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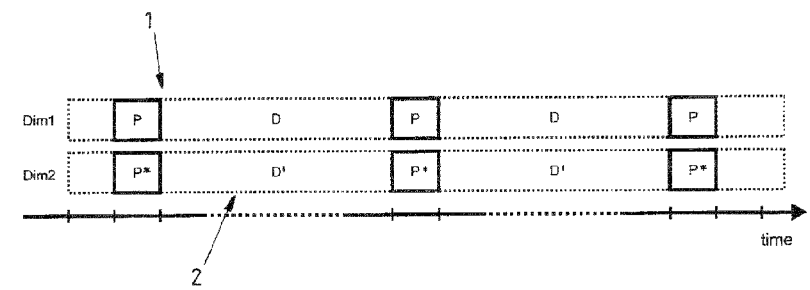
(54) Title: DATA COMMUNICATION METHODS AND DATA COMMUNICATION SYSTEMS

FIG 1



(57) Abstract: The invention relates to a data communication method and a communication system, the method comprising the steps of a) transmitting first data (1) using a first transmission variant (Dim1); b) transmitting second data (2) using a second transmission variant (Dim2), wherein c) the first data (1) comprises first payload data (D) and at least one first non-payload pilot symbol (P, P_1- P_N); and wherein d) the second data (2) comprises second payload data (D') and at least one second non-payload pilot symbol (P*, P_1*- P_N*), the second pilot symbol (P*, P_1* - P_N*) being a complex conjugate of the first pilot symbol (P, P_1- P_N); e) receiving the first and the second pilot symbol (P, P_1- P_N, P*, P_1* - P_N*); and f) determining information related to a transmission distortion using the received first and second pilot symbol (P, P_1- P_N, P*, P_1* - P_N*).

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Data communication methods and data communication systems

Description

The invention relates to data communication methods according to claims 1 and 19 and to data communication systems according to claims 20 and 21.

One of the major obstacles in (e.g. fiber-optic) multiplexing transmission systems (e.g. wavelength division multiplexing – WDM systems) is the mitigation and/or compensation of distortions caused by e.g. nonlinear effects. While nonlinear interference (NLI) originating from intra-channel nonlinear effects such as intra-channel four-wave mixing (IFWM) and intra-channel cross-phase modulation (IXPM) can, in principle, be compensated by means of single-channel digital back propagation (DBP), the remaining NLI caused by inter-channel nonlinear effects such as four-wave mixing (FWM), cross-phase modulation (XPM) and cross-polarization modulation (XPolM) still can be responsible for a significant performance degradation.

An approach for achieving a compensation of nonlinear effects (both intra- and inter-channel) is the application of co-propagating phase-conjugated optical variants (PCOV) in orthogonal dimensions on the payload as described in the article Xiang Liu, A. R. Chraplyvy, P. J.Winzer, R. W. Tkach and S. Chandrasekhar, “Phase-conjugated twin waves for communication beyond the Kerr nonlinearity limit,“ Nature Photonics, vol. 7, pp. 560-568, July 2013. However, the improved resilience to nonlinear effects comes at the expense of a significantly reduced spectral efficiency similar to other diversity schemes in telecommunications.

The object of the invention is to realize a data transmission with reduced distortions and good spectral efficiency.

According to the invention, a data communication method is provided, the method comprising the steps of:

a) transmitting first data using a first transmission variant;
b) transmitting second data using a second transmission variant (different from the first variant), wherein
c) the first data comprises first payload data and at least one first non-payload pilot symbol; and wherein
d) the second data comprises second payload data and at least one second non-payload pilot symbol, the second pilot symbol being a complex conjugate of the first pilot symbol;
e) receiving the first and the second pilot symbol; and
f) determining information related to a transmission distortion using the received first and second pilot symbol.

The invention thus uses at least one pilot symbol (pilot data) and the complex conjugates of the pilot symbol for an estimation and e.g. compensation of transmission distortions. For example, the method according to the invention allows an estimation of the NLI, wherein the estimation may be used for the compensation of intra- and/or inter-channel nonlinear effects. Also, the method could be used for cycle-slip mitigation. Of course, more than one first and second pilot symbols can be used, e.g. a sequence of first non-payload pilot symbols and a sequence of second non-payload pilot symbols (i.e. the complex conjugates of the first pilot symbols) are used. Examples of pilot symbol sequences will be discussed further below.

Compared to existing compensation methods (such as DBP - digital back propagation) and linear filters for compensation of chromatic dispersion, the hardware requirements for implementing the method according to the invention may be very small. Furthermore, the method not only may compensate NLI in the received optical bandwidth, but may also take into account NLI originating from other (e.g. out-of-band or arbitrary) frequencies. Further, compared to compensation methods using phase conjugated payload data (which e.g. need up to 100 % overhead), the spectral efficiency may be significantly enhanced. For example, the method according to the invention requires an overhead (the pilot symbols) in the order of some percent, only.

Further, the estimation of the NLI might be performed in time intervals of the order of the correlation time of the NLI process, only. A determination of NLI properties such as magnitude and phase can be obtained by superimposing (and e.g. subtracting) the first pilot symbols transmitted via the first transmission variant (“dimension”, e.g. a first carrier polarization) and its phase conjugated counterparts (i.e. the second pilot symbols) transmitted via the second transmission variant (i.e. another “dimension”). In contrast to using phase conjugated payload data for distortion estimation, thus only non-payload pilot (training) symbols, which might be inserted into the payload, are used for the distortion estimation and not to the payload data itself. For example, the first pilot symbol(s) is (are) inserted into a data sequence of the first payload data and/or the second pilot symbol(s) is (are) inserted into a data sequence of the second payload data.

The method according to the invention thus in particular provides an improved estimator scheme e.g. for nonlinear channels, whereas using phase conjugated payload symbols improves the reliability of the payload signal in the presence of nonlinearities.

