Study of EEPN mitigation using modified RF pilot and Viterbi-Viterbi based phase noise compensation

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Abstract: We propose – as a modification of the optical (RF) pilot scheme - a balanced phase modulation between two polarizations of the optical signal in order to generate correlated equalization enhanced phase noise (EEPN) contributions in the two polarizations. The method is applicable for *n*-level PSK system. The EEPN can be compensated, the carrier phase extracted and the *n*PSK signal regenerated by complex conjugation and multiplication in the receiver. The method is tested by system simulations in a single channel QPSK system at 56 Gb/s system rate. It is found that the conjugation and multiplication scheme in the Rx can mitigate the EEPN to within ½ orders of magnitude. Results are compared to using the Viterbi-Viterbi algorithm to mitigate the EEPN. The latter method improves the sensitivity more than two orders of magnitude. Important novel insight into the statistical properties of EEPN is identified and discussed in the paper.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications.

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1. Introduction

Chromatic dispersion (CD) and laser phase noise severely impact the performance of high speed optical fiber transmission systems [1,2]. Digital coherent receivers allow complete equalization of chromatic dispersion in the electrical domain by using discrete signal processing (DSP) techniques [3–7]. Several discrete (digital) filters have been applied to compensate the chromatic dispersion in the time and frequency domain [4–12]. These include the maximum likelihood sequence estimation (MLSE) method [5], a time domain fiber dispersion finite impulse response (FD-FIR) filter [7,8,12], or a frequency domain equalizer (FDE) [9–12]. It is important to note that there is a complicated interplay between the discrete chromatic dispersion compensation and the laser phase noise. This interplay leads to a combination of equalization enhanced phase noise (EEPN), amplitude noise and time jitter [13–21].

A traditional coherent receiver (Rx) utilizes a zero-forcing equalizer [13] which does not depend on the data (data pattern) or signal parameters (additive optical and electrical noise) and phase noise (laser linewidths). The derivation in [13] leads to an analytical form – with a simple physical interpretation - of the EEPN generation which results from the digital dispersion compensation. The zero-forcing equalizer is not optimal for minimizing EEPN generation in the electronic dispersion compensation stage of the Rx. It is possible to optimize a linear minimum mean square (MMSE) equalizer for specific laser phase noise influence by including laser linewidths in the equalizer description [14]. Reference [14] shows that this more optimal equalizer and the resulting EEPN is not given in closed form and that the optimization leads to very marginal influence on the EEPN generation. It is concluded that it is difficult to mitigate EEPN using simple DSP algorithms [14]. It should however be noted that the EEPN influence can be reduced significantly using a DSP implementation of the Viterbi-Viterbi algorithm [15]. In [15], the carrier phase is extracted using an optical (RF) pilot tone in the orthogonal polarization relative to the QPSK modulated signal and the Viterbi-Viterbi algorithm is applied for reducing EEPN influence. In the current paper we will – in order to simplify the discussion without sacrificing accuracy in any significant way - use the EEPN model in [13]. Based upon a leading order Taylor expansion of the laser phase noise it is possible to associate the EEPN effect with an effective laser linewidth [13,22,23]. It has been verified in brute force simulation results for the Bit-Error-Rate (BER) that this linewidth predicts resulting BER floors for differential QPSK systems well even when the EEPN influence is dominating [22,23]. The detailed effect is dependent on which type of discrete chromatic dispersion compensation is implemented in the receiver (Rx) or in the transmitter (Tx), using either post-CD compensation [23] or pre-CD compensation [24].

In this paper, we investigate - for the first time to our knowledge - how the resulting EEPN behavior can be mitigated by introducing modulation of the optical (RF) pilot phase which is correlated with the phase modulation of the QPSK signal. In the Rx, complex conjugation regenerates the deterministic (QPSK) signal, extracts the carrier phase (equivalent to the method used in [15]) and mitigates the influence of EEPN as much as possible. We include Viterbi-Viterbi algorithm into our results for the mitigation of EEPN. Our study provides significant new insight into the EEPN effect and the validation of the description via the effective linewidth [13,22]. The results of the study are presented on a BER basis using the VPI simulation platform [25].

The principle of an optical (RF) pilot tone with phase modulation is presented in section 2 of this paper. Section 3 reports simulation results, i.e. demonstrates benefit and problem areas. Section 4 gives conclusive remarks.

