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Optical signal-to-noise ratio estimator and estimation methodology for optical communication

Thrane, Jakob; Wass, Jesper; Zibar, Darko

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(71) Applicant: **DANMARKS TEKNISKE UNIVERSITET** [DK/DK]; Anker Engelunds Vej 101 A, 2800 Kgs. Lyngby (DK).

(72) Inventors: **THRANE, Jakob**; Aalborggade 24, 4. tv., 2100 Copenhagen Ø (DK). **WASS, Jesper**; Stærevej 34, 1.D, 2400 Copenhagen NV (DK). **ZIBAR, Darko**; Ellesvinget 93, 2950 Vedbæk (DK).

(74) Agent: **GUARDIAN IP CONSULTING I/S**; Diplomvej, Building 381, 2800 Kgs. Lyngby (DK).

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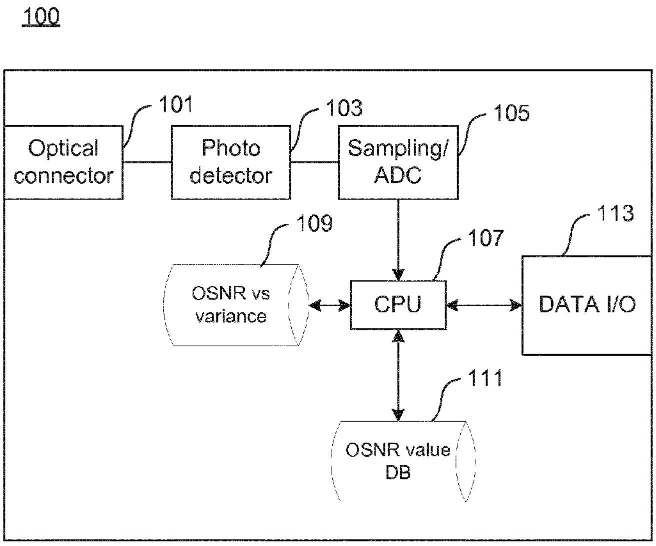

Fig. 1

(57) Abstract: The present invention provides a noise estimator for determining an optical signal-to-noise ratio (OSNR) value of a QAM optical signal. The noise estimator comprises an optical detector configured to directly detect the optical signal and provide an electrical QAM signal representing an instantaneous amplitude of the detected QAM optical signal. A signal processor is configured to determine a statistical parameter value of a predetermined probability density function representing a single fit to a power amplitude distribution of the QAM electrical signal at a first timing within a power eye diagram representation.

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OPTICAL SIGNAL-TO-NOISE RATIO ESTIMATOR AND ESTIMATION METHODOLOGY FOR OPTICAL COMMUNICATION

The present invention relates to estimation of noise properties of optical communication systems, in particular for complex modulation formats, such as quadrature amplitude modulation (QAM) formats.

BACKGROUND OF THE INVENTION

Information and communication technology has become essential to our standard of living. Cisco has presented an estimate of the global future data consumption that exceeds 18 Exabytes per month by the year 2018. To meet this demand, more efficient communication technologies are required.

In order to utilize the available optical spectrum optimally, advanced modulation schemes and so-called super channels are presently subjects to intense research. Some existing optical communication systems employ advanced modulation formats such as quadrature phase shift keying (QPSK) and/or quadrature amplitude modulation (QAM), for instance 16QAM, 64QAM or 256QAM, in some cases also together with polarization multiplexing.

Monitoring optical signal-to-noise-ratio (OSNR) is a vital element in configuration and maintenance of optical communication systems. The measured OSNR values provide insight into the quality of communication. However, the current OSNR measurement techniques are not useful in such state of the art systems. New equipment is required to solve this future issue.

Furthermore, existing OSNR estimation techniques are complex. Some methods that rely on integration of the optical spectrum are well-proven for estimating OSNR. However, these methods inherently require expensive equipment such as an optical spectrum analyzer, to perform the estimation.

Methods based on coherent detection are also complex since a coherent detector is needed in combination with demodulation algorithms before an estimate of the

OSNR can be produced. The reason is that these methods rely on a demodulated signal constellation diagram.

Another proposed method requires three photodiodes, an optical delay line, optical/electrical filters and an analog-to-digital converter. The method cannot be extended to high-order QAM formats such as 16QAM, 64QAM and 256QAM.

Neural networks for OSNR estimation have been proposed and demonstrated. However, such methods rely on a signal demodulation using delay demodulator prior to OSNR estimation.

Alternative methodologies for determining optical signal-to-noise ratios and corresponding noise estimators for reliably estimating OSNR values are therefore desirable in order to circumvent the complexity of the prior art measurement methods and equipment described above.

SUMMARY OF THE INVENTION

A first aspect of the present invention relates to a noise estimator for determining an optical signal-to-noise ratio (OSNR) value of a quadrature amplitude modulated (QAM) optical signal. The noise estimator comprising:

- an optical detector configured to directly detect the QAM optical signal and provide a QAM electrical signal representing an instantaneous amplitude of the detected QAM optical signal,
- a signal processor configured to determine at least one statistical parameter value, such as variance and/or mean value, of a predetermined probability density function representing a single fit to a power amplitude distribution of the QAM electrical signal at a first timing within a power eye diagram representation of the QAM electrical signal. The signal processor is furthermore configured to determine the OSNR value based on the at least one statistical parameter value.

The present invention uses power eye diagrams of the electrical QAM signal obtained from the direct detection of the QAM optical signal to estimate the OSNR. The present noise estimator, and a corresponding methodology for determining an

OSNR value of the QAM optical signal as discussed below, do not require signal demodulation. Elimination of the signal demodulation eliminates requirements for a complex coherent receiver and subsequent application of associated digital signal processing (DSP) algorithms. The latter would for example involve real-time calculation of constellation diagrams. Furthermore, the present noise estimator does not require any integration of optical spectra which eliminates the need for complex and costly optical spectrum analyzers.

The present noise estimator, and corresponding methodology of determining OSNR values, are easier to use while still generating reliable OSNR values for all types of QAM optical signals - for example 4QAM, 8QAM, 16QAM, 32QAM, 64QAM, 128QAM, 256QAM etc. The present noise estimator is also tolerant to common optical fiber channel impairments such as chromatic dispersion, phase noise, and noise from optical amplifiers.

Various types of predetermined probability density functions may be utilized by the present noise estimator, and the corresponding methodology, for fitting the measured power amplitude distribution of the QAM electrical signal. The predetermined probability density functions may comprise a Gaussian distribution or a gamma distribution.

The paper "Optical performance monitoring technique using software-based synchronous amplitude histograms" (DOI:10.1364/OE.22.024024) authored by Choi et al. describes a method of using eye-diagram-based amplitude histograms to determine a noise figure of an optical signal. The authors use multiple Gaussian functions to fit the determined amplitude histograms of a NRZ-16QAM signal. Based on a plurality of associated variances, a noise figure is determined. The number of Gaussians used in the fitting corresponds roughly to the number of visually identifiable features.

The present inventors have in contrast realized that fitting multiple Gaussian functions is cumbersome and imprecise for various reasons, in particular when there are many Gaussian components in the measured optical signal. The prior art methodology discussed above raises a number of unanswered questions and decisions: How many Gaussian functions should one use to resolve the histogram into individual Gaussians? Which eye bands are significant and should be taken into account and which could be left out; and what is the consequence of leaving out a Gaussian component of the utilized multiple Gaussian components? Furthermore, how is the plurality of identified variances to be combined to obtain a sort of noise figure? Should the plurality of identified variances be combined with equal weight, or with a weight corresponding to the weight of the eye band (by integrating the amplitude distribution around each band)? Choi et al. propose to use a weighted average of clearly identifiable eye bands.

The present inventors have realized that this prior art approach is rather arbitrary and cannot be extended to higher-order QAM formats such as 64QAM and higher. This insight has led the present inventors to discovering that, surprisingly, at least one statistical parameter value, such as variance and/or mean value, of a single predetermined probability density function (for example a Gaussian distribution), fitted to the measured power amplitude distribution corresponding to a specific timing of the eye diagram representation of the QAM electrical signal represents an accurate and reliable predictor or estimator of the OSNR of the QAM optical signal. This finding is contrary to prior art approaches such as the above-mentioned approach proposed by Choi et al.

Despite the straight-forward application of the present invention, the suggested approach provides an OSNR figure or value that can be interpreted consistently, independent of the characteristics of the optical communication system under investigation.

The present noise estimator and methodology furthermore handles highly complex modulation formats well, such as higher-order QAM formats, for instance 64QAM and higher which may be quite surprising. These higher-order QAM formats have quite complex eye diagrams due to the presence of corresponding 64 states, where each state has a unique corresponding amplitude and phase and each state is subjected to noise contributions. If the QAM optical signal under investigation or analysis is polarization-multiplexed, the eye diagram becomes even more complex.

Various transmission impairments further muddle the eye diagram even further. Resolving multiple Gaussian functions in an eye diagram of a 64QAM signal as proposed by the above-referenced prior art paper is simply impossible to do in a consistent manner while the proposed noise estimator and methodology handle such high-order QAM formats efficiently and supply accurate and predictable OSNR values.

The term "statistical parameter" comprises for example variance and/or mean or parameters derivable therefrom. Hence, the variance shall be interpreted broadly since any representation of the variance of the predetermined probability density function in question can be used by the noise estimator. This is one of many strengths of the present invention. The standard deviation, i.e. the square root of the variance, can be used instead of the "true" variance. Actually, any one-to-one representation of the variance may be used in place of the variance, although the simplest approach often is to use the variance (or inverse) or the standard deviation (or inverse), optionally multiplied or divided by the mean value of the amplitude distribution or the mean value squared.

In some embodiments, the determined OSNR value is determined based on an at least partly pre-determined noise relationship between a set of reference OSNR values and a corresponding set of reference statistical parameter values, wherein each reference OSNR value and corresponding reference statistical parameter value are determined based on a corresponding reference QAM optical signal from a training set of reference QAM optical signals.

In some embodiments, each reference OSNR value is determined based on a constellation representation of the corresponding reference QAM optical signal, and each reference statistical parameter value is a variance belonging to a predetermined probability density function, for example a best-fit probability density function, said predetermined probability density function being a best fit of a power amplitude distribution at the first timing within a power eye diagram representation of the corresponding reference QAM optical signal. This embodiment provides a very reliable and precise noise relationship, since the embodiment involves values obtained from the constellation diagram which is generally considered the best way to estimate the OSNR for QAM signals.