It is noted that the method according to the invention may be used in optical fiber transmission systems. The method is, however, not restricted to optical transmission systems, but may also be used in other transmission systems (such as wireless systems).

As already indicated above, determining information according to step f) may comprise superimposing (and e.g. evaluating the difference) of the received first and second pilot symbol. Of course, the method according to the invention might comprise other methods for evaluating the pilot symbols and/or processing the received pilot symbols as will be further discussed below.

For example, the first transmission variant is a first optical transmission variant and the second transmission variant is a second optical transmission variant. It is noted that the term “transmission variant” relates to a transmission scheme that is characterized by at least one property of a transmission channel used for transmission. For example, a transmission variant is related to a channel having a certain carrier polarization, time division multiplexing time domain, code division multiplexing code, carrier wavelength or carrier frequency. The first and the second transmission variant differ from one another in at least one channel property (transmission characteristic), wherein the channels might be assigned e.g. to different multiplexing schemes. It is of course also possible that the first and the second transmission variant belong to the same multiplexing scheme. For example, the first transmission variant uses a predetermined frequency channel and the second transmission variant uses another frequency channel.

According to an embodiment of the invention, the first transmission variant has at least one of the following transmission characteristics: a first carrier polarization, a first time division multiplexing time domain, a first code division multiplexing code, a first carrier wavelength and a first carrier frequency, and wherein the second transmission variant has at least one of the following transmission characteristics: a second carrier polarization, a second time division multiplexing time domain, a first code division multiplexing code, a second carrier wavelength and a second carrier frequency.

For example, the first and the second transmission variant both belong to a polarization division multiplexing (PDM) scheme, wherein the first transmission variant uses a first carrier polarization for transmitting the first payload and the first pilot symbol and the second transmission variant uses a second carrier polarization for transmitting the second payload and the second pilot symbol.

It is also possible that the first and the second transmission variant in addition (to belonging to the polarization division multiplexing scheme) belong to a time division multiplexing (TDM) scheme, wherein the first and the second pilot symbol may be transmitted via the same time domain (TDM channel).

Further more, in addition or as an alternative, the first and the second transmission variant in addition (to belonging to the polarization division multiplexing scheme and/or the TDM scheme) belong to a frequency division multiplexing scheme, wherein, however, the first and the second pilot symbol might be transmitted via the same carrier frequency.

According to another embodiment, at least one further pilot symbol is transmitted using the first carrier polarization, but e.g. a different time domain than the first pilot symbol, wherein the further pilot symbol is a complex conjugate of the first pilot symbol, and/or at least one further pilot symbol is transmitted using the second carrier polarization, but e.g. a different time domain than the second pilot symbol, wherein the further pilot symbol is a complex conjugate of the second pilot symbol.

For example, a plurality of first and/or the second pilot symbols are transmitted, wherein the first and/or the second pilot symbols comprises a CAZAC (constant-amplitude zero-autocorrelation) sequence that is e.g. embedded in a polarization-division multiplexed payload signal. For example, the first pilot symbol sequence in the form of a CAZAC sequence is inserted in a payload sequence; for example, an x-polarization payload signal. The CAZAC sequence can be generated by any suitable algorithm, e.g. as described in the articles "Some unique properties and applications of perfect squares minimum phase CAZAC sequences,", U. Rohrs and L. Linde, Proc. South African Symp. Comm. Signal Process. (COMSIG), 1992, pp. 155-160. 3GPP TS 36.211 Release 8 73 V8.9.0 (2009-12), pp. 22, M. Kuschnerov, et al. “Data-Aided Versus Blind Single-Carrier Coherent Receivers,” IEEE Photonics Journal, vol. 2, no.3, pp. 387-403, Jun. 2010, and F. Pittala, F. N. Hauske, and Y. Ye, "Fast and robust CD and DGD estimation based on data-aided channel estimation," in 13th Internat. Conf. on Transparent Opt. Netw. (ICTON), 2011, p. We. D1.5., these articles being incorporated by reference herewith.

The corresponding complex conjugate sequence (i.e. the second pilot symbol sequence) is inserted in another payload sequence (transmitted via the second transmission variant), e.g. a y-polarization payload signal. In particular, the CAZAC sequence and its complex conjugate are inserted into the payload sequences within corresponding time slots.

For example, a CAZAC-4 sequence could be used, which consist of four symbols x[k], $k \in \{1,2,3,4\}$ being the symbol time index, wherein

$$x[1] = -\frac{1}{\sqrt{2}} - j\frac{1}{\sqrt{2}}, x[2] = \frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}}, x[3] = \frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}}, x[4] = \frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}}$$

The corresponding complex conjugate sequence y[k] in y-polarization at the same time instants is then

$$y[1] = -\frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}}, y[2] = \frac{1}{\sqrt{2}} - j\frac{1}{\sqrt{2}}, y[3] = \frac{1}{\sqrt{2}} - j\frac{1}{\sqrt{2}}, y[4] = \frac{1}{\sqrt{2}} - j\frac{1}{\sqrt{2}}$$

According to another embodiment of the invention, a compensation of intra-channel nonlinear effects is carried out before using the received first and second pilot symbol for determining information according to step f). For example, the compensation uses DBP (digital back propagation) at the receiver or digital nonlinear pre-distortion at the transmitter. The pilot symbols might be used to extract properties of residual inter-channel nonlinearities.

