Receiver implemented RF pilot tone phase noise mitigation in coherent optical nPSK and nQAM systems

Gunnar Jacobsen,[1,*] Tianhua Xu,[1,2,3] Sergei Popov,[2] Jie Li,[1] Ari T. Friberg,[2] and Yimo Zhang[3]

[1] *Acreo AB, Electrum 236, SE-16440, Kista, Sweden*
[2] *Royal Institute of Technology, Stockholm, SE-16440, Sweden*
[3] *Tianjin University, Tianjin, 300072, China*
[*] *gunnar.jacobsen@acreo.se*

Abstract: In this paper, a novel method for extracting an RF pilot carrier signal in the coherent receiver is presented. The RF carrier is used to mitigate the phase noise influence in n-level PSK and QAM systems. The performance is compared to the use of an (ideal) optically transmitted RF pilot tone. As expected an electronically generated RF carrier provides less efficient phase noise mitigation than the optical RF. However, the electronically generated RF carrier still improves the phase noise tolerance by about one order of magnitude in bit error rate (BER) compared to using no RF pilot tone. It is also found, as a novel study result, that equalization enhanced phase noise - which appears as correlated pure phase noise, amplitude noise and time jitter - cannot be efficiently mitigated by the use of an (optically or electrically generated) RF pilot tone.

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

References and links

1. P. S. Henry, "Lightwave primer," IEEE J. Quantum Electron. **21**(12), 1862–1879 (1985).
2. G. P. Agrawal, *Fiber-optic communication systems 3rd Edition* (John Wiley & Sons, Inc., 2002), Chap. 2.
3. J. G. Proakis, *Digital Communications 5th Edition* (McGraw-Hill Companies, Inc., 2008), Chap.10.
4. M. G. Taylor, "Coherent detection method using DSP for demodulation of signal and subsequent equalization of propagation impairments," IEEE Photon. Technol. Lett. **16**(2), 674–676 (2004).
5. A. Färbert, S. Langenbach, N. Stojanovic, C. Dorschky, T. Kupfer, C. Schulien, J. P. Elbers, H. Wernz, H. Griesser, and C. Glingener, "Performance of a 10.7 Gb/s Receiver with digital equaliser using maximum likelihood sequence estimation," in *Proceeding of IEEE European Conference on Optical Communication* (Stockholm, Sweden, 2004), paper Th4.1.5.
6. S. J. Savory, G. Gavioli, R. I. Killey, and P. Bayvel, "Electronic compensation of chromatic dispersion using a digital coherent receiver," Opt. Express **15**(5), 2120–2126 (2007).
7. S. J. Savory, "Digital filters for coherent optical receivers," Opt. Express **16**(2), 804–817 (2008).
8. S. J. Savory, "Compensation of fibre impairments in digital coherent systems," in *Proceeding of IEEE European Conference on Optical Communication* (Brussels, Belgium, 2008), paper Mo.3.D.1.
9. K. Ishihara, T. Kobayashi, R. Kudo, Y. Takatori, A. Sano, E. Yamada, H. Masuda, and Y. Miyamoto, "Coherent optical transmission with frequency-domain equalization," in *Proceeding of IEEE European Conference on Optical Communication* (Brussels, Belgium, 2008), paper We.2.E.3.
10. M. Kuschnerov, F. N. Hauske, K. Piyawanno, B. Spinnler, A. Napoli, and B. Lankl, "Adaptive chromatic dispersion equalization for non-dispersion managed coherent systems," in *Proceeding of IEEE Conference on Optical Fiber Communication* (San Diego, California, 2009), paper OMT1.
11. R. Kudo, T. Kobayashi, K. Ishihara, Y. Takatori, A. Sano, E. Yamada, H. Masuda, Y. Miyamoto, and M. Mizoguchi, "Two-stage overlap frequency domain equalization for long-haul optical systems," in *Proceeding of IEEE Conference on Optical Fiber Communication* (San Diego, California, 2009), paper OMT3.
12. T. Xu, G. Jacobsen, S. Popov, J. Li, E. Vanin, K. Wang, A. T. Friberg, and Y. Zhang, "Chromatic dispersion compensation in coherent transmission system using digital filters," Opt. Express **18**(15), 16243–16257 (2010).
13. W. Shieh and K. P. Ho, "Equalization-enhanced phase noise for coherent-detection systems using electronic digital signal processing," Opt. Express **16**(20), 15718–15727 (2008).