In some embodiments, the training set of reference QAM optical signals are based on real optical signals and the corresponding reference OSNR values are obtained from the corresponding constellation diagram representations, and the corresponding reference statistical parameter values are obtained by determining corresponding statistical parameter values from corresponding power amplitude distribution representations of the reference QAM optical signals. This embodiment of the noise estimator is well-suited to handle an optical system that operates with components similar to, or identical to, those components used for establishing the noise relationship.

In some embodiments, a first reference QAM optical signal of the training set has a first OSNR value, and a second reference QAM optical signal of the training set is obtained by adding noise to or subtracting noise from the first reference QAM optical signal; and a reference statistical parameter value for the second reference QAM optical signal is a statistical parameter belonging to a single predetermined probability density function, for example a single Gaussian distribution, said single predetermined probability density function being a best fit of a power amplitude distribution at the first timing within a power eye diagram representation of the second reference QAM optical signal; and a reference OSNR value of the second reference QAM optical signal is the OSNR value of the first reference optical signal plus or minus, as appropriate, an OSNR value of the added noise.

This approach allows a faster computation of the noise relationship since the methodology does not require the determination of constellation diagrams or manual or semi-automated measurements. Noise is simply added, and it is assumed that the added or subtracted noise reduces/increases the OSNR by a corresponding amount. The only thing left to do is calculate the statistical parameter values, e.g. variance values, of the QAM optical signals with the added or subtracted noise. This can be carried out easily by using a suitably programmed or configured computer. Training sets involving different fiber lengths for different fiber types, different polarization combinations and so on can be provided almost entirely automatically using models, of which there are already many that are well-established.

In some embodiments, the signal processor is configured to determine a timing at which the power eye diagram representation of the electrical signal has a minimum, and to use said timing as the first timing. In some embodiments, the signal processor is configured to determine a timing at which the power eye diagram representation of the electrical signal has a maximum, and to use said timing as the first timing. Some embodiments are capable of doing both.

In some embodiments, the first timing corresponds to a peak amplitude of an in-phase carrier signal of the QAM optical signal and/or to a peak amplitude of a quadrature carrier signal of the QAM optical signal. In some embodiments, the OSNR value is determined based on a first statistical parameter value corresponding to a first timing within the power eye diagram representation of the electrical signal and based on a second statistical parameter value corresponding to a second timing within the power eye diagram representation of the QAM electrical signal, where the first timing is different from the second timing.

Some embodiments of the noise estimator are configured to identify a modulation format, e.g. order, of the QAM optical signal by obtaining a first variance value at a first timing within the power eye diagram representation of the QAM electrical signal and obtaining a second variance value at a second timing within the power eye diagram representation of the QAM electrical signal, the first timing being different from the second timing. The modulation format may be identified or classified as the modulation format most likely to exhibit the first statistical parameter value at the first timing and the second statistical parameter value at the second timing.

The noise estimator embodiments with modulation format identification or classification capability may be based on a Support Vector Machine (SVM) and Neural Networks (NN) for modulation format identification. The noise estimator and corresponding noise estimation methodology may comprise:

1) sample the eye diagram and extract features that vary with modulation,
2) train classifier based on extracted features for given modulation format; and
3) use a trained classifier to classify a modulation format of new observed features.

The task of the classifier is to learn a mapping function. A linear SVM classifier may be trained in a supervised manner using input features obtained from the eye diagram and target classes. The target classes are assigned labels determining the modulation format. The training may be carried out using off-the-shelf tools such as the MATLAB R2015b classification toolbox or customized tools.

The modulation format identification or classification has been experimentally tested by the inventors using a SVM classifier comprising a multi-input feature such as an 8-D input feature associated with the QAM optical signal. The 8 features include minimum and maximum variance, minimum and maximum mean, mean, variance mean, the ratio between maximum and minimum variance and the difference between maximum and minimum variance. The 8 features were measured twice for 53 different OSNR values running from 4-30 dB with a 0.5 dB resolution. Each feature vector f are labeled, L, corresponding to the known modulation format to form the training data set $D = \{(f_i; L);i = 1,\ldots 106\}$. Four classes were defined corresponding to QPSK (optional), 8QAM, 16QAM and 64QAM using a RC pulse shape with a roll-off of 0.01. As only variance features are used for training, the classifier may lack a priori knowledge of the OSNR values. Thus, the classification functionality depends only on the 8-D input feature vector and the target label corresponding to the modulation format. Evaluation of the classification model is done using new feature measurements for each modulation format. An average classification accuracy of 94% was obtained. Similar classification accuracy has been achieved for less aggressive roll-off factors for RC pulse shaping as well as NRZ.

Some embodiments of the noise estimator comprise a relationship storage comprising a representation of the noise relationship. Such embodiments allow the noise estimator itself to convert a measured statistical parameter value to an OSNR value without the need for external equipment. By also adding a display, for example an LED or OLED computer screen, the determined OSNR can be displayed to a user of the noise estimator.

Some embodiments furthermore comprise a data input port configured to receive the noise relationship, and the noise estimator is furthermore configured to store the received noise relationship in the relationship storage. This allows the noise estimator to receive updated noise relationships, for instance representing a different modulation format or modulation order. Advantageously, the noise estimator can be updated at regular time intervals or as needed. The relationship storage may be integrated in a customized personal computer or a standard personal computer for example a laptop computer. The relationship storage may comprise a non-volatile memory such as a magnetic disc or semiconductor memory such as flash memory.

Some embodiments comprise an OSNR database configured to store determined OSNR values. By furthermore including a data output port, these values can be read out to another device.

Some embodiments of the noise estimator comprise:

- an optical connector configured to receive the QAM optical signal,
- a photodetector configured to detect the received QAM optical signal,
- a sampling device configured to provide the power amplitude distribution at the first timing, and a relationship storage configured to store the noise relationship. The sampling device may comprise an A/D converter.

A second aspect of the invention relates to a method of determining an OSNR value of a quadrature amplitude modulated (QAM) optical signal, wherein the method comprises:

- receiving the QAM optical signal at an optical detector,

- converting the QAM optical signal into a corresponding QAM electrical signal representing an instantaneous amplitude of the QAM optical signal, determining at least one statistical parameter value, such as variance and/or mean value, of a predetermined probability density function; wherein the predetermined probability density function represents a single fit, such as a best fit, to a power amplitude distribution at a first timing within a power eye diagram representation of the QAM electrical signal. The determining being based on an at least partly predetermined noise relationship between a set of reference OSNR values and a corresponding set of reference statistical parameter values, wherein each reference OSNR value and corresponding reference statistical parameter value are determined for a corresponding reference QAM optical signal from a training set of reference optical signals.

In some embodiments, the electrical signal corresponds to an electronic response of a photodetector receiving the optical signal.

The embodiments and considerations described in relation to the first aspect of the invention apply similarly to the second aspect.

BRIEF DESCRIPTION OF THE DRAWINGS

Several embodiments of the present invention are described in more detail below in connection with the appended drawings in which:

Figure 1 illustrates a noise estimator in accordance with an embodiment of the invention,
Figures 2a and 2b illustrate eye diagrams for two different 4QAM signals,
Figures 3a and 3b illustrate power amplitude distributions for the eye diagrams in Figures 2a and 2b,
Figures 4a-4c illustrate eye diagrams for three different 4QAM signals,
Figures 5a and 5b illustrate noise relationships, including variance figures for the eye diagrams depicted in Figures 4a-4c,
Figures 6a-6c illustrate respective eye diagrams for three different 16QAM signals,
Figures 7a and 7b illustrate noise relationships, including variance figures for the

eye diagrams depicted in Figures 6a-6c,

Figures 8a-8c illustrate eye diagrams for three different 64QAM signals,

Figures 9a and 9b illustrate noise relationships, including variance figures for the eye diagrams in Figures 8a-8c,

Figure 10 illustrate a system for obtaining a noise relationship for use in a noise estimator; and

Figures 11a and 11b illustrate various uses of a noise estimator in accordance with the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

Figure 1 illustrates one embodiment of a noise estimator 100 in accordance with the present invention. The noise estimator 100 comprises an optical connector 101 for receiving a QAM optical signal, a photodetector 103 for directly detecting the QAM optical signal to provide a corresponding QAM electrical signal, a sampler/ADC 105 for sampling the QAM electrical signal and construct an eye diagram, a noise relationship database 109 comprising the noise relationship, an OSNR value database 111 comprising determined OSNR values, and DATA I/O interface 113 for communicating information to and/or from the noise estimator, and a CPU 107 for determining variance values and converting them to OSNR values based on the noise relationship.

Fig. 2a and 2b illustrate eye diagrams for a single polarization 4QAM signal (Fig. 2a) and for a polarization-multiplexed 4QAM signal (Fig. 2b). The eye diagrams are calculated in a computer. The vertical lines near t=8 illustrate timings at which power amplitude distributions are obtained.

Fig. 3a shows a power amplitude distribution corresponding to the eye diagram in Fig. 2a and the timing shown by the vertical line in Fig. 2a. Three visually distinct power amplitude distribution peaks can be seen. In the prior art, each contributing Gaussian power amplitude distribution is analyzed and a corresponding variance extracted. By some formula, the plurality of variances is combined to provide a noise figure. The present invention preferably relies on the fitting of a single probability density function. A statistical parameter value or figure, such as a variance value, a mean value etc. is used for determining the corresponding OSNR value.

One way to determine the statistical parameter value is to fit the power amplitude distribution to the selected type of probability density function, such as a Gaussian probability distribution, using for instance at least squares method. In certain embodiments, a single statistical parameter value such as the variance value may be utilized which provides a particularly simple way of calculating the statistical parameter value. The advantages cannot easily be overstated. If $\{X\}$ is the set of *n* power amplitude samples at the selected timing (such as t=8 as in Figs. 2a-2b), the variance can be directly calculated as

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2$$

where

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$

is the mean of the power amplitude samples. In other words, the variance can be determined dynamically with relatively little computational power.

In case more than one Gaussian distribution is used to describe the power amplitude distribution, a fitting algorithm such as an expectation-maximization algorithm would be a useful way of establishing the most appropriate number of Gaussian distribution functions needed to describe the observed power amplitude distribution, and the variance and mean of the individual Gaussian distributions. This is computationally significantly more complex. Furthermore, the higher the order of the modulation format, and the higher the noise level, the more smeared the amplitude distribution will be, and the more complicated the fitting process will be, and the less precise the result will be. Using only a single statistical parameter value, e.g. the variance value, is a surprisingly effective way of determining the OSNR.

The expression above precisely corresponds to a best-fit Gaussian variance value. Therefore, the calculation above corresponds to fitting the observed power amplitude distribution with a single Gaussian distribution in accordance with some embodiments of the invention.

