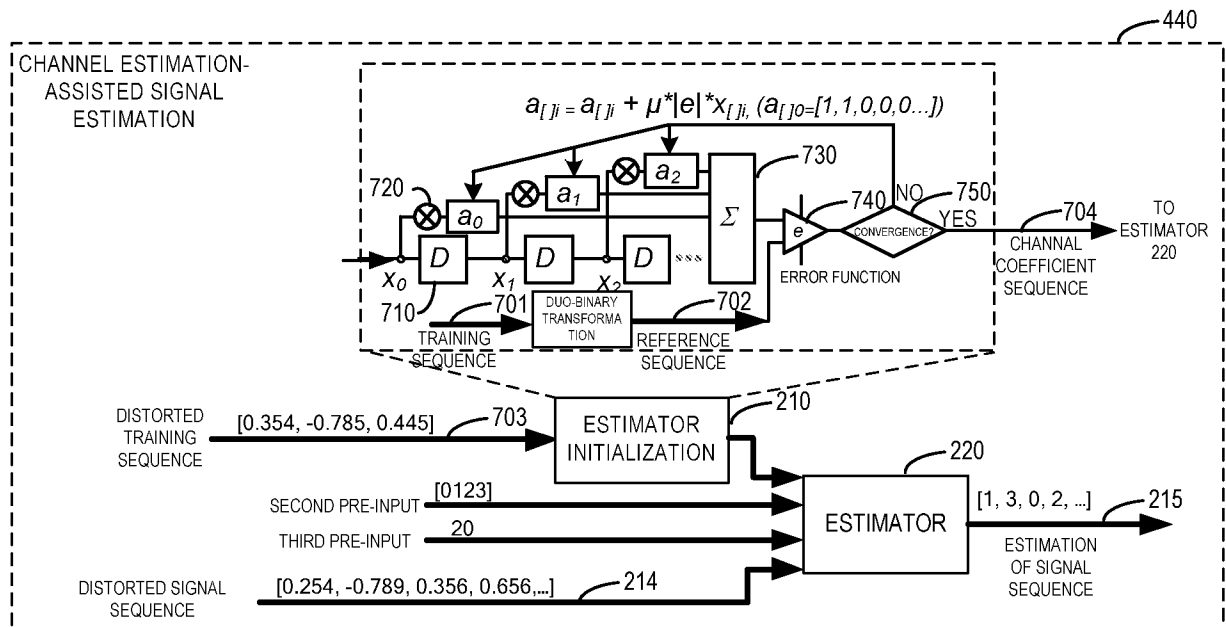


FIG. 7

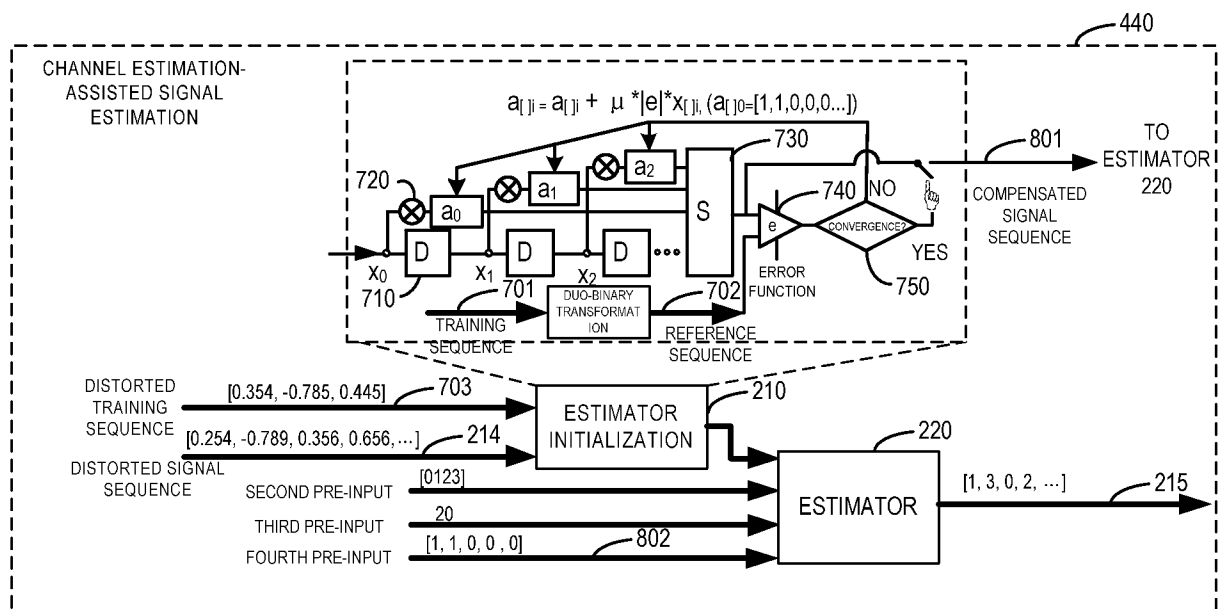


FIG. 8

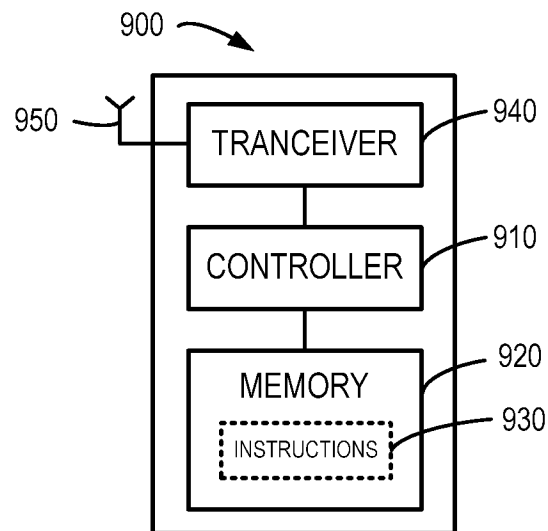


FIG. 9

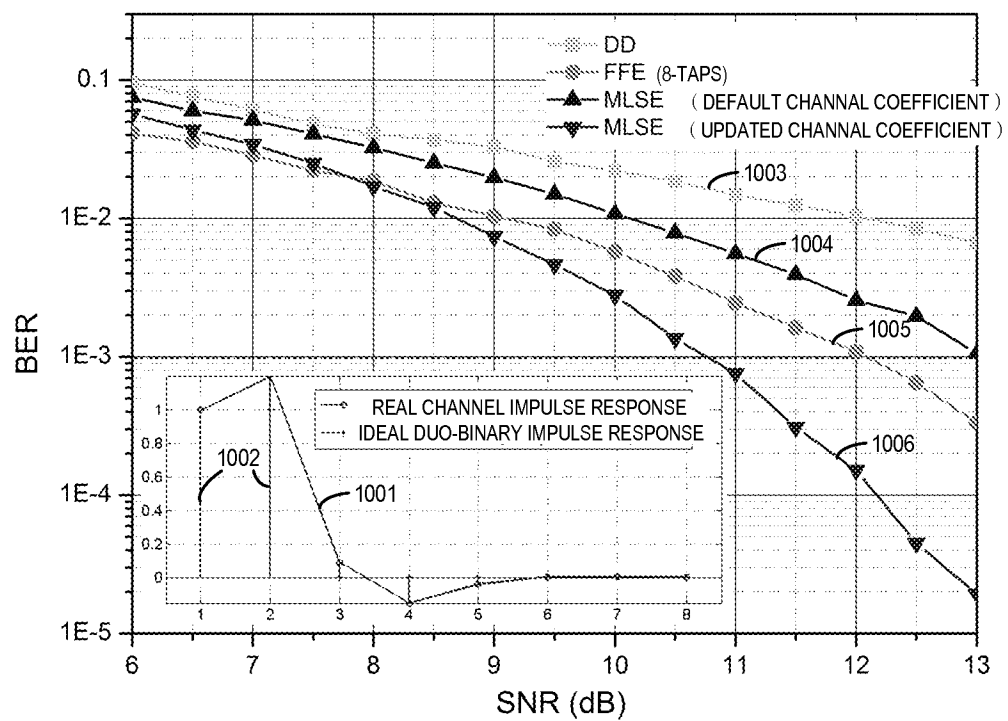


FIG. 10

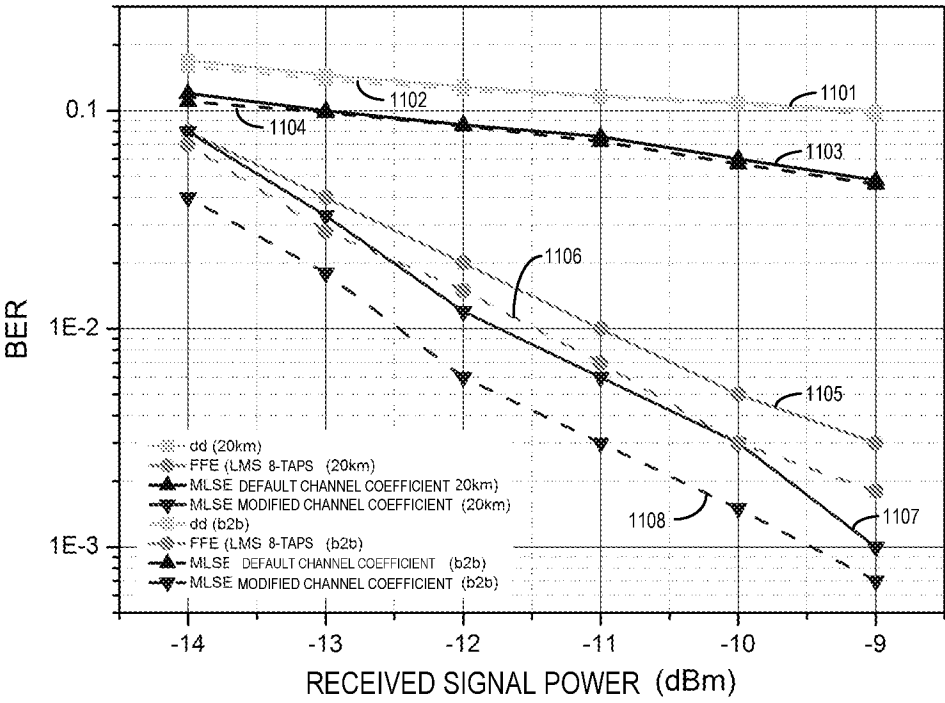


FIG. 11

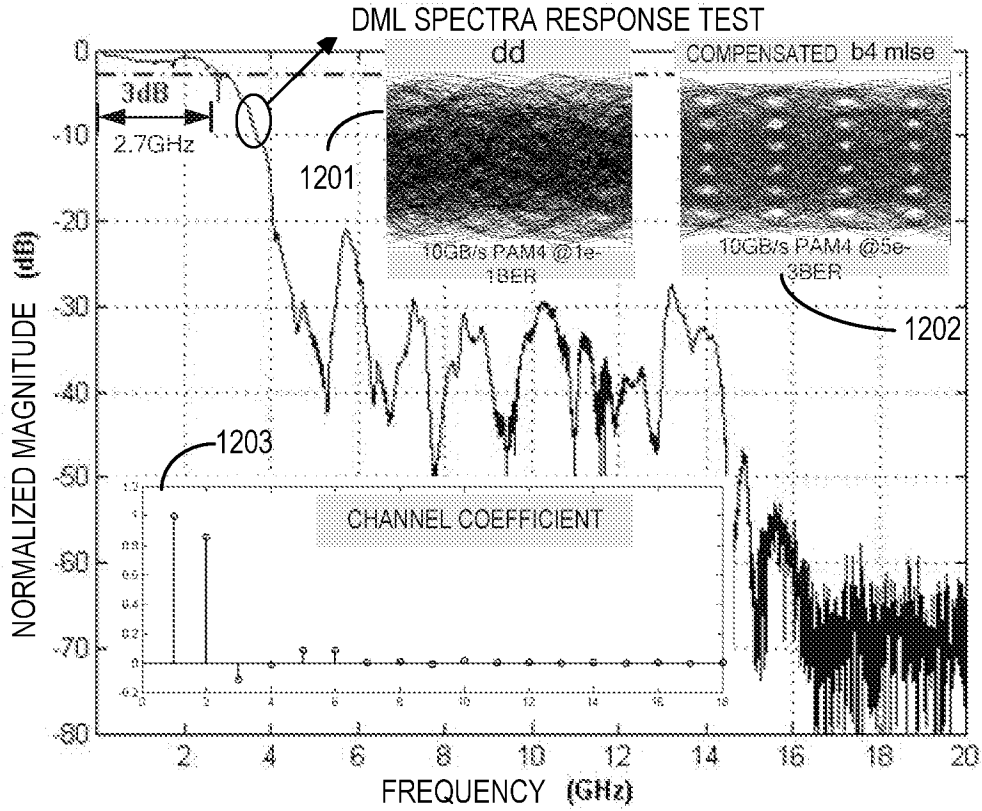


FIG. 12

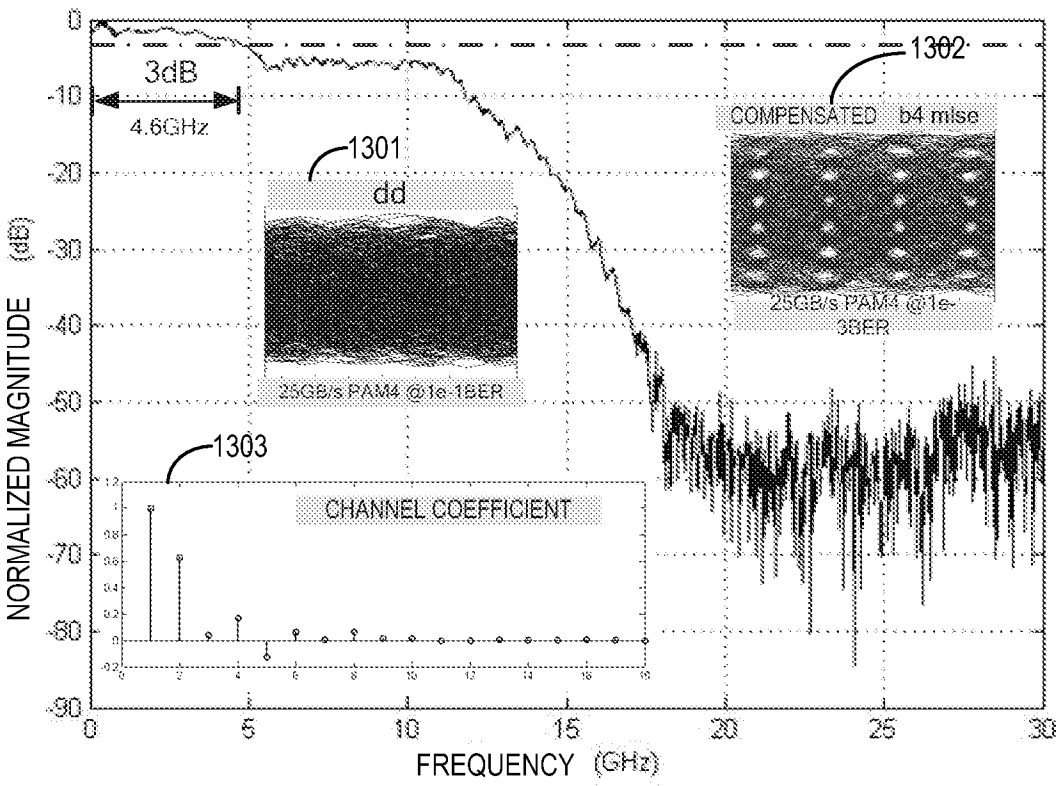


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2018/000591

A. CLASSIFICATION OF SUBJECT MATTER INV. H04L25/02 H04B10/516 H04L25/03 H04L25/49 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H04L