2. Theory

2.1 Principle and structure for Rx using optical (RF) pilot tone or distributed phase modulation in combination with CD equalization

A complete single channel coherent system is schematically shown in Fig. 1 including distributed phase modulation in two orthogonal polarizations (insert a)) or including the use of an optical (RF) pilot tone for eliminating the phase noise (insert b)) [26,27]. In the case of distributed phase modulation the system is a modified version of the classical system using an optical (RF) pilot tone since the pilot tone now includes part of the modulated signal. Two polarization states are used to transmit the modulated optical signal; one polarization has a total four level phase modulation amplitude of $2\pi\alpha$ ($0 \leq \alpha \leq 1$) and the other a modulation amplitude of $2\pi(\alpha-1)$. Negative amplitude means that the phase modulation is reversed. With this Tx configuration we will attempt to generate a correlated EEPN contribution in both polarization states. In order for the correlation to be best possible, the modulation in the two polarizations must be identical i.e. the capacity is the same as for a system with full modulation in a single polarization. The complex conjugation and multiplication in the Rx will cancel the intrinsic phase noise from the Tx and LO laser as well as the EEPN contribution in the best possible way and will extract the carrier phase. With the selected distributed and balanced modulation the complex conjugation and multiplication will furthermore recover a normal QPSK modulated deterministic signal.

In the case of using one polarization state for the modulated *n*PSK signal and the other polarization for the optical (RF) pilot tone the conjugation and multiplication in the Rx will cancel the intrinsic phase noise from the Tx and LO lasers and recover the carrier phase.

We note that the distributed modulation case is equal to the case with full modulation in one polarization and an optical (RF) pilot tone in the other when α equals 0 or 1.

We will consider an FDE filter for the chromatic dispersion compensation. We note that in this configuration the FDE and the FD-FIR filters give the same Bit-Error-Rate (BER) performance [12]. The FDE, rather than the FD-FIR filter, is selected as commonly used in most practical system demonstrations at this time. Some earlier works for PSK/QAM systems have considered an optical (RF) pilot tone transmitted in the orthogonal polarization relative to the signal [26,27]. This represents a limiting (best possible) situation for the elimination of phase noise and it is equivalent to the implementations of the optical (RF) pilot tone - and of the distributed *n*PSK modulation in two polarizations - considered in this paper.

We note that for OFDM systems it is more natural to have the optical (RF) pilot tone as one tone in the center of the OFDM signal grid since each OFDM tone is demodulated separately [28]. The OFDM signal and the optical (RF) pilot tone are in the same polarization state.

The principle of phase noise cancellation and carrier phase extraction by an optical (RF) pilot tone is simple. Let the detected coherent signal field be represented as (in the ideal case where the EEPN is seen as noise on the optical phase):

$$E_s(t) = A \cdot \exp\left(j\left(\varphi_s + \varphi_{Tx}(t) + \varphi_{LO}(t) + \varphi_{EEPN}(t) + m(t)\right)\right) \tag{1}$$

where *n*-level PSK modulation is considered, i.e. *A* is the modulated (real-valued) amplitude, φ_S is the carrier phase of the signal (the difference of carrier phase contributions from the transmitter (Tx) and local oscillator (LO) lasers), $\varphi_{Tx}(t)$ is the phase noise from the transmitter, $\varphi_{LO}(t)$ is the phase noise from the local oscillator, $\varphi_{EEPN}(t)$ is the noise from EEPN, and *m(t)* represents the phase modulation. The optical (RF) pilot tone is a CW optical signal from the same optical signal source as the modulated signal (i.e. it has the same phase noise but possibly a different carrier phase φ_{RF}). Then in the ideal case the field is given as:

$$E_{RF}(t) = B \cdot \exp\left(\left(j(\varphi_{RF} + \varphi_{Tx}(t) + \varphi_{LO}(t))\right)\right) \tag{2}$$

where *B* is an arbitrary constant amplitude. The conjugated signal operation that eliminates the intrinsic laser phase noise is given (within the arbitrary amplitude constant, *B*) as:

$$E_s(t) \cdot E_{RF}^*\left(t\right) = B \cdot A \cdot \exp(j\left(\varphi_S - \varphi_{RF} + \varphi_{EEPN}(t) + m(t)\right)) \tag{3}$$

where '*' denotes complex conjugation. In Eq. (3) $\varphi_S - \varphi_{RF}$ is the extracted carrier phase and it appears that the influence of EEPN is not cancelled by the conjugated signal operation.

It is clear that if we can introduce an EEPN on the optical (RF) pilot which is fully correlated with (identical in this particular case) the EEPN on the signal then the conjugated signal operation in the Rx will eliminate the EEPN as well as the intrinsic laser phase noise. We investigate one way of doing this by distributed *n*-PSK modulation in two polarization states. If the generation of EEPN in the two polarizations is not fully correlated we can specify the effective correlation between the EEPN of the two polarization states through the parameter ρ ($-1 \le \rho \le 1$) which is specified through $\sigma_{Eff}^2 = (1-\rho)^2\sigma_{EEPN}^2$, where σ_{Eff}^2 corresponds to the BER-floor position (see Eq. (7) in the following section). Then the conjugation and multiplication operation of the Rx will only partly mitigate the EEPN influence and Eq. (3) is modified to read:

$$E_1(t)\cdot E_2^*(t)=B\cdot A\cdot\exp\left(j\left(\varphi_1-\varphi_2+(1-\rho)\cdot\varphi_{EEPN}(t)+m(t)\right)\right) \tag{4}$$

where the carrier phase $\varphi_1-\varphi_2$ is the difference in initial phase between the optical signals in the two polarization states for the system.