Fig. 3b shows a power amplitude distribution corresponding to the eye diagram in Fig. 2b and the timing shown by the vertical line in Fig. 2b. The QAM optical signal comprises two polarizations. Now, five visually distinct Gaussian distribution peaks can be seen. Again, the prior art encourages the person skilled in the art to extract individual variances, with five being the obvious number of Gaussian distributions to use. Fig. 4a illustrates another eye diagram corresponding to a 4QAM polarization-multiplexed optical signal. The two polarizations do not overlap. It has five levels, and is similar (but not identical) to the illustration in Fig. 2b.

Fig. 4b illustrates partly overlapping polarizations. One polarization is 45 degrees ahead of the other. The eye is somewhat more complicated than that in Fig. 4a, having many additional levels, caused by the phase difference.

Fig. 4c illustrates a single polarization 4QAM signal. It has three levels, and is similar (but not identical) to the illustration in Fig. 2a.

The eyes in Figs. 4a-4c are a back-to-back situation, i.e. there is no distortion due to propagation in an optical fiber.

Fig. 5a illustrates a significant feature of the invention, namely a relationship between the OSNR and the measured or observed value of the statistical parameter in question such as the depicted variance, in this case for the specific eye diagram in Fig. 4c. Case A and Case B correspond to the two vertical lines shown in Fig. 4c. It shows that the variance depends on the timing at which the power amplitude distribution is obtained. The different OSNR values are obtained by adding noise with increasing OSNR to an optical signal. The corresponding variance values are obtained by performing the fitting illustrated with Figs. 2a-2b and Figs. 3a-3b. Fig.

5a furthermore illustrates the relationship after propagation through 100 km optical fiber and 200 km optical fiber.

Fig. 5b illustrates the relationship between OSNR and variance values for a two-polarization 4QAM signal. Fig. 5b depicts the results for the timings "A" and "B" shown in Figs. 4a and 4b (the back-to-back scenario), for 100 km fiber propagation and for 200 km fiber propagation.

When deploying an optical link in the field the fiber length and the transmitter OSNR are both well-known variables. By measuring the values of the selected statistical parameter at the receiver end using various embodiments of the present invention, an OSNR value can be computed or determined using the noise relationship - for instance computed as described above. This is possible even without a receiver by connecting the fiber to the noise estimator. By a priori established relationships for a number of fiber lengths, interpolation or other algorithms can be used to obtain an approximate relationship for instance for other fiber lengths. By pre-establishing the relationship for many scenarios, the estimation can be made precise for many different fiber lengths. By establishing the relationship for instance for other types of fiber and/or other modulation formats, the noise estimator can be used in the field (or laboratory) for such configurations as well.

Figs. 6a-6c are similar to Figs. 4a-4c expect for the modulation format of the optical signal which is 16QAM in Figs. 6a-6c. Figs. 6a and 6b are optical signals with two polarizations. In Fig. 6a, the two polarizations are non-overlapping. In Fig. 6b the polarizations overlap by 45 degrees which leads to a more smeared eye compared to Fig. 6a.

Fig. 6c illustrates an eye diagram for an optical signals with a single polarization. It is clear that for the single polarization signal, it is relatively straightforward to extract at least some Gaussian components, in particular at timing "A". At timing "B", however, the situation gets significantly more complicated, and resolving a fair number of Gaussian components is both complicated and error prone. As discussed previously, another very important question is: How should the extracted variances be combined to arrive at a representative OSNR value? As mentioned previously, the present invention may rely on one or more statistical parameter value(s) for example a variance value, be it at timing "A" or at timing "B" or some other timing if desired or required. The obtained result can be converted to a corresponding OSNR value in a straight-forward manner. Fitting multiple Gaussians, for instance by using an expectation-maximization algorithm, is not necessary. This is clearly particularly important for high-order formats that have symbols at many different amplitudes.

The eyes depicted by Figs. 6a and 6b are even more complicated than for a single polarization (Fig. 6c), especially for overlapping polarizations, which is shown in Fig. 6b. Fitting multiple Gaussian distributions is virtually impossible.

Fig. 7a illustrates, similarly to Fig. 5a, a relationship established between the power amplitude distribution variance and the OSNR at timings "A" and "B" for the signal in Fig. 6c.

Fig. 7b illustrates, similarly to Fig. 5b, the relationship between the OSNR and the variance for signals with two polarizations. It shows the results for the timings "A" and "B" for the eyes shown in Fig. 6a and 6b (back-to-back), as well as for 100 km fiber propagation and 200 km fiber propagation.

Figs. 8a-8c correspond to Figs. 4a-4c and 6a-6c, but the modulation format is 64QAM. Resolving Gaussian components is impossible.

Figs. 9a-9b correspond to Figs. 5a-5b and 7a-7b, but the modulation format is 64QAM. In accordance with preferred embodiments, the relationships are based on single variances. Fig. 10 illustrates a system 1000 configured to determine or compute a noise relationship between statistical parameter value and the OSNR. A transmitter 1001 produces a QAM optical signal, which propagates through a length of optical fiber 1003 and perhaps other optical components. At the receiver end, a non-coherent photodetection is performed at photodetector 1005. A digital signal processor (DSP) 1009 produces an eye diagram 1012 based on the QAM electrical signal produced by the photodetector 1005. The DSP, or other type of microprocessor, is configured to determine the variance at a selected timing within the eye diagram 1012, for instance as described in detail above. The system 1000 also includes a coherent detector 1007 which receives the same signal and produces a constellation diagram 1011. The OSNR is typically calculated as the average of the variance divided by the mean amplitude across all points in the constellation diagram.

Having both the OSNR value and the variance value, a noise relationship has been established. By varying for instance the fiber length or adding noise with a noise generator (AWGN), a more detailed relationship can be established and used in the field for obtaining OSNR values based on variance.

Certain embodiments of the invention uses a neural network trained with a number of individual pairs of OSNR vs. statistical parameter values for different working or operating conditions such as different modulation formats, fiber lengths, transmitter types, output OSNRs, etc. Using a neural network is an effective way of using the training points to provide OSNR value estimation based on statistical parameter values for conditions that are not represented in the training set.

Fig. 11a shows schematically an optical link 1100 comprising a transmitter 1101, a transmission medium (optical fiber) 1103, and a noise estimator 100. This setup can be used for monitoring the OSNR for instance during deployment of the optical link to evaluate the quality of the link before a permanent optical receiver is added. When it has been established that the optical signal received by the noise estimator has a satisfactory quality - for example complying with certain predetermined signal quality parameters, the permanent optical receiver can be added. By adding an optical splitter, the noise estimator can remain connected to the link to allow monitoring of the link quality.

Fig. 11b illustrates the combination of a noise estimator with a receiver. Compared to Fig. 11a, it further comprises a splitter 1105 for splitting the optical signal into two parts, one of which is provided to the receiver 1107, the other being provided to the noise estimator 100. In this example the noise estimator can be used for instance to monitor the optical signal quality of the optical link and detect and flag degradation of the optical link. The noise estimator can advantageously be used to monitor for instance signal strength as well as noise, whereas the receiver 1107 is used purely for extracting digital data from the optical signal.

CLAIMS

1. A noise estimator for determining an optical signal-to-noise ratio (OSNR) value of a quadrature amplitude modulated (QAM) optical signal, comprising:

- an optical detector configured to directly detect the QAM optical signal and provide a QAM electrical signal representing an instantaneous amplitude of the detected QAM optical signal,
- a signal processor configured to determine at least one statistical parameter value, such as variance and/or mean value, of a predetermined probability density function representing a single fit to a power amplitude distribution of the QAM electrical signal at a first timing within a power eye diagram representation; and

  the signal processor is furthermore configured to determine the OSNR value based on the at least one statistical parameter value.

2. A noise estimator in accordance with claim 1, wherein the OSNR value is determined based on an at least partly predetermined noise relationship between a set of reference OSNR values and a corresponding set of reference statistical parameter statistical parameter values, wherein each reference OSNR value and corresponding reference statistical parameter value are determined based on a corresponding reference optical signal from a training set of reference optical signals.

3. A noise estimator in accordance with claim 2, wherein:
   - each reference OSNR value is determined based on a constellation representation of the corresponding reference QAM optical signal, and
   - each reference statistical parameter value is a statistical parameter belonging to a t predetermined probability density function , said predetermined probability density function being a best fit of a power amplitude distribution at the first timing within a power eye diagram representation of the corresponding reference QAM optical signal.

4. A noise estimator in accordance with claim 2, wherein a first reference QAM optical signal in the training set has a first OSNR value, and a second reference QAM optical signal in the training set is obtained by adding noise, to or subtracting noise from, the first reference QAM optical signal; and a reference statistical parameter value for the second reference QAM optical signal is a variance belonging to a single predetermined probability density function which is, a best fit of a power amplitude distribution at the first timing within a power eye diagram representation of the second QAM reference optical signal; and a reference OSNR value of the second reference QAM optical signal is the OSNR value of the first reference QAM optical signal plus or minus an OSNR value of the added or subtracted noise.

5. A noise estimator in accordance with one of the preceding claims, wherein the signal processor is configured to determine the first timing where the power eye diagram representation of the QAM electrical signal has a minimum or a maximum.

6. A noise estimator in accordance with any of the preceding claims, wherein the first timing corresponds to a peak amplitude of an in-phase carrier signal of the QAM optical signal and/or to a peak amplitude of a quadrature carrier signal of the QAM optical signal.

7. A noise estimator in accordance with one of the preceding claims, wherein the OSNR value is determined based on:
a first statistical parameter value corresponding to a first timing within the power eye diagram representation of the QAM electrical signal; and
a second variance value corresponding to a second timing within the power eye diagram representation of the QAM electrical signal, the first timing being different from the second timing.

8. A noise estimator in accordance with one of the preceding claims, furthermore comprising an electronic optical signal format identifier configured to identify a

modulation format of the QAM optical signal by obtaining a first statistical parameter value at a first timing within the power eye diagram representation of the QAM electrical signal and obtaining a second statistical parameter value at a second timing within the power eye diagram representation of the QAM electrical signal, the first timing being different from the second timing, the identified modulation format being the modulation format most likely to exhibit the first statistical parameter value at the first timing and the second statistical parameter value at the second timing.

9. A noise estimator in accordance with any of the preceding claims, furthermore comprising a relationship storage comprising a representation of the noise relationship.

10. A noise estimator in accordance with claim 9, furthermore comprising a data input port configured to receive the noise relationship, the noise estimator furthermore being configured to store the received noise relationship in the relationship storage.

11. A noise estimator in accordance with any of the preceding claims, wherein the predetermined probability density function comprises a Gaussian distribution or a gamma distribution.