For example, the pilot symbols could be used for an estimation of the nonlinear distortion of the transmission link as follows: $\boldsymbol{E}(z)$ may be the first and second pilot symbol inserted into the payload data at the input side ($z = 0$) of the transmission link (e.g. a fiber link) in two transmission variants (e.g. orthogonal polarizations), wherein

$$\boldsymbol{E}(0) = \begin{pmatrix} E_x(0) \\ E_y(0) \end{pmatrix} = \begin{pmatrix} E(0) \\ E^*(0) \end{pmatrix}$$

After propagation along a transmission link of length L the received pilot symbol can be written as

$$\boldsymbol{E}(L) = \begin{pmatrix} E_x(L) \\ E_y(L) \end{pmatrix} = \begin{pmatrix} E(0) + \delta E_x(L) \\ E^*(0) + \delta E_y(L) \end{pmatrix}$$

wherein $\delta E_x(z = L)$ is the distortion of the first transmission variant (e.g. the x-polarization) and $\delta E_y(z = L)$ is the distortion in the second transmission variant (i.e. the y-polarization). Assuming nonlinear contributions and neglecting uncorrelated noise contributions, the distortion in the first transmission variant can be written as $\delta E_x(L) = -[\delta E_y(L)]^*$. The operation $(\cdot)^*$ denotes complex conjugation of its argument. For extracting the nonlinear distortion from the received pilot symbols the following operation can be performed:

$$\delta E_x(L) = -[\delta E_y(L)]^* = (E_x(L) - [E_y(L)]^*)/2$$

According to another embodiment of the invention, a unitary matrix transformation may be applied to the first and/or the second pilot symbol(s) before their transmission (e.g. before they are added to the payload sequence) or after their receipt (e.g. before they are evaluated). One exemplary matrix transformation is the following:

$$\boldsymbol{U} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ -i & i \end{pmatrix},$$

with $i = \sqrt{-1}$. For example, a specific set $\boldsymbol{A}$ of PCOV pilot symbols is mapped on a polarization-division multiplexed (PDM) quadrature phase shift keying (QPSK) symbol alphabet and written as

$$\boldsymbol{A} = \begin{pmatrix} A_x \\ A_y \end{pmatrix} = \left\{ \frac{1}{\sqrt{2}}\begin{pmatrix} 1+1i \\ 1-1i \end{pmatrix}, \frac{1}{\sqrt{2}}\begin{pmatrix} 1-1i \\ 1+1i \end{pmatrix}, \frac{1}{\sqrt{2}}\begin{pmatrix} -1+1i \\ -1-1i \end{pmatrix}, \frac{1}{\sqrt{2}}\begin{pmatrix} -1-1i \\ -1+1i \end{pmatrix} \right\}.$$

The set $\boldsymbol{A}$ will be transformed by $\boldsymbol{U}$ to

$$\boldsymbol{B} = \begin{pmatrix} B_x \\ B_y \end{pmatrix} = \left\{ \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ -1 \end{pmatrix}, \begin{pmatrix} -1 \\ 1 \end{pmatrix}, \begin{pmatrix} -1 \\ -1 \end{pmatrix} \right\},$$

which can be interpreted as a PDM- binary phase shift keying (BPSK) symbol alphabet.

The pilot symbols could also be arranged in an Alamouti code (space-time block code) fashion, e.g. as

$$\boldsymbol{C} = \begin{pmatrix} C_{x,1} & C_{y,1} \\ C_{x,2} & C_{y,2} \end{pmatrix} = \begin{pmatrix} C_{x,1} & {C_{x,1}}^* \\ -C_{x,1} & -{C_{x,1}}^* \end{pmatrix}$$

wherein the first subscript (x, y) designates a property (e.g. a carrier polarization) of the first and the second transmission variant, respectively, and the second subscript (1, 2) designates another property (e.g. a time slot) of the first and the second transmission variant.

Moreover, the information determined in step f) is used for initialization and/or update of at least one coefficient of a digital filter used for the compensation of linear and/or non-linear effects. Digital filters can be used for the compensation of linear and/or nonlinear channel effects as described e.g. in the article “Time varying ISI model for nonlinear interference noise,” R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, Opt. Fiber Commun. Conf. (OFC), Mar. 2014, paper W2A.62, which is incorporated by reference herewith. That article proposes an adaptive decision feedback equalizer (DFE) for compensating non-linear inter-channel crosstalk. The filter coefficients of the DFE could be updated based on the evaluation of the received pilot symbols.

Further, a symmetric dispersion map may be applied to the first and/or the second data (e.g. the carrier polarization) before the information according to step f) is determined (e.g. before the transmission of the data). For example, a dispersion compensation may be carried out at the transmitter and/or at the receiver. According to a variant of this embodiment, an electronic compensation of a part of the chromatic dispersion is carried out at the transmitter and of a corresponding part of the chromatic dispersion is carried out at the receiver. Further, the dispersion map may applied to the complete data, i.e. the payload data and the pilot symbols. The dispersion map of the first and/or second transmission variant can be used to make nonlinear distortions of the first and second pilot symbols anti-correlated. The anti-correlated pilot symbols can then be exploited to get an estimate of the (residual) nonlinear crosstalk.

For example, the symmetric dispersion map is a power weighted accumulated dispersion map as discussed e.g. in the article “Power-weighted dispersion distribution function long-haul optical transmission links,”, X. Wei, Opt. Lett., vol. 31, no. 17, pp. 2544–2546, 2006, which also in that respect is incorporated by reference. The power weighted accumulated dispersion map weighs the dispersion map with the loss/gain profile of the optical signal. The power weighted accumulated dispersion map can be defined as

$$J = \frac{1}{L_{eff}} \int_0^L e^{G(z)} C(z) dz,$$

where L is the transmission link distance, L_{eff} is the effective length of the transmission link, C(z) is the accumulated dispersion at distance z defined as

$$C(z) = \int_0^z \beta_2(z') dz',$$

where $\beta_2(z')$ is the group-velocity dispersion coefficient at distance z′. The gain/loss profile of the optical signal is given as

$$G(z) = \int_0^z \left(g(z') - \alpha(z')\right)dz',$$

where g(z′) is the gain coefficient at distance z′ and α(z′) is the loss coefficient at the position z′ along the transmission link. The effective length L_{eff} is defined as

$$L_{eff} = \int_0^L e^{G(z)}dz.$$

For example, at the transmitter (i.e. upon transmitting the payload data and the pilot symbols) a dispersion of approximately –J/2 is induced with respect to the payload data and the pilot symbols in order to make the power weighted accumulated dispersion map symmetric about zero dispersion.