2.2 Phase noise analysis

It is relevant to discuss the total phase noise influence in the system. We will use a FDE filter for CD equalization. In this configuration the EEPN scales linearly with the accumulated chromatic dispersion and the linewidth of the LO laser [13]. The LO laser that contributes to the generation of EEPN in the digital CD compensation process described via the variance

$$\sigma_{EEPN}^2=\frac{\pi\lambda^2}{2c}\cdot\frac{D\cdot L\cdot\Delta f_{LO}}{T_S}\equiv 2\pi\Delta f_{EE}\cdot T_s \tag{5}$$

where λ is the central wavelength of the transmitted optical carrier wave, c is the light speed in vacuum, D is the chromatic dispersion coefficient of the transmission fiber, L is the transmission fiber length, Δf_{LO} is the 3-dB linewidth of the LO laser, Δf_{EE} is the 3 dB linewidth associated with EEPN and T_s is the symbol period of the transmission system. The effective phase noise variance specified in Eq. (5) has 2/3 contribution from the phase noise of EEPN and 1/3 from the amplitude noise [13] showing that EEPN is not a pure phase noise and in this way differs from intrinsic laser phase noise. Equation (5) enables a definition of the effective intermediate frequency (IF) linewidth [22] - which defines the phase noise influence in the receiver:

$$\Delta f_{Eff}\approx\frac{\sigma_{Tx}^2+\sigma_{LO}^2+\sigma_{EEPN}^2}{2\pi T_S}\equiv\frac{\sigma_{Eff}^2}{2\pi T_s}=\Delta f_{Tx}+\Delta f_{LO}+\Delta f_{EE} \tag{6}$$

where Δf_{Tx} is the 3-dB transmitter laser linewidth, $\sigma_{Tx}^2=2\pi\Delta f_{Tx}\cdot T_S$ is the transmitter laser phase noise variance, Δf_{LO} is the 3-dB local oscillator laser linewidth and $\sigma_{LO}^2=2\pi\Delta f_{LO}\cdot T_S$ is the LO laser phase noise variance. Equation (6) implies that correlation between the LO and EEPN phase noise contributions can be neglected which is a valid approximation for a normal transmission fiber for very short (few km) or longer distances (above the order of 80 km) [22]. The BER-floor position which is defined from the phase noise influence using the optical (RF) pilot tone or the single tap normalized lease mean square (NLMS) filter to determine the carrier phase [29] is specified as (for an nPSK Rx) [22,30]:

$$BER_{floor}^{NLMS}\approx\frac{1}{\log_2 n}erfc\left(\frac{\pi}{n\sqrt{2}\sigma_{Eff}}\right) \tag{7}$$

Numerical examples will be considered in Section 3 of this paper.

In this paper we focus on n-level PSK systems which effectively utilize two polarizations to transmit the capacity of a normal one polarization system. The same total capacity can be implemented by using both polarizations for transmission with a capacity per polarization which is halved. Then the symbol time T_s is doubled and Eq. (5)–Eq. (7) show that the *BER* floor position is moved down. If the floor position system with high single channel capacity is BER_{HC} then the floor for the system with low capacity is in the order of $BER_{LC}\approx(BER_{HC})^2$. Thus the dual polarization system can very much eliminate the EEPN influence. For dual polarization operation the carrier phase extraction cannot be done using the optical (RF) pilot scheme as used in this paper, a single tap NLMS filter or the Viterbi-Viterbi algorithm has to be applied [31]. It is to be noted that the BER-floor approximation in Eq. (7) becomes poor (too optimistic by one order of magnitude or more) for dual polarization QPSK systems when the

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EEPN is significant and the carrier phase is estimated using the single tap NLMS filter or using the Viterbi-Viterbi algorithm (see e.g [31].). Thus a detailed comparison between dual polarization systems and single polarization systems using the optical (RF) principle to extract the carrier phase requires further studies. The results of the current paper show that Eq. (7) is an accurate approximation for large EEPN when the carrier phase is extracted using the optical (RF) principle as presented in section 2.1.