H04B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	QI GUO ET AL: "20-Gb/s Single-Feeder WDM-PON Using Partial-Response Maximum Likelihood Equalizer", IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 23, no. 23, 1 December 2011 (2011-12-01), pages 1802-1804, XP011366327, ISSN: 1041-1135, DOI: 10.1109/LPT.2011.2169663 the whole document	1-19
A	----- US 2016/087821 A1 (CHEN E-HUNG [US]) 24 March 2016 (2016-03-24) paragraph [0013] - paragraph [0015]; figure 5 ----- -/-	1-19
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents :		
"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family	
Date of the actual completion of the international search 26 July 2018	Date of mailing of the international search report 02/08/2018	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer El Hajj Shehadeh, Y	

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2018/000591

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JIANQIANG LI ET AL: "Approaching Nyquist Limit in WDM Systems by Low-Complexity Receiver-Side Duobinary Shaping", JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 30, no. 11, 1 June 2012 (2012-06-01), pages 1664-1676, XP011440743, ISSN: 0733-8724, DOI: 10.1109/JLT.2012.2190972 Sections II-III -----	1-19
A	YANG CHAO ET AL: "IM/DD-Based 112-Gb/s/lambda PAM-4 Transmission Using 18-Gbps DML", IEEE PHOTONICS JOURNAL, IEEE, USA, vol. 8, no. 3, 1 June 2016 (2016-06-01), pages 1-7, XP011607966, DOI: 10.1109/JPHOT.2016.2555621 [retrieved on 2016-04-29] Sections 1-2 -----	1-19

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2018/000591

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2016087821 A1	24-03-2016	US 2014140389 A1	22-05-2014
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