According to another aspect of the invention, a data communication method, in particular as claimed in any of the preceding claims, is provided, the method comprising the steps of:

a) providing data that comprises payload data, at least one first non-payload pilot symbol and at least one second non-payload pilot symbol, the second pilot symbol being a complex conjugate of the first pilot symbol,
b) transmitting the payload data, the first non-payload pilot symbol and the second non-payload pilot symbol using the same transmission variant;
c) receiving the first and the second pilot symbol; and
d) determining information related to a transmission distortion using the received first and second pilot symbol.

According to that aspect of the invention, the first and the second pilot symbol are inserted into the same payload data sequence and thus are transmitted via the same transmission variant. For example, the second pilot symbol(s) directly follows the first pilot symbol(s).

For example, the first and the second pilot symbols are embedded in a polarization-division multiplexed payload data signal as follows: A first pilot symbol P_1 followed by a second pilot symbol P_2, which is the complex conjugate P_1^* of P_1, is inserted in an x-polarization payload data signal. In addition, pilot symbols P_1’ (which may be the complex conjugate P_1^* of P_1) and P_2’ (the complex conjugate $P_1'^*$ of P_1') are inserted in the y-polarization of the payload data signal. The NLI in x-polarization may be then estimated by evaluating the difference of P_1 and P_1^*, while the NLI in y-polarization is estimated by evaluating the difference of P_1' and $P_1'^*$.

The invention also relates to a data communication system, in particular for carrying out the method as describe above, comprising:

- at least one transmitting unit configured for transmitting first data using a first transmission variant and second data using a second transmission variant, wherein
- the first data comprises first payload data and at least one first non-payload pilot symbol; and wherein
- the second data comprises second payload data and at least one second non-payload pilot symbol, the second pilot symbol being a complex conjugate of the first pilot symbol;
- at least one receiving unit configured for receiving the first and the second pilot symbol; and
- an evaluation unit for determining information related to a transmission distortion using the received first and second pilot symbol.

The transmitting unit may comprises one or more transmitters. For example, one transmitter is used for transmitting the first data and another transmitter is used for transmitting the second data. Similarly, the receiving unit may comprise one or more receivers. The transmitting unit may further comprise at least one signal source that supplies the data (i.e. a data signal) to the transmitter(s).

The invention further is related to a data communication system, in particular for carrying out the method claimed according to the second aspect of the invention, comprising:

- at least one transmitting unit for transmitting data that comprises payload data, at least one first non-payload pilot symbol and at least one second non-payload pilot symbol using the same transmission variant, the second pilot symbol being complex conjugates of the first pilot symbol;
- at least one receiving unit configured for receiving the first and second pilot symbol; and
- an evaluation unit for determining information related to a transmission distortion using the received first and second pilot symbol.

Again, the transmitting unit may comprise one or more transmitters and the receiving unit may comprise one or more receivers. The transmitting unit may further comprise a signal source that supplies the data to the transmitter(s).

The evaluation unit may be any suitable hardware device programmed for carrying out the determination of information related to the transmission distortion.

Embodiments of the invention are described in more details hereinafter with reference to the drawings, which show:

Fig. 1	a diagram relating to a method according to a first embodiment of the invention;
Fig. 2	a modification of the method illustrated in Figure 1;
Fig. 3A	a diagram relating to a method according to another embodiment of the invention; and
Fig. 3B	a modification of the method illustrated in Figure 3A.

According to Figure 1, first data 1 is transmitted via a first transmission variant Dim1 (e.g. a first carrier polarization) and second data 2 is transmitted via a second transmission variant Dim2 (e.g. a second carrier polarization).

The first data 1 comprises a stream of first payload data D and first pilot symbols P are inserted into the payload D. The second data 2 comprises second payload data D' (e.g. different from the first payload data D), wherein second pilot symbols P* are inserted into the second payload data D'. The second pilot symbols P* are complex conjugates of the first pilot symbols P. By means of the first and second pilot symbols P, P*, information about transmission distortions related to the first and/or second transmission variant Dim1, Dim2 can be determined and using that information the distortions may be compensated.

It is noted that the first and second pilot symbols P, P* might be transmitted simultaneously. It is, however, also possible that the pilot symbols P, P* are transmitted with a slight relative delay. Further, each pilot symbol P, P* might be replaced by a plurality of pilot symbols (i.e. instead of a single pilot symbol a sequence of pilot symbols is used).

Further, according to another embodiment of the invention, the first and second pilot data P, P* might be added to the same payload data stream as illustrated in Fig. 2. According to Fig. 2, data 1 is transmitted via a first transmission variant in the form of an x-polarized a carrier signal. Data 1 similarly to Fig. 1 comprises payload data and pilot data. Different from Fig. 1, however, the pilot data comprises a plurality of first pilot symbols P_1 - P_N, wherein each one of the first pilot symbols P_1 - P_N is followed by a second pilot symbol P_1^* - P_N^*, which is a complex conjugate of the corresponding first pilot symbol P_1 - P_N. Thus, the first data 1 comprises pairs of first and second pilot symbols, wherein payload data might be provided between the pilot symbol pairs. In principle, an arbitrary number of pilot symbol pairs might be used.