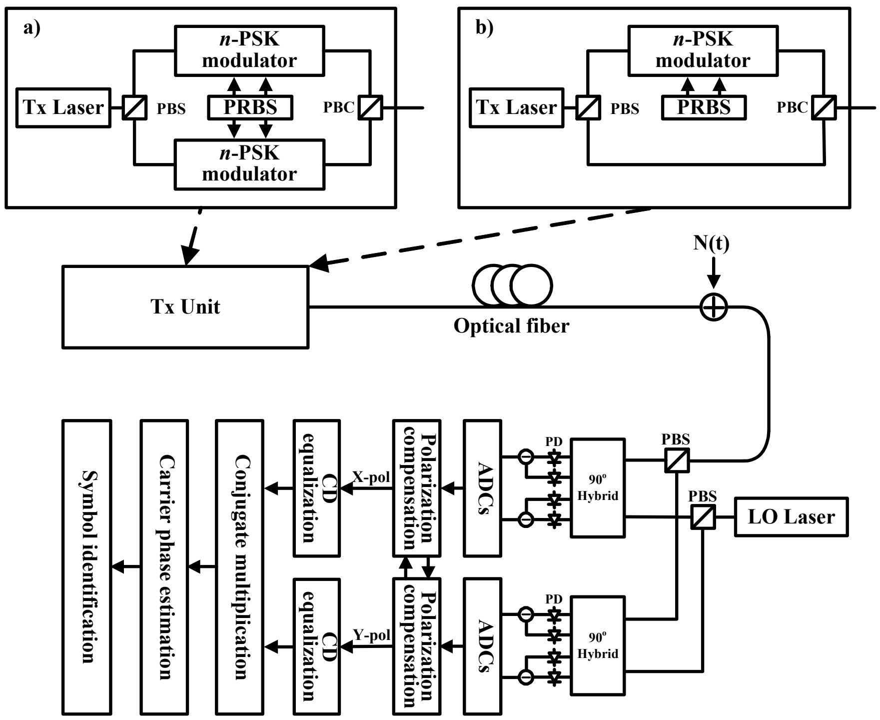

Fig. 1. Block diagram for single channel *n*PSK system. Figure insert a) is the transmitter Tx) unit for the dual polarization distributed *n*PSK modulation case. Figure insert b) is for *n*PSK modulation in one polarization and using the orthogonal polarization signal for an optical (RF) pilot tone. In both cases carrier phase estimation is done in the conjugate multiplication in the Rx. The Viterbi-Viterbi algorithm may be used to filter the phase noise. N(t) shows the added optical noise which is used to measure the Bit-Error-Rate (BER) as a function of optical signal-to-noise ratio (OSNR). Figure abbreviations: Tx – transmitter; PBS – polarizing beam splitter; PBC – polarizing beam combiner; PRBS – pseudo random bit sequence ; LO – local oscillator; ADC – analogue to digital conversion; CD – chromatic dispersion.

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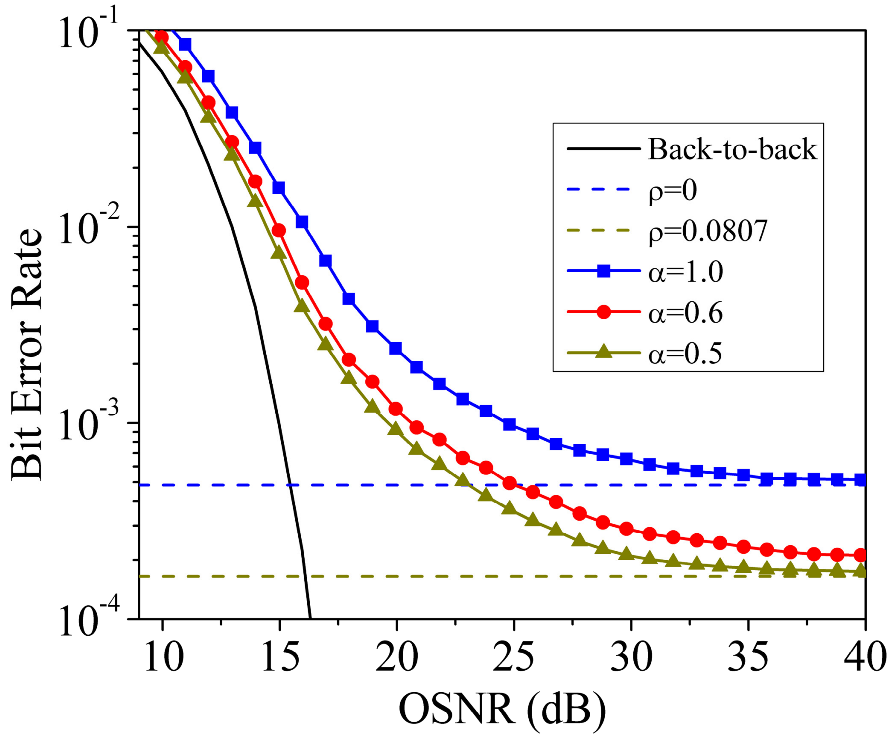

Fig. 2. BER for single channel QPSK coherent system of Fig. 1 for transmitter and Local Oscillator linewidths equal to 5 MHz. Results are for transmission distance of 2000 km. Three curves with markers are simulation results for different phase modulation balance as indicated by the α-value. The PRBS length is 2^{16}-1. Analytically specified BER-floors (Eq. (7)) are shown by dashed lines with specified ρ-values. Figure abbreviations: OSNR - optical signal-to-noise ratio.