12. A noise estimator in accordance with any of the preceding claims, further comprising:
- an optical connector configured to receive the QAM optical signal,
- a photodetector configured to detect the received QAM optical signal,
- a sampling device configured to provide the power amplitude distribution at the first timing, and
- a relationship storage configured to store the noise relationship.

13. A method of determining an OSNR value of a quadrature amplitude modulated (QAM) optical signal, the method comprising:

- receiving the QAM optical signal at an optical detector,
- converting the QAM optical signal into a corresponding QAM electrical signal representing an instantaneous amplitude of the QAM optical signal,
    - determining at least one statistical parameter value, such as variance and/or mean value, of a predetermined probability density function; wherein the predetermined probability density function represents a single fit to a power amplitude distribution at a first timing within a power eye diagram representation of the QAM electrical signal, wherein the determining being based on an at least partly predetermined noise relationship between a set of reference OSNR values and a corresponding set of reference statistical parameter values, wherein each reference OSNR value and corresponding reference statistical parameter value are determined for a corresponding reference QAM optical signal from a training set of reference QAM optical signals.

14. A method in accordance with claim 13, wherein the QAM electrical signal corresponds to an electronic response of a photodetector receiving the QAM optical signal.

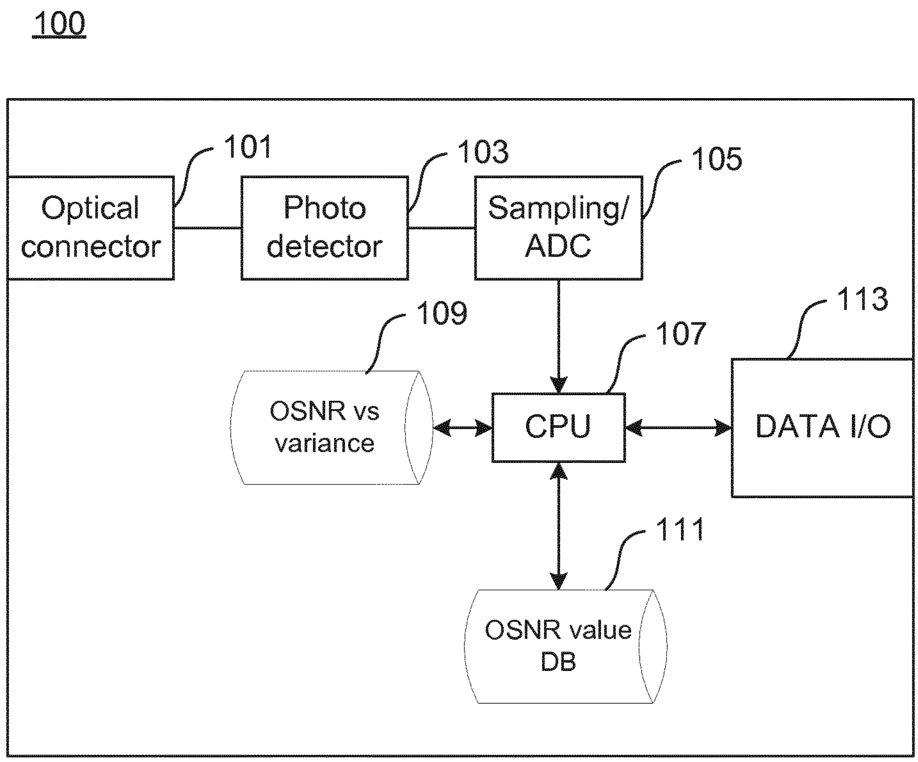

100
Optical connector
101
Photo detector
103
Sampling/ ADC
105
109
OSNR vs variance
CPU
107
113
DATA I/O
111
OSNR value DB

Fig. 1

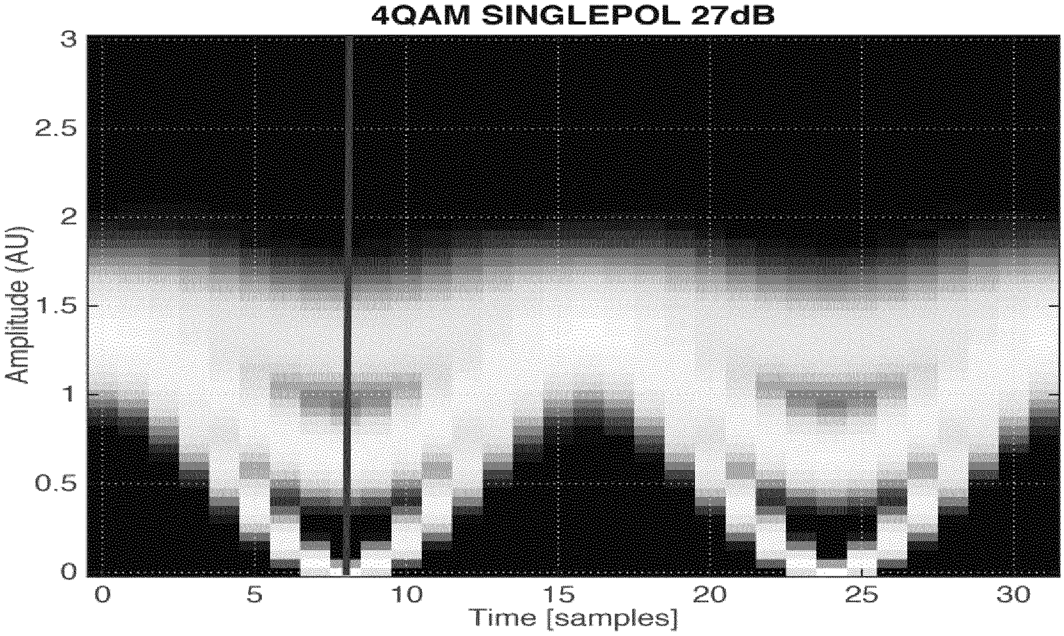

4QAM SINGLEPOL 27dB
Amplitude (AU)
Time [samples]
0
0.5
1
1.5
2
2.5
3
0
5
10
15
20
25
30

Fig. 2a

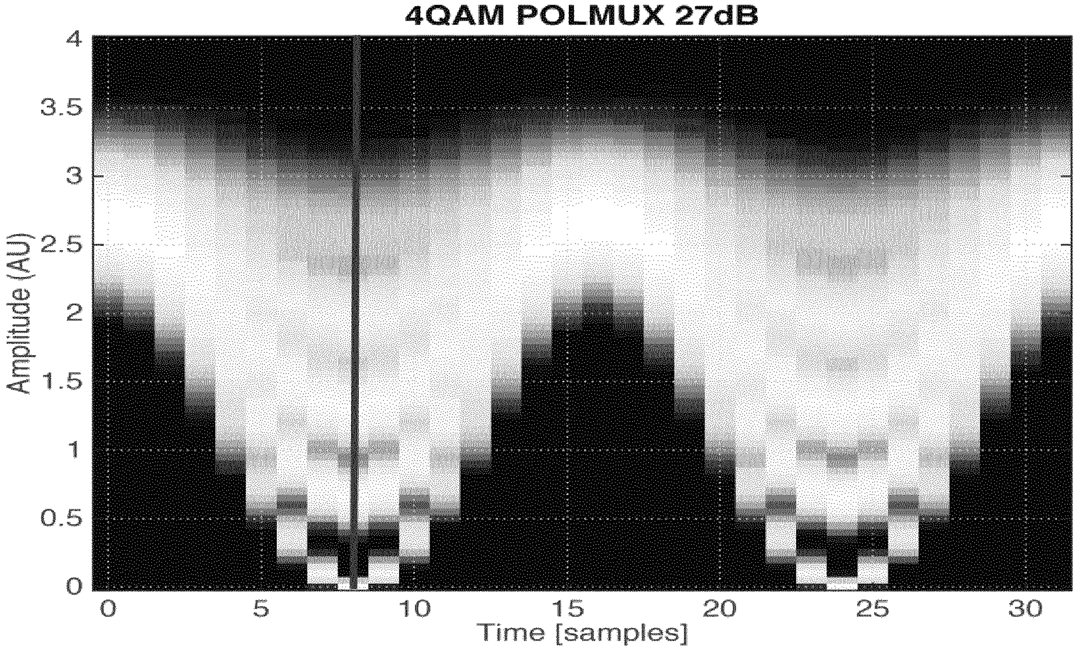

4QAM POLMUX 27dB
Amplitude (AU)
Time [samples]
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20
25
30

Fig. 2b

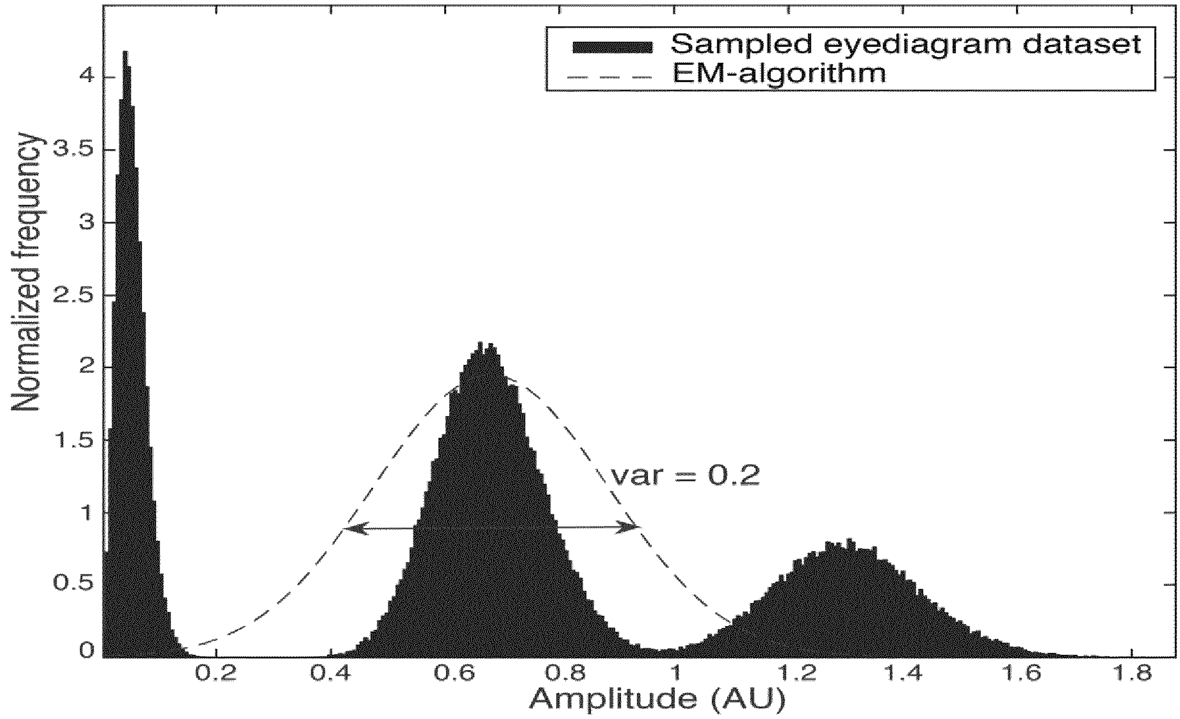

Sampled eyediagram dataset
EM-algorithm
Normalized frequency
0
0.5
1
1.5
2
2.5
3
3.5
4
var = 0.2
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Amplitude (AU)