In addition, second data 2 might be transmitted over another (second) transmission variant in the form of a y-polarized carrier signal. The second data 2 similarly to the first data 1 comprises payload data (which might be different from the payload data transmitted via the x-polarization carrier signal) and a plurality of first pilot symbols followed by second pilot symbols. The first pilot symbols are complex conjugates P_1^* - P_N^* of the first pilot symbols P_1 - P_N of the first data transmitted over the x-polarization carrier signal. Accordingly, the second pilot symbols of the second data 2 correspond to the first pilot symbols P_1 - P_N of the first data 1. Putting it another way, the method according to Fig. 2 corresponds to the method of Figure 1, wherein, however, each one of the first and second data 1, 2 comprises complex conjugated further pilot symbols.

Thus, for determining transmission distortions pilot symbol pairs P_1 - P_N, P_1^* - P_N^* transmitted over the x-polarization or over the y-polarization carrier signal could be used. In addition or alternatively, the pilot symbols P_1 - P_N, P_1^* - P_N^* transmitted over the x-polarization carrier signal could be used in combination with the pilot data P_1^* - P_N^*, P_1 - P_N transmitted over the y-polarization carrier signal. The pilot symbols thus can be evaluated both in time and polarization. In particular, the NLI for the x-polarization carrier might be estimated by evaluating the difference of pilot symbols $P_1 \dots P_N$ and $P_1^* \dots P_N^*$ of the first data sequence 1, while the NLI for the y-polarization carrier might be estimated by evaluating the difference of pilot symbols $P_1 \dots P_N$ and $P_1^* \dots P_N^*$ of the second data sequence 2. It is noted that the pilot symbols of the second data sequence 2 do not have to be complex conjugates of the pilot symbols of the first data sequence 1. Rather, other symbols could be used as pilot symbols of the second data 2.

Another embodiment of the invention is illustrated in Fig. 3A. According to this embodiment, a plurality of transmission variants Dim1 - Dim4 in the form of different frequency channels of a frequency division multiplexing scheme is used for transmitting a plurality of data sequences 1 - 4. Each one of the data sequences 1 – 4 comprises sequences of payload data, wherein pairs (e.g. “phase conjugated optical variants” – PCOV) of first and second pilot symbols P_1 - P_N, P_1^* - P_N^* are embedded in the payload data, the second pilot symbols P_1^* - P_N^* of the first data sequence being complex conjugates of the first pilot symbols P_1 - P_N. Data sequence 2 comprises pilot symbols that are transmitted simultaneously with the pilot symbols of data sequence 1, wherein the pilot symbols of data sequence 2 are complex conjugates of the concurrent pilot symbols of data sequence 1. Thus, the method depicted in Fig. 3A resembles the method shown in Fig. 2, wherein, however, different carrier frequencies are used as transmission variants instead of different carrier polarizations.

Similarly to the first and the second data sequence 1 and 2, data sequences 3 and 4 comprises pairs of first and second pilot symbols P_1 - P_N, P_1^* - P_N^* embedded in the payload data, wherein the pilot symbols are shifted in time relative to the pilot symbols of the first and the second data sequence 1 and 2. It is noted that the pilot symbols (and the payload data) of the data sequences 1 - 4, of course, do not have to be identical and in particular do not have to be complex conjugates of one another (e.g. the pilot symbols used in data sequence 1 may be different from the pilot symbols of data sequences 2 - 4). Thus, complex conjugated pilot symbols might be used in the time and/or frequency domain.

Figure 3B relates to another variant of the invention. Similar to Fig. 2, different carrier polarizations (x- and y-polarization) are used for transmitting first and second data 1, 2, wherein first and second pilot symbols P_1 - P_N, P_1^* - P_N^* (arranged as pairs P_1, P_1^* - P_N, P_N^*) of the first data 1 are transmitted via the x-polarization carrier while their complex conjugated counterparts P_1^* - P_N^*, P_1 - P_N^* (the first and second pilot symbols of the second data 2, arranged as pairs P_1^*, P_1, - P_N^*, P_N) are transmitted via the y-polarization carrier. In contrast to Fig. 2, however, the first and second pilot symbols P_1 - P_N, P_1^* - P_N^* of the first and the second data 1, 2, respectively, are not transmitted in a timely sequence, but via different frequency channels, wherein the pilot symbols of the different data sequences 1, 2 are transmitted in the same frequency channel. In particular, the pilot symbols of each one of the pilot symbol pairs P_1, P_1^* - P_N, P_N^* and P_1^*, P_1, - P_N^*, P_N, respectively, are transmitted via adjacent frequency channels. This embodiment thus permits the evaluation of the pilot symbols both for different carrier frequencies and carrier polarizations.

It is again noted that the denotation "P_1", "P_2", ..., "P_N" is not necessarily a representation of a single pilot symbol, only. Rather, each one of the denotations "P_1", "P_2", ..., "P_N" might represent a plurality of pilot symbols, i.e. a sequence of pilot symbols. For example, "P_1" might be a representation of a pilot symbol sequence comprising a CAZAC sequence.

* * * * *

Claims

1. Data communication method, comprising the steps of:
   a) transmitting first data (1) using a first transmission variant (Dim1);
   b) transmitting second data (2) using a second transmission variant (Dim2), wherein
   c) the first data (1) comprises first payload data (D) and at least one first non-payload pilot symbol (P, P_1 - P_N); and wherein
   d) the second data (2) comprises second payload data (D') and at least one second non-payload pilot symbol (P*, P_1^* - P_N^*), the second pilot symbol (P*, P_1^* - P_N^*) being a complex conjugate of the first pilot symbol (P, P_1 - P_N);
   e) receiving the first and the second pilot symbol (P, P_1 - P_N, P*, P_1^* - P_N^*); and
   f) determining information related to a transmission distortion using the received first and second pilot symbol (P, P_1 - P_N, P*, P_1^* - P_N^*).

2. The method as claimed in claim 1, wherein the first transmission variant (Dim1) is a first optical transmission variant and the second transmission variant (Dim2) is a second optical transmission variant.