3. Simulation method, results and discussion

3.1 Use of distributed QPSK modulation

In the simulations, we consider a QPSK system with a symbol frequency of 28 GS/s, i.e. the single channel system capacity using In-phase and Quadrature modulation is 56 Gb/s.

We consider a normal single mode transmission fiber with dispersion coefficient $D = 16$ ps/nm/km and zero dispersion slope. The transmission distance L is 2000 km. We consider an intrinsic intermediate frequency 3 dB linewidth of $\Delta f_{LO} = \Delta f_{Tx} = 5$ MHz. This gives an effective linewidth of $\Delta f_{EE} = 206$ MHz (see Eq. (6)). We utilize the software tool from VPI [25] for the system simulations, and we evaluate the Bit-Error-Rate versus optical signal-to-noise ratio (OSNR). In the Rx we apply optical (RF) pilot tone principle (see section 2.1) for carrier phase extraction.

Figure 2 shows BER results. As a reference, we consider the case of α = 1 where the phase modulation is in one polarization only and an optical (RF) pilot tone is transmitted in the orthogonal polarization (Fig. 1 insert b)). In this case the EEPN is not cancelled by the optical (RF) pilot tone and the resulting BER-floor - given by Eq. (7) - of $4.9 \cdot 10^{-4}$ – see dashed blue line. When the cases of α = 0.6/0.5 are considered, part of the EEPN is cancelled resulting in a BER-floor of $1.7 \cdot 10^{-4}$ in the best case (α = 0.5).

We can observe that the implementation of the balanced phase modulation in two polarizations creates a partly correlated EEPN, and this is weakly dependent on the balancing (there is a very small difference in the EEPN cancellation effect between α of 0.6 and 0.5) with

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the strongest correlation for full balancing ($\alpha = 0.5$). The EEPN cancellation improves the BER-floor position by about ½ order of magnitude, and thus it has a partial effect. This will be discussed more in section 3.2.

It may be of interest to describe the EEPN cancellation by fitting a BER-floor into the results for $\alpha = 0.5$ we can specify the effective correlation between the EEPN of the two polarization states through the parameter ρ ($-1 \le \rho \le 1$) which is specified through $\sigma_{Eff}^2 = (1-\rho)^2\sigma_{EEPN}^2$ - where σ_{Eff}^2 corresponds to the BER-floor position – Eq. (7). In our case we find $\rho = 0.0807$ where a value of 1 corresponds to full correlation i.e. complete EEPN mitigation.

3.2 Using the Viterbi-Viterbi algorithm

We will now use the Viterbi-Viterbi algorithm in the Rx considering the transmission cases of Fig. 2. First we look at the effect of this on constellation diagrams for OSNR = 35 dB i.e. when EEPN generates a phase noise error-rate-floor. Figure 3 shows the constellation diagrams for the single polarization QPSK system including an optical (RF) pilot tone in the orthogonal polarization state ($\alpha = 1$). Results are given without using (Fig. 3(a)) and using (Fig. 3(d)) the Viterbi-Viterbi algorithm. Here we observe in Fig. 3(a) that the constellation symbols are influenced partly by phase noise (the noise cloud is partly banana-shaped) and partly by amplitude noise (the cloud center is circular) in agreement with the nature of EEPN discussed in section 2. The use of the Viterbi-Viterbi algorithm removes the part of the noise cloud which is due to phase noise and a large improvement in the BER is seen (to be quantified later).

Figure 3(b) and 3(e) show diagrams for the QPSK system with distributed phase modulation in two polarizations ($\alpha = 0.5$). It appears that the modulation generates EEPN which is correlated with the QPSK symbols where the two upper symbols are dominated by phase noise whereas the lower symbols are dominated by additive noise. Also, the Viterbi-Viterbi algorithm does not improve the BER in this particular case. The reason for this is tentatively explained as follows: The Viterbi-Viterbi algorithm [32] is in the normal implementation for coherent optical QPSK systems (as used here [31]) raising the complex signal to power 4 in the QPSK case in order to eliminate the signal modulation. For this particular constellation (Fig. 3(b)) the noise is modulation dependent. Thus the Viterbi-Viterbi algorithm does not fully remove the modulation dependence and this is suggested to be the reason why it does not in an effective way mitigate the EEPN. Further theoretical investigation is needed in order to explain the simulation results in all details.

As an important reference case (considering Wiener phase noise) we have in Fig. 3(c) and 3(f) shown results for a back-to-back (for the QPSK system with an optical (RF) pilot tone) with Tx and LO laser linewidths equal to 103 MHz (the sum of the two linewidths equals the EEPN generated linewidth for the previous case - see Eq. (5)) and using a single tap NLMS filter for the carrier phase extraction [29]. The Viterbi-Viterbi algorithm is used to mitigate the phase noise as much as possible. Here we observe a clearly phase noise dominated constellation in Fig. 3(c) and the phase noise is significantly removed using the Viterbi-Viterbi algorithm – leaving a very narrow but still strongly phase noise influenced (banana shaped) noise part in Fig. 3(f). The resulting BER is expected to be improved at least somewhat.