Fig. 3a

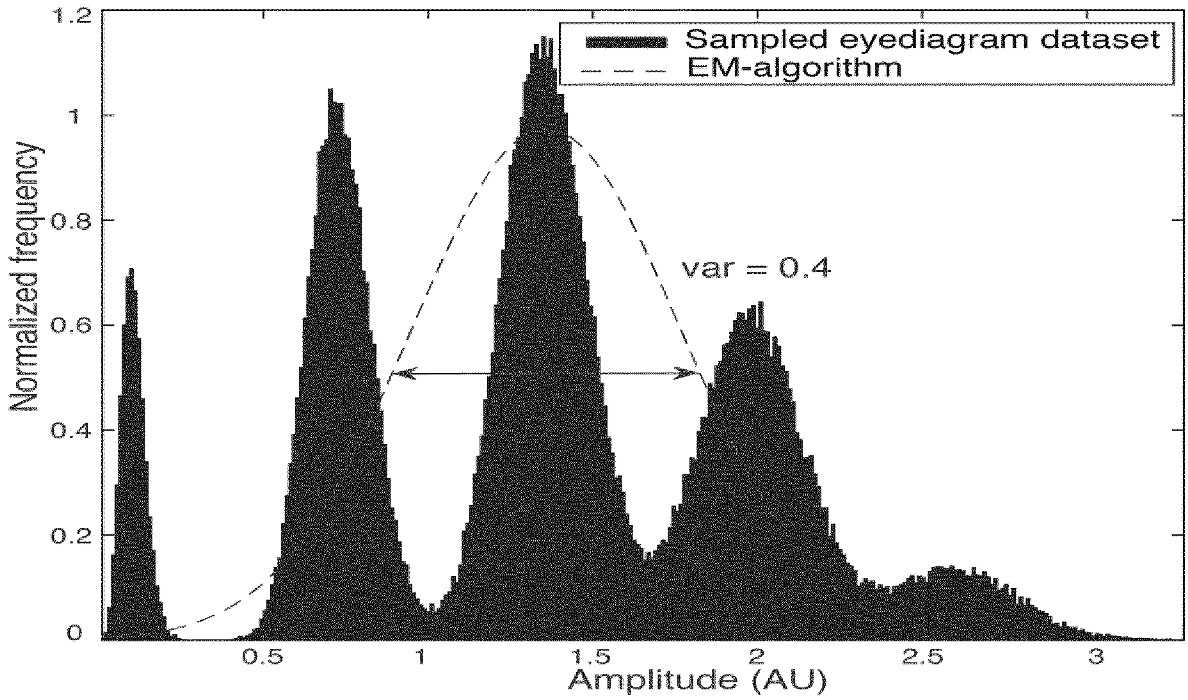

Sampled eyediagram dataset
EM-algorithm
Normalized frequency
0
0.2
0.4
0.6
0.8
1
1.2
var = 0.4
0.5
1
1.5
2
2.5
3
Amplitude (AU)

Fig. 3b

Fig. 4a

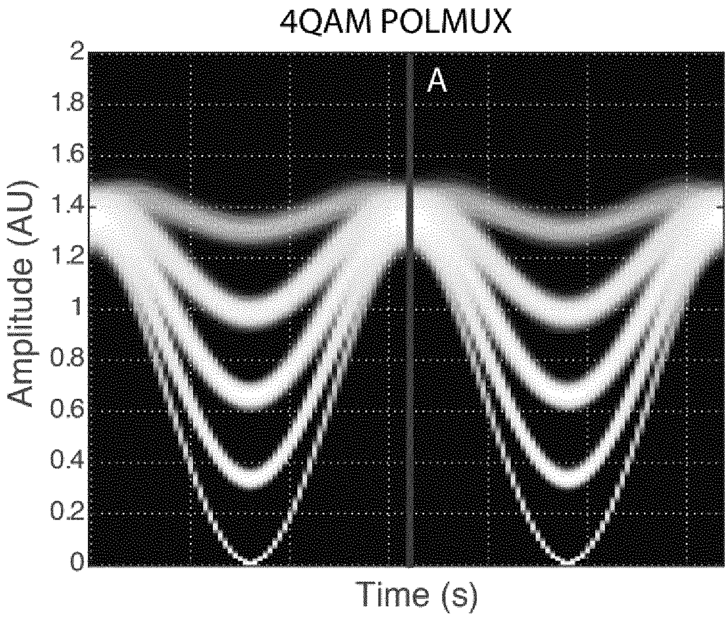


Fig. 4b

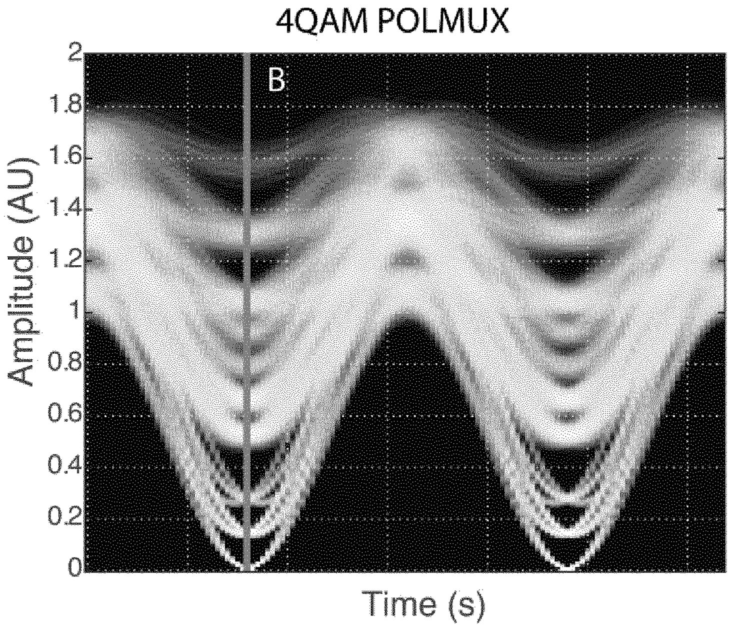
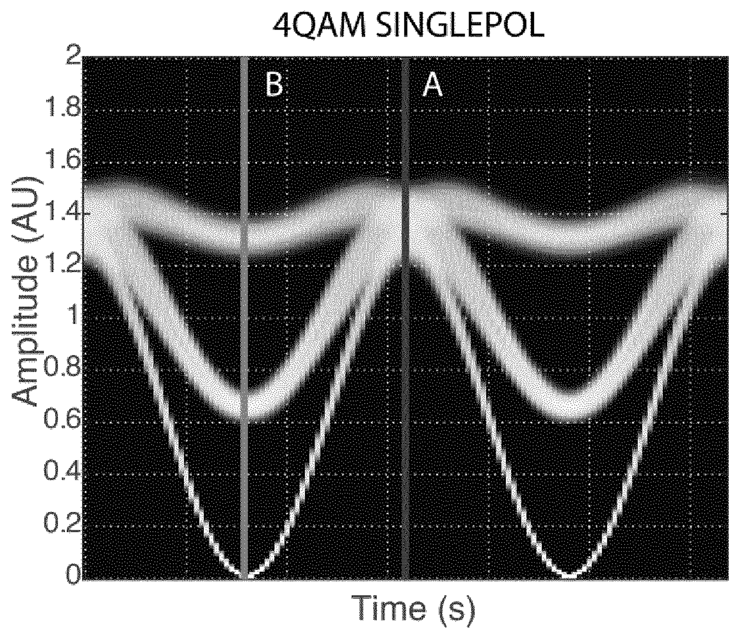


Fig. 4c



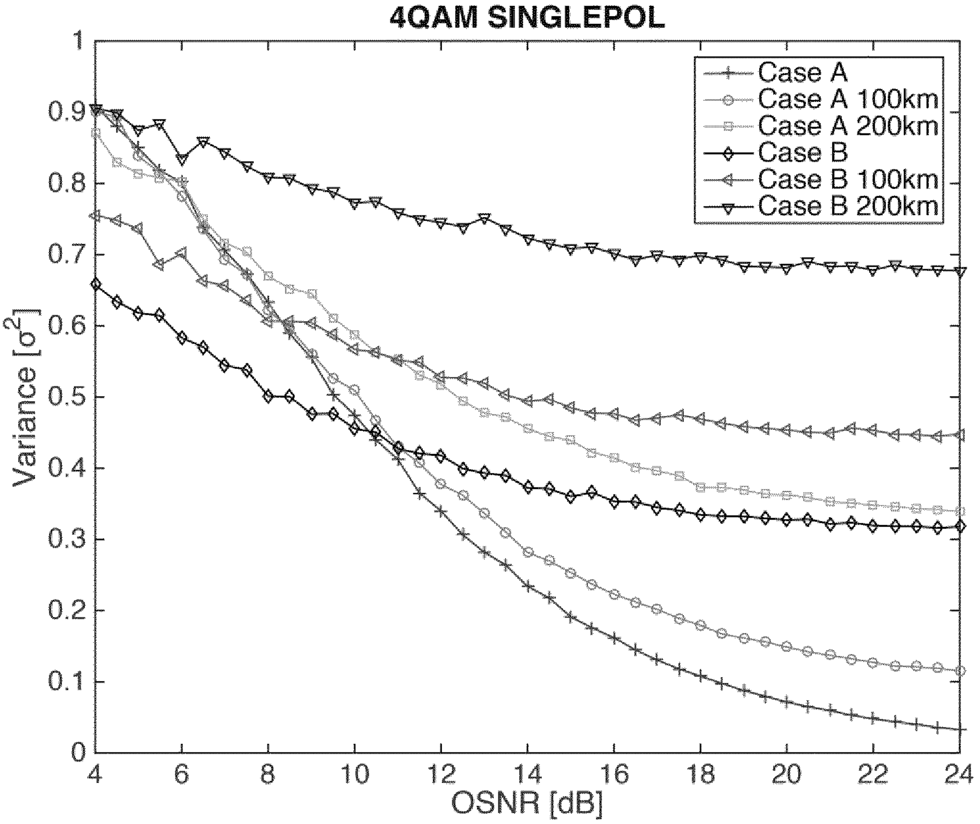

4QAM SINGLEPOL
Case A
Case A 100km
Case A 200km
Case B
Case B 100km
Case B 200km
Variance [σ²]
OSNR [dB]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
4
6
8
10
12
14
16
18
20
22
24