3. The method as claimed in claim 1 or 2, wherein the first pilot symbol (P, P_1 - P_N) is inserted into a data sequence of the first payload data (D) and/or the second pilot symbol (P*, P_1^* - P_N^*) is inserted into a data sequence of the second payload data (D').

4. The method as claimed in any of the preceding claims, wherein determining information according to step f) comprises superimposing the received first and second pilot symbol (P, P_1 - P_N, P*, P_1^* - P_N^*).

5. The method as claimed in any of the preceding claims, wherein the first and the second transmission variant (Dim1, Dim2) differ from one another in at least two transmission characteristics.

6. The method as claimed in any of the preceding claims, wherein the first and the second transmission variant (Dim1, Dim2) belong to the same multiplexing scheme.

7. The method as claimed in any of the preceding claims, wherein the first transmission variant (Dim1) has at least one of the following transmission characteristics: a first carrier polarization, a first time division multiplexing time domain, a first code division multiplexing code, a first carrier wavelength and a first carrier frequency, and wherein the second transmission variant (Dim2) has at least one of the following transmission characteristics: a second carrier polarization, a second time division multiplexing time domain, a first code division multiplexing code, a second carrier wavelength and a second carrier frequency.

8. The method as claimed in any of the preceding claims, wherein the first and the second transmission variant (Dim1, Dim2) belong to a polarization division multiplexing scheme, wherein the first transmission variant (Dim1) uses a first carrier polarization for transmitting the first payload data (D) and the first pilot symbol (P, P_1 - P_N) and the second transmission variant (Dim2) uses a second carrier polarization for transmitting the second payload data (D') and the second pilot symbol (P^*, P_1^* - P_N^*).

9. The method as claimed in claim 8, wherein the first and the second transmission variant (Dim1, Dim2) in addition belong to a time division multiplexing scheme, wherein the first and the second pilot symbol (P, P_1 - P_N, P^*, P_1^* - P_N^*) are transmitted via the same time domain.

10. The method as claimed in claim 8 or 9, wherein at least one further pilot symbol is transmitted using the first carrier polarization, wherein the further pilot symbol is a complex conjugate of the first pilot symbol (P, P_1 - P_N), and/or at least one further pilot symbol is transmitted using the second carrier polarization, the further pilot symbol being a complex conjugate of the second pilot symbol (P^*, P_1^* - P_N^*).

11. The method as claimed in any of claims 8 to 10, wherein the first and the second pilot symbol (P, P_1 - P_N, P^*, P_1^* - P_N^*) are transmitted via the same carrier frequency.

12. The method as claimed in any of the preceding claims, wherein a plurality of first and/or second pilot symbols (P, P_1 - P_N, P^*, P_1^* - P_N^*) is provided, wherein the plurality of the first and/or the second pilot symbols (P, P_1 - P_N, P^*, P_1^* - P_N^*) comprises a CAZAC sequence.

13. The method as claimed in any of the preceding claims, wherein a compensation of intra-channel nonlinear effects is carried out before using the received first and second pilot symbol (P, P_1 - P_N, P*, P_1^* - P_N^*) for determining information according to step f).

14. The method as claimed in any of the preceding claims, wherein a unitary matrix transformation is applied to the first and/or the second pilot symbol (P, P_1 - P_N, P*, P_1^* - P_N^*) before their transmission or after their receipt.

15. The method as claimed in any of the preceding claims, wherein the information determined in step f) is used for initialization and/or update of at least one coefficient of a digital filter used for the compensation of linear and/or non-linear inter-channel effects.

16. The method as claimed in claim 15, wherein the digital filter is a decision feedback equalizer.

17. The method as claimed in any of the preceding claims, wherein a symmetric dispersion map is applied to the first and/or the second data before the information according to step f) is determined.

18. The method as claimed in claim 17, wherein the symmetric dispersion map is a power weighted accumulated dispersion map.

19. Data communication method, in particular as claimed in any of the preceding claims, comprising the steps of:
    a) providing data (1, 2) that comprises payload data (D, D'), at least one first non-payload pilot symbol (P, P_1 - P_N) and at least one second non-payload pilot symbol (P*, P_1^* - P_N^*), the second pilot symbol (P*, P_1^* - P_N^*) being a complex conjugate of the first pilot symbol (P, P_1 - P_N),
    b) transmitting the payload data (D, D'), the first non-payload pilot symbol (P, P_1 - P_N) and the second non-payload pilot symbol (P*, P_1^* - P_N^*) using the same transmission variant (Dim1, Dim2);
    c) receiving the first and the second pilot symbol (P, P_1 - P_N, P*, P_1^* - P_N^*); and

d) determining information related to a transmission distortion using the received first and second pilot symbol (P, $P_1 - P_N$, P^*, $P_1^* - P_N^*$).

20. Data communication system, in particular for carrying out the method as claimed in any of the claims 1 to 18, comprising:
    - at least one transmitting unit configured for transmitting first data (1) using a first transmission variant (Dim1) and second data (2) using a second transmission variant (Dim2), wherein
    - the first data (1) comprises first payload data (D) and at least one first non-payload pilot symbol (P, $P_1 - P_N$); and wherein
    - the second data (2) comprises second payload data (D’) and at least one second non-payload pilot symbol (P^*, $P_1^* - P_N^*$), the second pilot symbol (P^*, $P_1^* - P_N^*$) being a complex conjugate of the first pilot symbol (P, $P_1 - P_N$);
    - at least one receiving unit configured for receiving the first and the second pilot symbol (P, $P_1 - P_N$, P^*, $P_1^* - P_N^*$); and
    - an evaluation unit for determining information related to a transmission distortion using the received first and second pilot symbol (P, $P_1 - P_N$, P^*, $P_1^* - P_N^*$).