In Fig. 4 we show how the phase noise sensitivity is dependent on the use of the Viterbi-Viterbi carrier phase extraction for the three QPSK implementations considered already in Fig. 3. It is observed that the improvement is very significant for the classical QPSK system with an optical (RF) pilot tone which is influenced by EEPN (as may be expected from Figs. 3(a) and 3(d)). An improvement of the BER-floor of more than two orders of magnitude is seen. The use of the Viterbi-Viterbi algorithm does not improve the situation for the distributed QPSK modulation case. We have shown in the figure also the classical QPSK case influenced by pure (Wiener) laser phase noise (Tx and LO linewidths of 103 MHz) using no optical (RF) pilot tone and using NLMS single tap carrier phase extraction. This gives a strong influence of the phase noise and using Viterbi-Viterbi for carrier phase extraction gives only a marginal improvement. Including an optical (RF) pilot tone for phase noise cancellation and carrier phase extraction provides complete phase noise cancellation in the pure phase noise case, and the resulting BER performance is given by the back-to-back results in Fig. 4 for linewidths of 5 MHz. These back-to-back results apply both for the QPSK system with distributed phase modulation between the orthogonal polarizations ($\alpha = 0.5$) and to the QPSK system with full phase modulation in one polarization and an optical (RF) pilot tone in the orthogonal one ($\alpha = 1$). The results are the same regardless of the use of the Viterbi-Viterbi algorithm as should be expected since no EEPN has been generated and the Wiener phase noise is small.

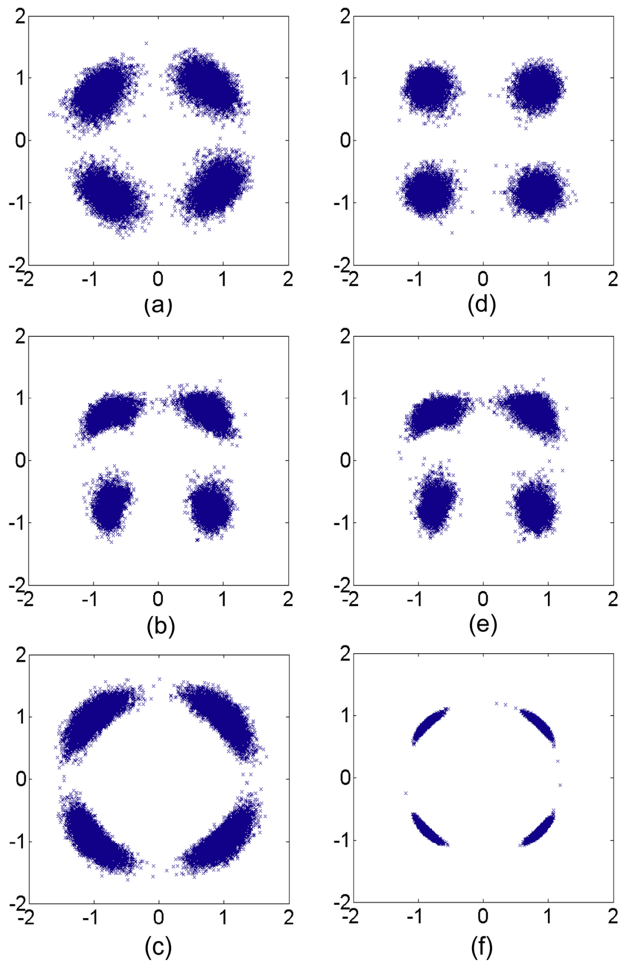

Fig. 3. Constellation diagrams for single channel QPSK coherent system of Fig. 1 for transmitter and Local Oscillator linewidths equal to 5 MHz. Results are for transmission distance of 2000 km and OSNR of 35 dB. Subfigures (a) and (d) are for $\alpha = 1$ (classical QPSK system) with optical (RF) pilot tone carrier phase extraction (CPE) (a) and in addition using the Viterbi-Viterbi algorithm (d). Subfigures (b) and (e) are for distributed modulation QPSK ($\alpha = 0.5$) with optical (RF) pilot tone CPE (b) and using in addition the Viterbi-Viterbi algorithm (e). Subfigures (c) and (f) are for classical QPSK with no optical (RF) pilot tone (using NLMS CPE) with Wiener phase noise and back-to-back transmission (Tx and LO linwidths of 103 MHz) (c) and using in addition the Viterbi-Viterbi algorithm (f).