Fig. 5a

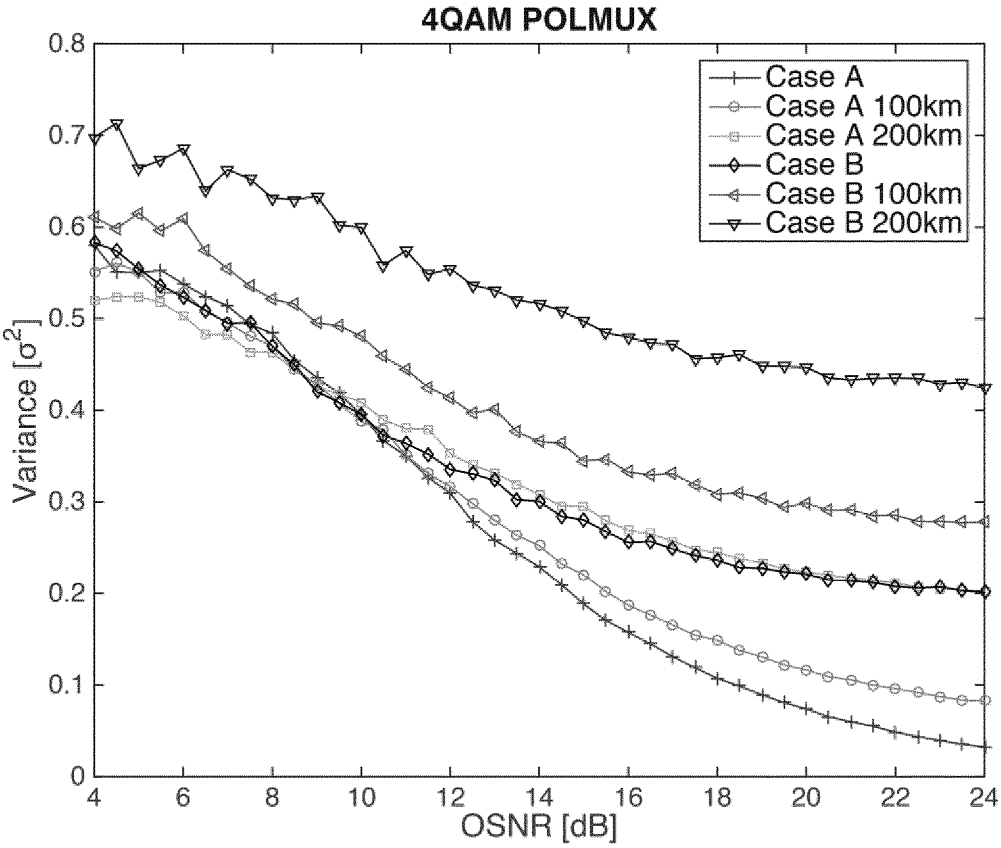

4QAM POLMUX
Case A
Case A 100km
Case A 200km
Case B
Case B 100km
Case B 200km
Variance [σ²]
OSNR [dB]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
4
6
8
10
12
14
16
18
20
22
24

Fig. 5b

Fig. 6a

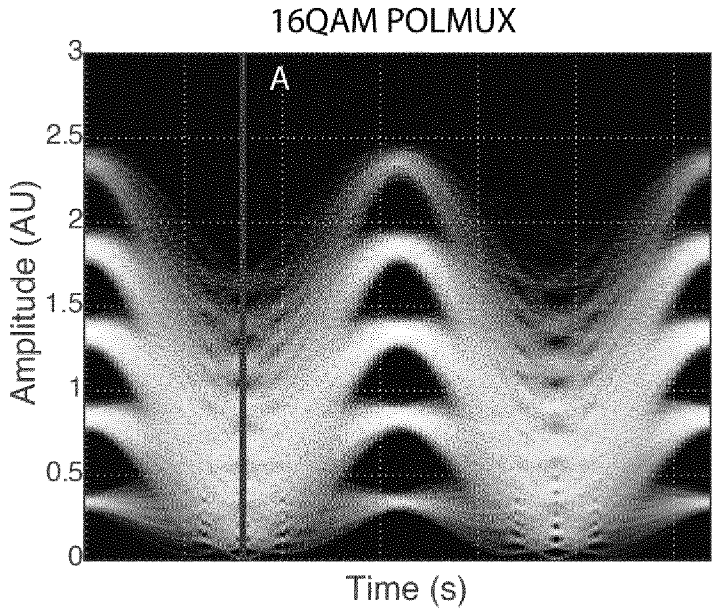


Fig. 6b

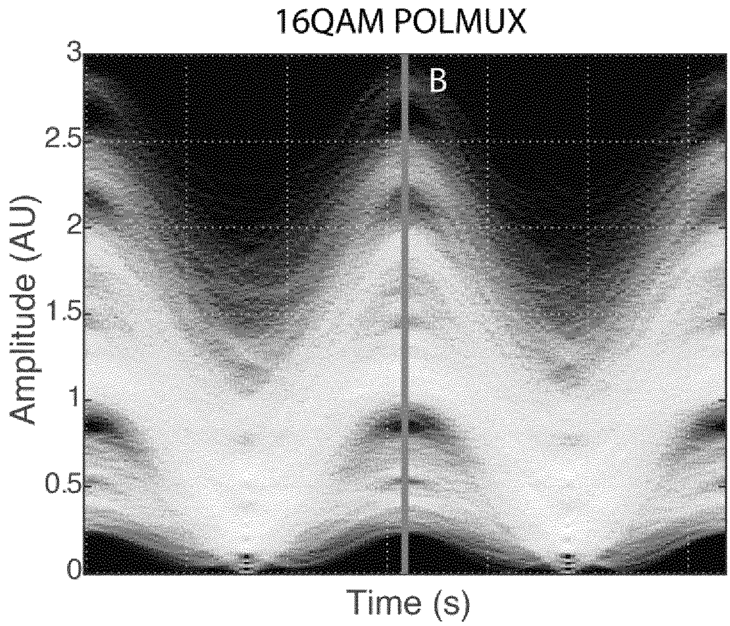
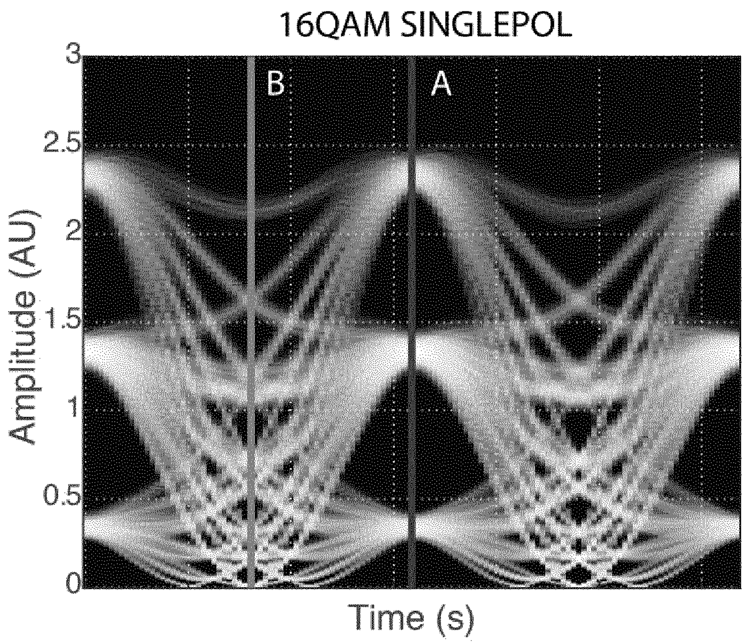


Fig. 6c



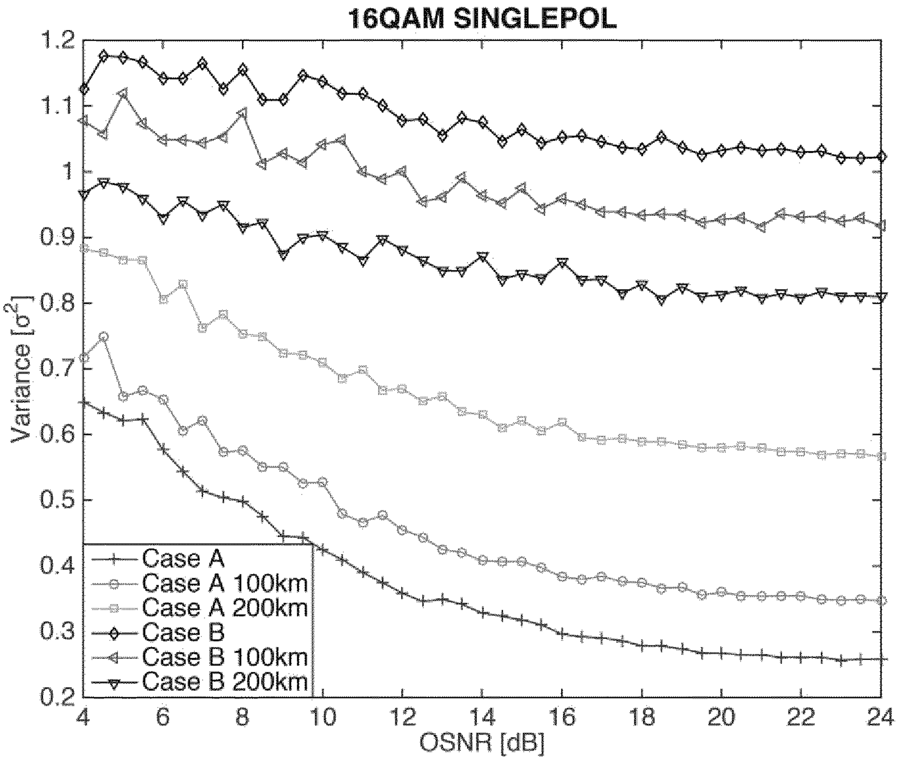

16QAM SINGLEPOL
Variance [σ²]
OSNR [dB]
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
4
6
8
10
12
14
16
18
20
22
24
Case A
Case A 100km
Case A 200km
Case B
Case B 100km
Case B 200km