21. Data communication system, in particular for carrying out the method claimed in claim 19, comprising:
    - at least one transmitting unit for transmitting data (1, 2) that comprises payload data (D, D’), at least one first non-payload pilot symbol (P, $P_1 - P_N$) and at least one second non-payload pilot symbol (P^*, $P_1^* - P_N^*$) using the same transmission variant (Dim1, Dim2), the second pilot symbol (P^*, $P_1^* - P_N^*$) being a complex conjugate of the first pilot symbol (P, $P_1 - P_N$);
    - at least one receiving unit for receiving the first and second pilot symbol (P, $P_1 - P_N$, P^*, $P_1^* - P_N^*$); and
    - an evaluation unit for determining information related to a transmission distortion using the received first and second pilot symbol (P, $P_1 - P_N$, P^*, $P_1^* - P_N^*$).

FIG 1

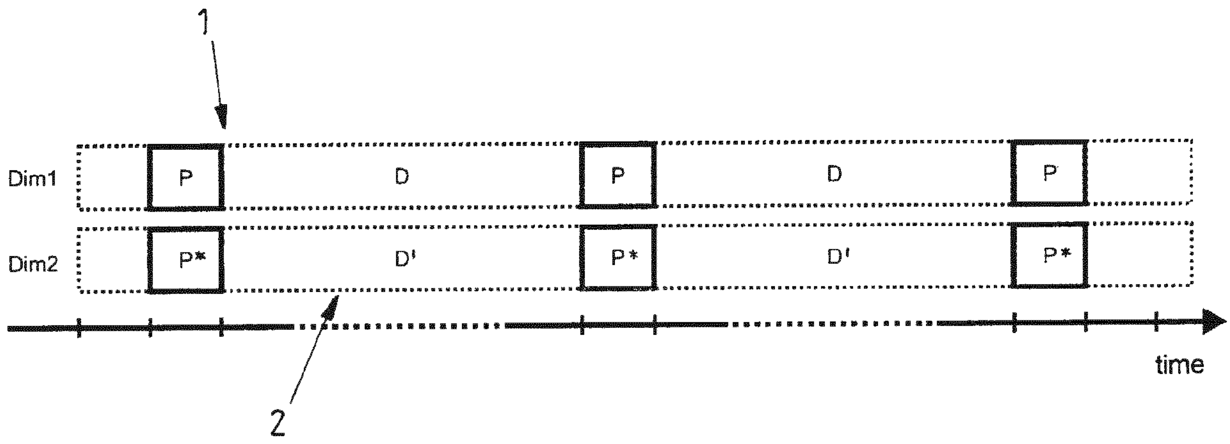

1
Dim1
P
D
P
D
P
Dim2
P*
D'
P*
D'
P*
time
2

FIG 2

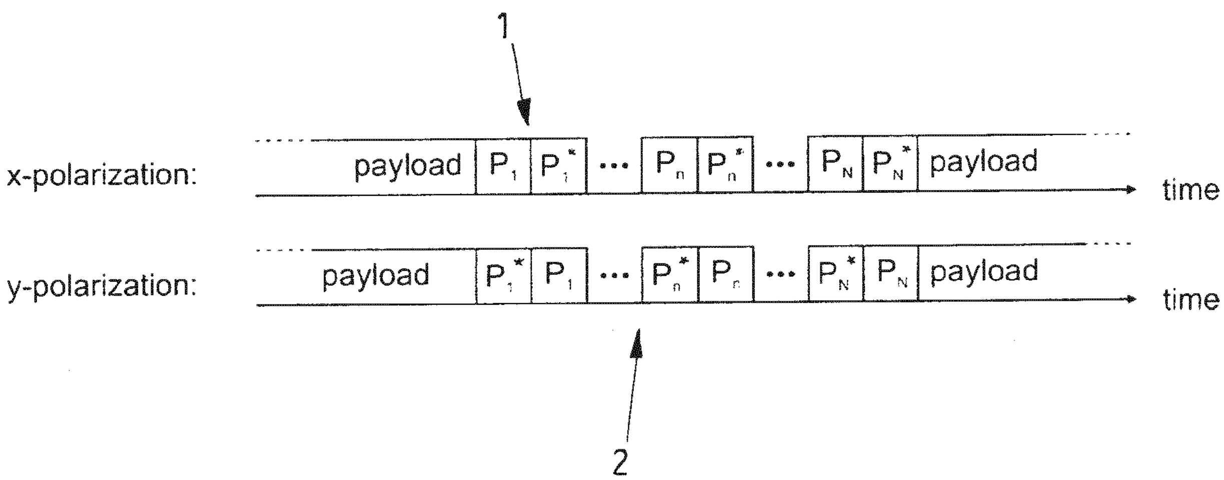

1
x-polarization:
payload
P_1
P_1^*
P_n
P_n^*
P_N
P_N^*
payload
time
y-polarization:
payload
P_1^*
P_1
P_n^*
P_n
P_N^*
P_N
payload
time
2