#186116 - $15.00 USD Received 27 Feb 2013; revised 5 Apr 2013; accepted 8 May 2013; published 13 May 2013

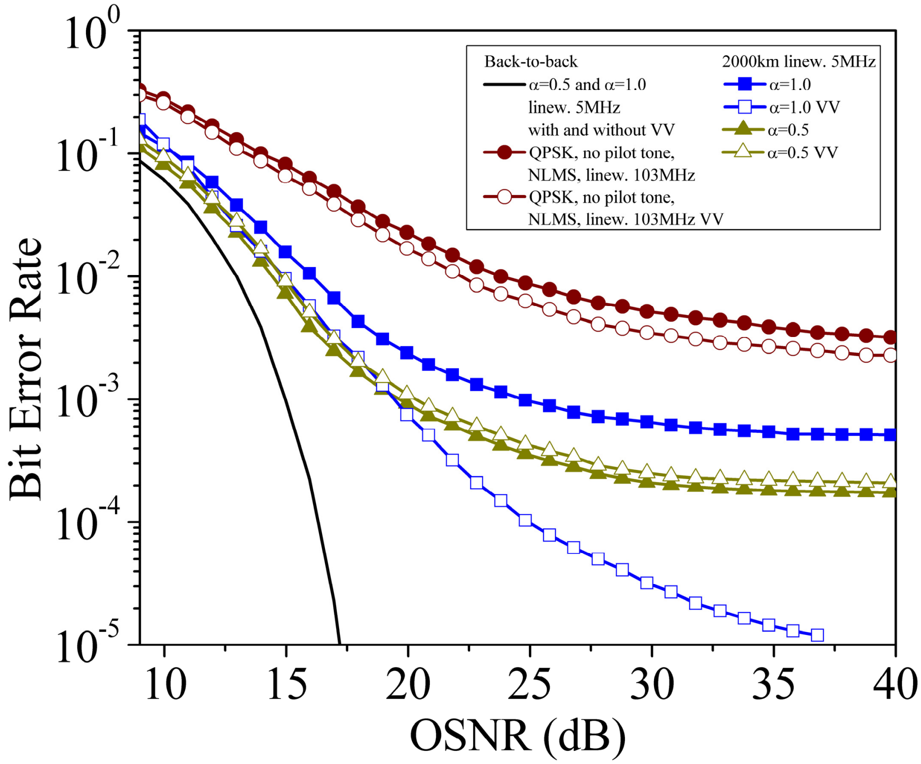

Fig. 4. BER for single channel QPSK coherent systems of Fig. 1. Curves are referred to the figure insert. Curves with α = 0.5 are for the distributed PSK modulation in two polarizations. Curves with α = 1 are for the full PSK modulation in one polarization and including an optical (RF) pilot tone in the orthogonal polarization state. Transmission distances are either back-to-back or 2000 km as indicated. Tx and LO laser have equal linwidths as specified in figure inserts. In the reference case with linewidths of 103 MHz and back-to-back transmission no optical (RF) pilot tone is included in the system and the carrier phase estimation is performed using a single tap NLMS filter (also indicated in the insert). Systems are compared using the Viterbi-Viterbi (VV) algorithm or not using it as indicated. The PRBS length for all cases is 2^{16}-1. Figure abbreviations: OSNR - optical signal-to-noise ratio; VV – Viterbi-Viterbi; PN – phase noise; NLMS – normalized least mean square.

From Fig. 4 we conclude that the Viterbi-Viterbi algorithm is a "lucky punch" case particularly for classical QPSK systems influenced by EEPN. The algorithm is expected to work equally well for n-level PSK systems with $n > 4$.

We have extended our transmission range to 3000 km in order to compare in detail to BER-results of [15] for QPSK systems with and without using the Viterbi-Viterbi algorithm and have found excellent agreement.

3.3 Comparison of shared modulation and Viterbi-Viterbi EEPN mitigation techniques for practical systems

The results presented here show that the use of the Viterbi-Viterbi algorithm to improve EEPN sensitivity for classical QPSK systems gives by far the best performance reducing the BER-floor induced by EEPN by more than two orders of magnitude. Furthermore, this implementation allows dual polarization operation of the system and thus it is capacity effective. A disadvantage is that the method is computational demanding as can be seen from the comparison in Table 1 between using the Viterbi-Viterbi algorithm (both to eliminate EEPN and/or to extract the carrier phase), using the optical (RF) pilot tone principle, or using a single tap NLMS filter. (The table is derived from considerations analogous to those for

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different dispersion compensation implementations in [12].) This is especially the case when using many cells N_{VV} in the Viterbi-Viterbi algorithm. This is required when dealing with EEPN dominated noise (in the order of $N_{vv} \approx 35$ in our case). This may especially be a problem when transmitting real time services that do not allow buffering in the receiver or services requiring low latency. Also the Viterbi-Viterbi method (as implemented as in [31]) does work for *n*-level PSK modulation but not for classical *n*-level QAM modulation (with non-circular constellations) where the single tap NLMS carrier phase extraction or the classical (unmodulated) optical (RF) pilot tone implementation works well.