Fig. 7a

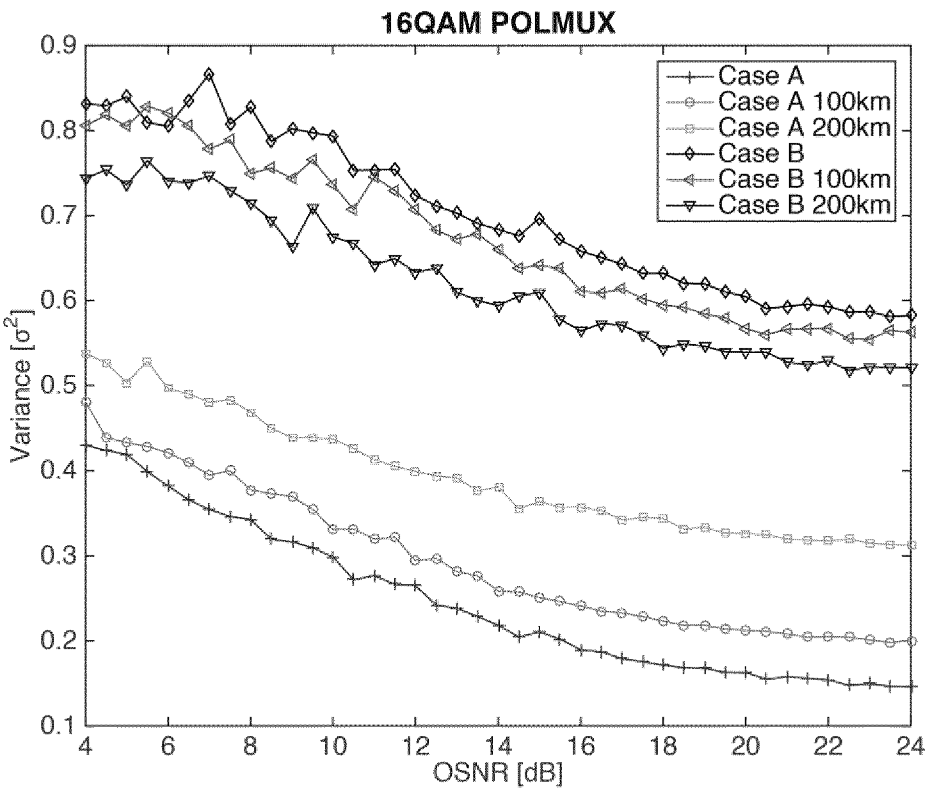

16QAM POLMUX
Variance [σ²]
OSNR [dB]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
4
6
8
10
12
14
16
18
20
22
24
Case A
Case A 100km
Case A 200km
Case B
Case B 100km
Case B 200km

Fig. 7b

Fig. 8a

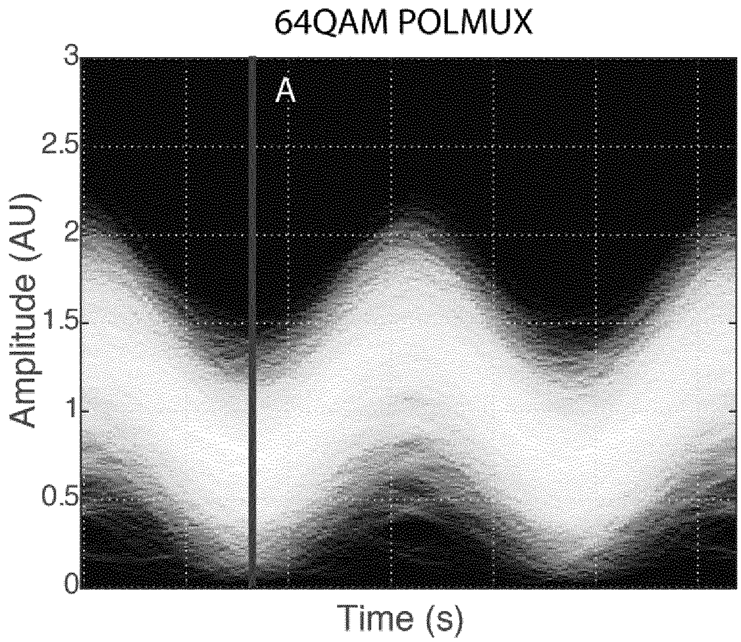


Fig. 8b

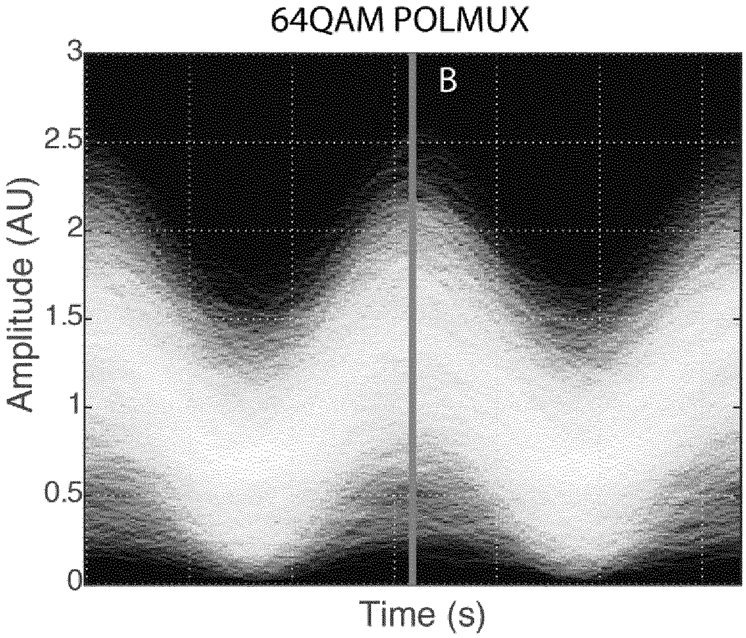
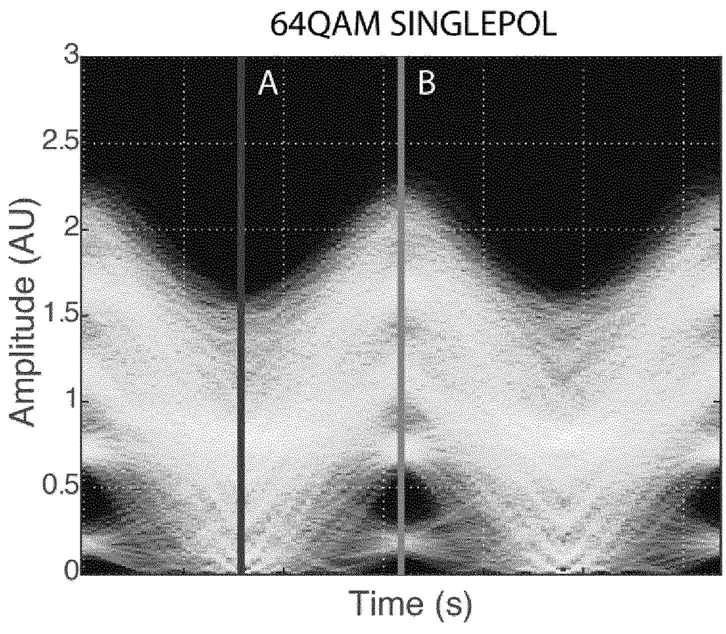


Fig. 8c



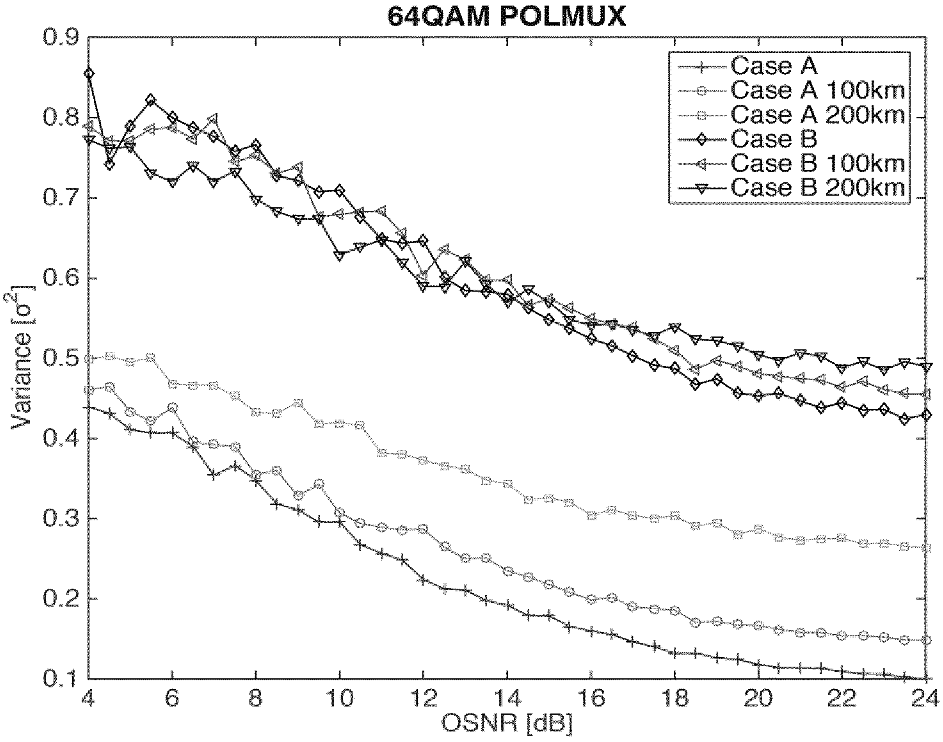

64QAM POLMUX
Variance [σ²]
OSNR [dB]
Case A
Case A 100km
Case A 200km
Case B
Case B 100km
Case B 200km
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
4
6
8
10
12
14
16
18
20
22
24