#148326 - $15.00 USD Received 27 May 2011; revised 21 Jun 2011; accepted 22 Jun 2011; published 13 Jul 2011

14. A. P. T. Lau, W. Shieh, and K. P. Ho, “Equalization-enhanced phase noise for 100Gb/s transmission with coherent detection,” in *Proceedings of OptoElectronics and Communications Conference* (Hong Kong, 2009), paper FQ3.
15. A. P. T. Lau, T. S. R. Shen, W. Shieh, and K. P. Ho, “Equalization-enhanced phase noise for 100 Gb/s transmission and beyond with coherent detection,” Opt. Express **18**(16), 17239–17251 (2010).
16. K.-P. Ho, A. Pak Tao Lau, and W. Shieh, “Equalization-enhanced phase noise induced timing jitter,” Opt. Lett. **36**(4), 585–587 (2011).
17. C. Xie, “Local oscillator phase noise induced penalties in optical coherent detection systems using electronic chromatic dispersion compensation,” in *Proceeding of IEEE Conference on Optical Fiber Communication* (San Diego, California, 2009), paper OMT4.
18. C. Xie, “WDM coherent PDM-QPSK systems with and without inline optical dispersion compensation,” Opt. Express **17**(6), 4815–4823 (2009).
19. I. Fatadin and S. J. Savory, “Impact of phase to amplitude noise conversion in coherent optical systems with digital dispersion compensation,” Opt. Express **18**(15), 16273–16278 (2010).
20. S. Oda, C. Ohshima, T. Tanaka, T. Tanimura, H. Nakashima, N. Koizumi, T. Hoshida, H. Zhang, Z. Tao, and J. C. Rasmussen, “Interplay between Local oscillator phase noise and electrical chromatic dispersion compensation in digital coherent transmission system,” in *Proceeding of IEEE European Conference on Optical Communication* (Torino, Italy, 2010), paper Mo.1.C.2.
21. T. Xu, G. Jacobsen, S. Popov, J. Li, A. T. Friberg, and Y. Zhang, “Analytical estimation of phase noise influence in coherent transmission system with digital dispersion equalization,” Opt. Express **19**(8), 7756–7768 (2011).
22. E. Vanin and G. Jacobsen, “Analytical estimation of laser phase noise induced BER floor in coherent receiver with digital signal processing,” Opt. Express **18**(5), 4246–4259 (2010).
23. G. Jacobsen, “Laser phase noise induced error rate floors in differential n-level phase-shift-keying coherent receivers,” Electron. Lett. **46**(10), 698–700 (2010).
24. M. Nakamura, Y. Kamio, and T. Miyazaki, “Pilot-carrier based linewidth-tolerant 8PSK self-homodyne using only one modulator” in *Proceeding of IEEE European Conference on Optical Communication* (Berlin, Germany, 2007), paper 8.3.6.
25. M. Nakamura, Y. Kamio, and T. Miyazaki, “Linewidth-tolerant 10-Gbit/s 16-QAM transmission using a pilot-carrier based phase-noise cancelling technique,” Opt. Express **16**(14), 10611–10616 (2008).
26. S. L. Jansen, I. Morita, N. Takeda, and H. Tanaka, 20-Gb/s OFDM transmission over 4,160-km SSFM enabled by RF-pilot tone for phase noise compensation”, in *Proceeding of Conference on Optical Fiber Communications,* (Anaheim, California, 2007), paper PDP 15.
27. Y. Mori, C. Zhang, K. Igarashi, K. Katoh, and K. Kikuchi, “Unrepeated 200-km transmission of 40-Gbit/s 16-QAM signals using digital coherent receiver,” Opt. Express **17**(3), 1435–1441 (2009).
28. G. Jacobsen, *Noise in Digital Optical Transmission Systems*, (Artech House, Inc., 1994), pp 1 - 387.
29. www.vpiphotonics.com