Table 1. Complexity of carrier phase estimation (CPE) methods

CPE method	Complex multiplications per symbol (n - PSK modulation level, C_{update} - update effort per symbol, N_{vv} - block size)
Optical (RF) pilot	$C_{RF} = 1 + C_{update}$
NLMS	$C_{NLMS} = 3 + C_{update}$
Viterbi-Viterbi (VV)	$C_{VV} = n - 1 + C_{update} \cdot N_{vv}$

Pilot-tone EEPN mitigation (with distributed QPSK modulation) works for *n*-level PSK modulated systems. It does not allow dual polarization operation. It gives less improvement of the EEPN sensitivity – about ½ order of magnitude for BER-floor position. However, it is computational effective and suited for real time system operation with low latency.

4. Conclusions

In this paper we propose a balanced phase modulation between two orthogonal polarizations of the optical signal in order to generate correlated equalization enhanced phase noise (EEPN) contributions in the two polarizations. The method is applicable for *n*-level PSK systems with coherent detection in the receiver. Then the EEPN can be in principle compensated by complex conjugation multiplication in the receiver, and the full phase modulated *n*PSK signal is regenerated. The proposed method is tested by system simulations in a single channel QPSK system at 56 Gb/s system rate. It is found that the conjugation and multiplication scheme cannot fully mitigate the EEPN. An improvement of about ½ order of magnitude in Bit-Error-Rate (BER) floor position is observed.

Results are compared to using the Viterbi-Viterbi algorithm to mitigate the EEPN in a classical QPSK system with an optical (RF) pilot tone in the orthogonal polarization relative to the signal. The Viterbi-Viterbi method improves the sensitivity by more than two orders of magnitude. We note that the Viterbi-Viterbi algorithm is equally effective in mitigating EEPN for dual polarization QPSK implementations (where the carrier phase is extracted e.g. from the Viterbi-Viterbi algorithm or using single tap NLMS filtering [31]).

It is seen that the use of the Viterbi-Viterbi algorithm does not improve the EEPN sensitivity any further for the system with distributed QPSK modulation in two orthogonal polarization states. For this system implementation, the receiver statistics is clearly symbol dependent and this seems to be the reason why the Viterbi-Viterbi method has problems. The Viterbi-Viterbi algorithm is found to be only marginally efficient for improving the sensitivity for Wiener laser phase noise rather than EEPN in the classical QPSK case. Thus, important novel insight into the statistical properties of EEPN is identified and discussed in this paper presenting subjects which need further investigation.

In this paper we show results for *n*-level PSK systems which effectively utilize two polarizations to transmit the capacity of a normal one polarization system. The same total capacity can be implemented by using both polarizations for transmission with a capacity per polarization which is halved. Then the symbol time T_s is doubled and Eq. (5)–Eq. (7) shows that the *BER* floor position is moved down. If the floor position system with high single channel capacity is BER_{HC} then the floor for the system with low capacity is about $BER_{LC} \approx (BER_{HC})^2$. Thus the dual polarization system design can significantly eliminate the EEPN influence and the influence is mitigated further using the Viterbi-Viterbi algorithm. For dual polarization operation the carrier phase extraction cannot be done using the optical (RF) pilot scheme as used in this paper, a single tap NLMS filter or the Viterbi-Viterbi algorithm has to be applied. It is to be noted that the BER-floor approximation in Eq. (7) (without using the Viterbi-Viterbi algorithm) becomes poor (too optimistic by one order of magnitude or more) for dual polarization QPSK systems when the EEPN is significant and the carrier phase is estimated using the single tap NLMS filter or using the Viterbi-Viterbi algorithm (see e.g [31].). Thus a detailed comparison between dual polarization systems and single polarization systems using the optical (RF) principle to extract the carrier phase requires further studies. The results of the current paper show that Eq. (7) is an accurate approximation for large EEPN when the carrier phase is extracted using the optical (RF) principle as presented in section 2.1.

It is of practical interest to consider implications that can be derived from the study in this paper – which is focused on n-level PSK systems - to n-level QAM systems. For practical coherent n-level QAM systems, the use of optical (RF) pilot tone phase noise compensation using distributed modulation does not seem to be feasible. Nor does the Viterbi-Viterbi algorithm (in its current implementation [31]) work for classical QAM systems. For QAM systems it is advisable to select a dual polarization design using a LO-laser with little phase noise in order to eliminate EEPN effects as much as possible or to use hardware based chromatic dispersion compensation implementations. Such are the use of Dispersion Compensating Fibers (DCFs) (rather than digital dispersion compensation in the electronic domain) or the implementation of local oscillator phase noise cancellation by digital coherence enhancement [33]. The use of DCFs require a DSP implementation of an adaptive (few taps) NLMS dispersion compensation in the receiver [12] in order to admit fluctuations in the dispersion (e.g. due to temperature drafts). The DCF is commercially realized and simple to implement, whereas the LO phase noise cancellation is under research investigation and currently requires rather complex hardware implementation [33].

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