Fig. 9a

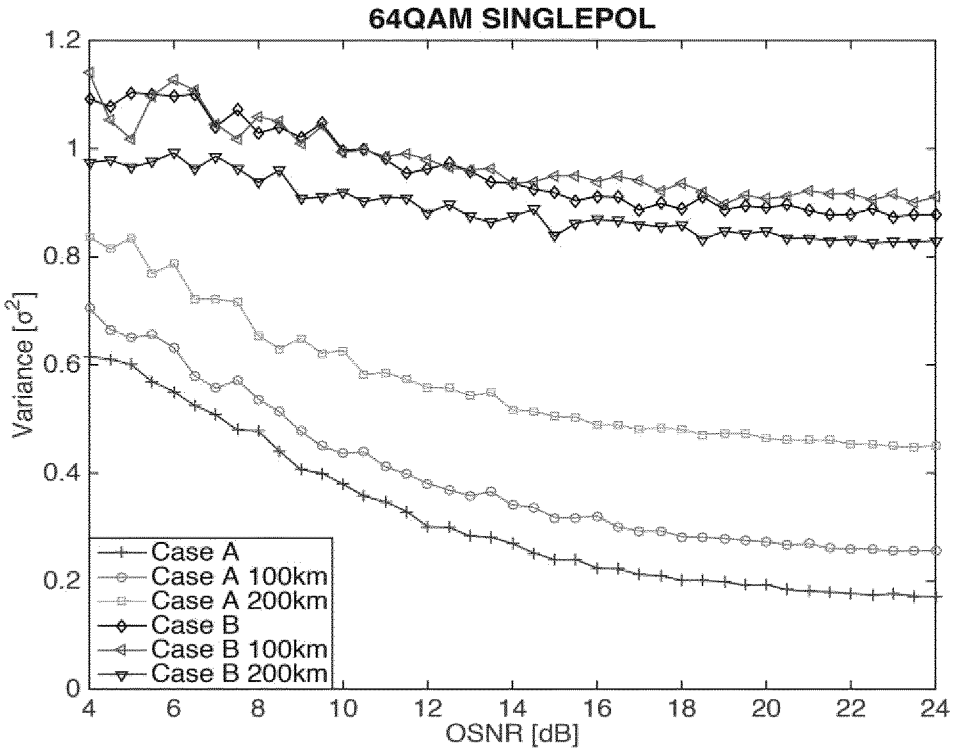

64QAM SINGLEPOL
Variance [σ²]
OSNR [dB]
Case A
Case A 100km
Case A 200km
Case B
Case B 100km
Case B 200km
1.2
1
0.8
0.6
0.4
0.2
0
4
6
8
10
12
14
16
18
20
22
24

Fig. 9b

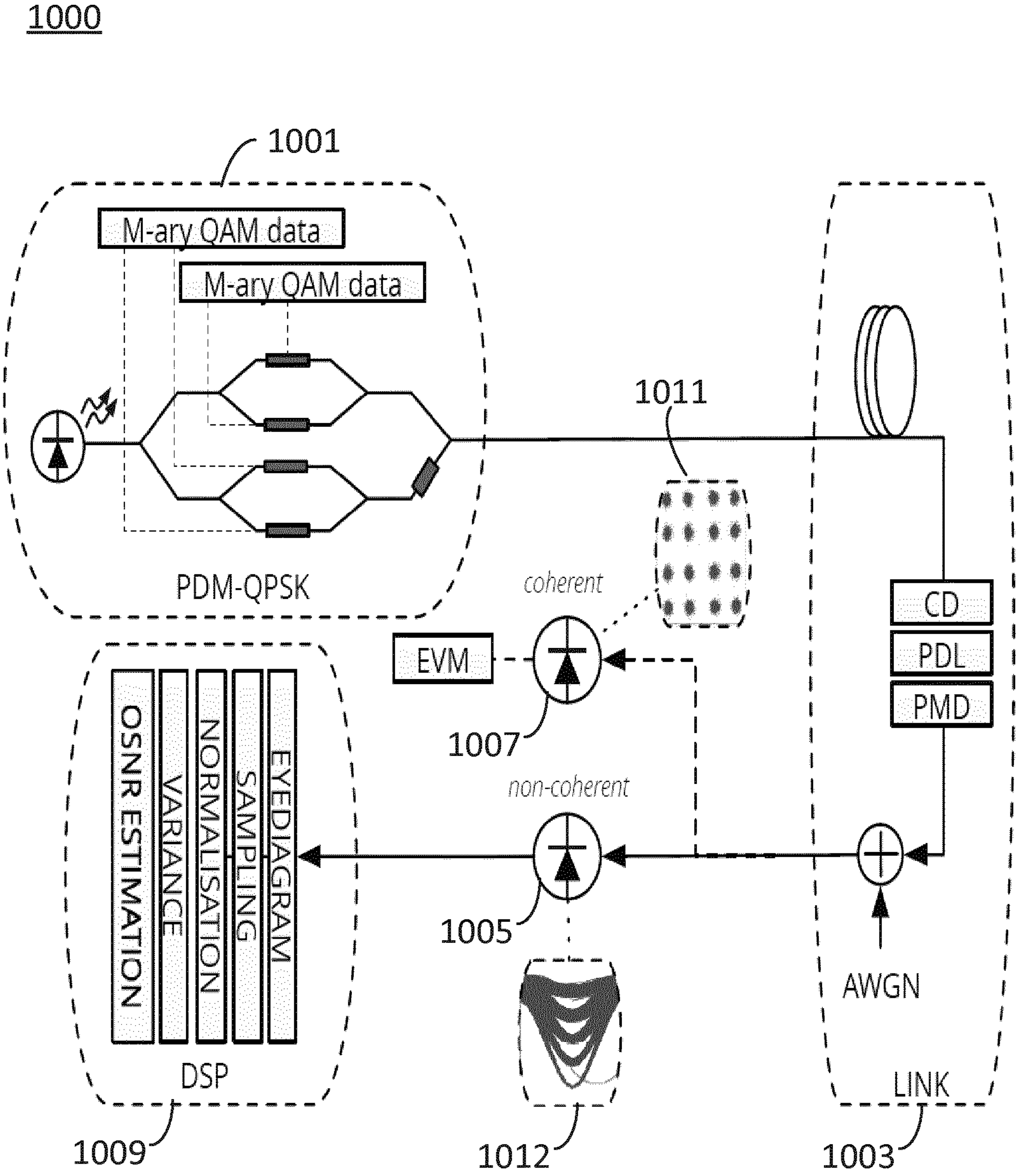

1000
1001
M-ary QAM data
M-ary QAM data
PDM-QPSK
1011
coherent
EVM
1007
CD
PDL
PMD
non-coherent
OSNR ESTIMATION
VARIANCE
NORMALISATION
SAMPLING
EYEDIAGRAM
1005
AWGN
DSP
LINK
1009
1012
1003

Fig. 10

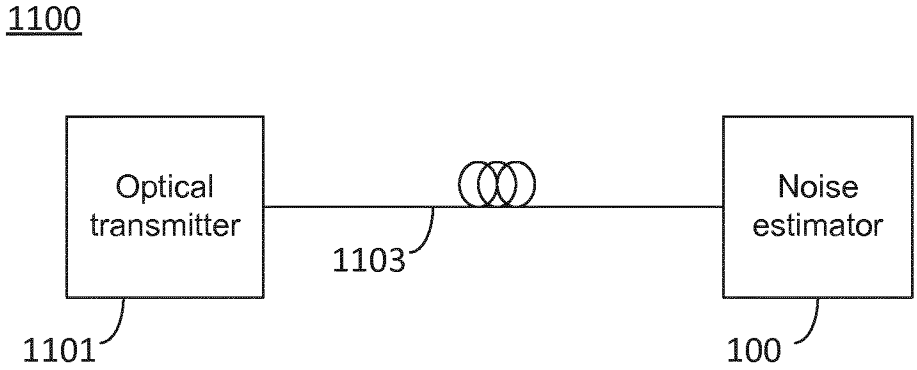


Fig. 11a

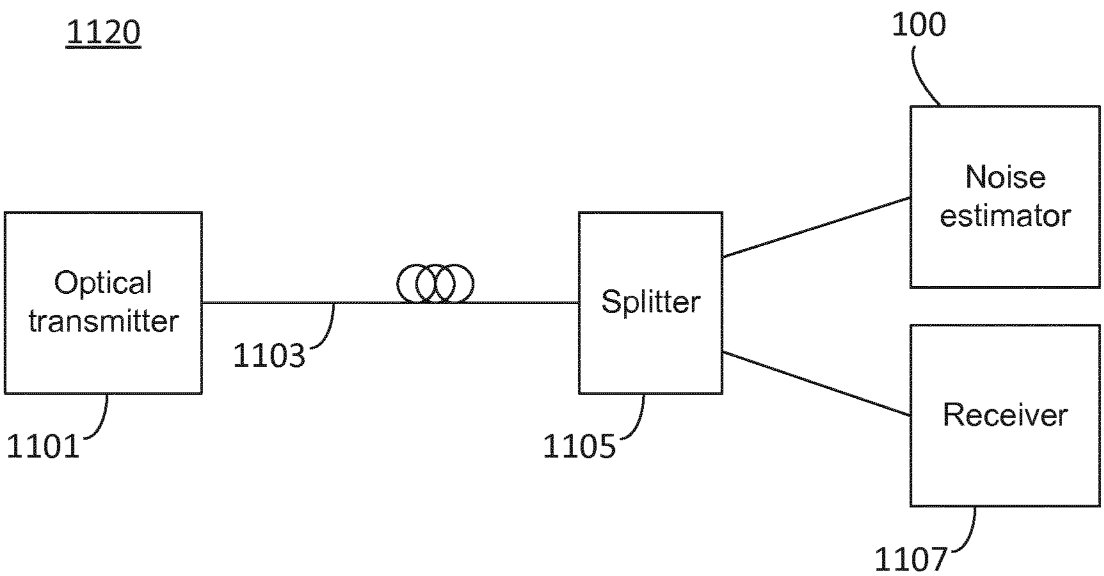


Fig. 11b

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/063887

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B10/079
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)
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, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CHOI ET AL.: "Optical performance monitoring technique using software-based synchronous amplitude histograms", OPTICS EXPRESS, vol. 22, no. 20, 6 October 2014 (2014-10-06), XP002751205, cited in the application	1-6,9-14
A	the whole document	7,8

X	US 2014/308034 A1 (CHUNG YUN CHUR [KR] ET AL) 16 October 2014 (2014-10-16)	1-6,9-14
A	abstract paragraphs [0001] - [0030] paragraphs [0050] - [0053] figures 3A, 3B	7,8

	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] 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	Date of mailing of the international search report
16 August 2016	30/08/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Rolan Cisneros, E

1

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Juan Manual Lopez F. ET AL: "Low level Optical Signal to Noise Ratio measurement using basic statistical data from Asynchronous Amplitude Histogram Gaussian fitting", , 23 February 2011 (2011-02-23), pages 1-6, XP055295372, Bogota (Colombia) Retrieved from the Internet: URL:http://www.diegopeluffo.com/publicaciones/IBERCHIP2011.pdf [retrieved on 2016-08-12]	1-6,9-14
A	the whole document	7,8

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/063887

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014308034 A1	16-10-2014	KR 20140122396 A	20-10-2014
		US 2014308034 A1	16-10-2014