FIG 3A

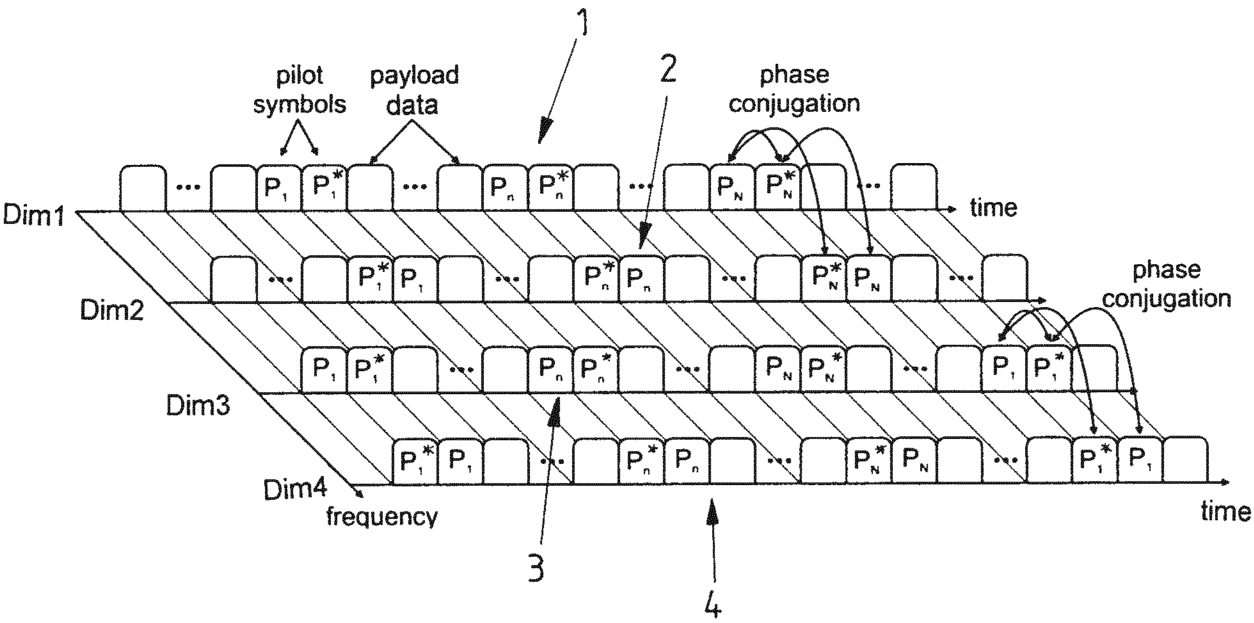
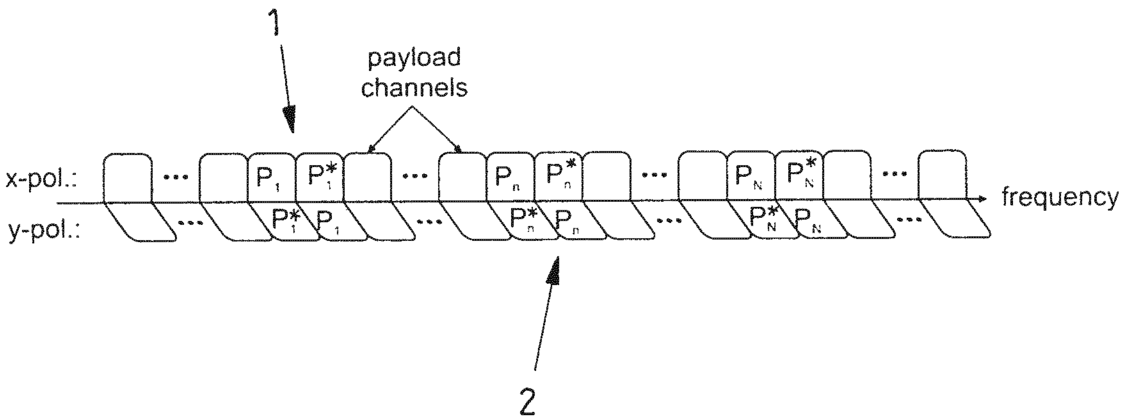

1
pilot symbols
payload data
2
phase conjugation
time
phase conjugation
Dim1
Dim2
Dim3
Dim4
frequency
time
3
4

FIG 3B


1
payload channels
x-pol.:
y-pol.:
frequency
2

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/061562

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B10/61
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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	LE SON THAI ET AL: "Phase-Conjugated Pilots for Fibre Nonlinearity Compensation in CO-OFDM Transmission", JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 33, no. 7, 1 April 2015 (2015-04-01), pages 1308-1314, XP011575170, ISSN: 0733-8724, DOI: 10.1109/JLT.2015.2388854 [retrieved on 2015-03-09]	1,20
Y	Section II and Section III first three paragraphs ----- -/--	1-21

[X] 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

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"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
12 February 2016	22/02/2016

Name and mailing address of the ISA/	Authorized officer
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2

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	XIANG LIU ET AL: "Phase-conjugated twin waves for communication beyond the Kerr nonlinearity limit", NATURE PHOTONICS, vol. 7, no. 7, 26 May 2013 (2013-05-26), pages 560-568, XP055194867, ISSN: 1749-4885, DOI: 10.1038/nphoton.2013.109 cited in the application Section Basic Principle; figure 1c -----	1-21
A	NOLLE MARKUS ET AL: "Investigation of CAZAC sequences for data-aided channel estimation considering nonlinear optical transmission", 2015 OPTICAL FIBER COMMUNICATIONS CONFERENCE AND EXHIBITION (OFC), OSA, 22 March 2015 (2015-03-22), pages 1-3, XP032784540, [retrieved on 2015-06-10] page 1 - page 2 figure 2 -----	12
A	HENRIK ELIASSON ET AL: "Mitigation of nonlinearities using conjugate data repetition", OPTICS EXPRESS, vol. 23, no. 3, 9 February 2015 (2015-02-09), page 2392, XP055248276, ISSN: 2161-2072, DOI: 10.1364/OE.23.002392 Section 2 -----	1-21
A	LE S T ET AL: "Phase-conjugated pilots for fibre nonlinearity compensation in CO-OFDM transmission", 2014 THE EUROPEAN CONFERENCE ON OPTICAL COMMUNICATION (ECOC), SYSTEMATIC PARIS REGION SYSTEMS AND ICT CLUSTER, 21 September 2014 (2014-09-21), pages 1-3, XP032689682, DOI: 10.1109/ECOC.2014.6963871 [retrieved on 2014-11-20] the whole document -----	1-21

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