1. Introduction

Fiber impairments, such as chromatic dispersion (CD) and phase noise, severely impact the performance of high speed optical fiber transmission systems [1,2]. Digital coherent receivers allow complete equalization of chromatic dispersion (a linear transmission impairment) in the electrical domain by using discrete signal processing (DSP) techniques, and have become a promising alternative approach to the use of dispersion compensation fibers [3–7]. Several discrete (digital) filters have been applied to compensate the chromatic dispersion in the time and frequency domain [4–12]. These include using the maximum likelihood sequence estimation (MLSE) method [5,12], 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 correlated equalization enhanced phase noise (EEPN), amplitude noise and time jitter [13–21]. The detailed effect is dependent on which type of discrete chromatic dispersion compensation is implemented in the receiver (Rx). Adaptive dispersion compensation - using the least mean square (LMS) method – has a different impact than using fixed filter implementations such as a time domain fiber dispersion finite impulse response filter or a frequency domain equalizer (FDE) [21].

When it comes to the system impact of phase noise, it is important to understand that moving to higher constellations (which is a way of increasing the system capacity using the same symbol rate) tends to increase the phase noise impact [21,22]. This means that higher constellation systems (i.e. realized as n-level PSK or QAM implementations with n = 4,8,16,64,…) put more stringent requirements to the spectral purity of the system transmitter (Tx) and local oscillator (LO) lasers [23]. This can be further enhanced by the total EEPN

#148326 - $15.00 USD Received 27 May 2011; revised 21 Jun 2011; accepted 22 Jun 2011; published 13 Jul 2011

effect for systems using discrete signal processing for chromatic dispersion compensation. Due to the existence of EEPN, the requirement of laser linewidth cannot be generally relaxed for the transmission system with higher symbol rate. It is important to investigate ways of eliminating, or at least partly mitigating, the phase noise effect in nPSK or nQAM systems. Here, the use of a radio frequency (RF) pilot tone - which is used in the receiver to mitigate the phase noise by complex multiplication of the received signal field - is an obvious candidate [24,25], but other DSP based methods might also be considered in future work. The RF pilot tone has been successfully used to eliminate the phase noise also in OFDM systems [26]. The practical transmission of an un-modulated (DC) RF pilot tone in the optical domain leads to reduced effective signal power (and thus system range) because of reduced modulated signal power. It may also lead to inefficient use of the two fiber polarization states for system capacity if the RF tone has to be transmitted in an orthogonal polarization state relative to the modulated signal [25]. The latter problem may be at least partly eliminated by smart modulation schemes [24]. It is important to keep in mind that the full information about the laser phase noise is present in the phase of the coherently received (modulated) signal field and, thus, the phase noise impact may be reduced using dedicated electronic DSP techniques. In this paper, we propose a method for extracting the RF pilot tone information directly in the receiver in order to mitigate the phase noise influence based on the extracted pilot tone - thus eliminating entirely the need for modifying the optical part of the transmission system.

The principle of an Rx-extracted RF pilot tone is presented in section 2 of this paper. Section 3 reports simulation results which benchmark the method, i.e. show benefits and problem areas. Section 4 gives conclusive remarks.

2. Theory

2.1 Principle and structure for extracting an RF pilot tone in the Rx

The Rx based pilot tone extraction is shown in generic form in Fig. 1. It consists of three stages: 1) extraction of the modulated signal phase after compensation for chromatic dispersion; 2) high pass filtering (HPF) to remove as much as possible the phase noise; 3) creation of the RF tone (see Eq. (4) below). The principle is described in a format which is suitable for a system that employs a combination of amplitude and phase modulation i.e. for general PSK/QAM system configurations. It should be noted that pure phase modulated (PSK) systems allow a simpler practical implementation.

The principle of phase noise cancellation by an RF pilot tone carrier is very simple. Let the detected coherent signal field be represented as:

$$E_s(t) = A(t) \cdot \exp\left(j \left(\varphi((t) + m(t) \right) \right) \tag{1}$$

where n-level PSK or QAM modulation is considered, i.e. *A(t)* is the modulated (real-valued) amplitude, $\varphi(t)$ is the phase noise, and *m(t)* represents the phase modulation. The RF pilot tone in the ideal case (i.e. generated optically) is:

$$E_{RF}(t) = B \cdot \exp(j\varphi(t)) \tag{2}$$

where *B* is an arbitrary constant amplitude, and the conjugated signal operation that eliminates the phase noise is given – to within the arbitrary amplitude constant, *B* - as:

$$E_s(t) \cdot E_{RF}^*\left(t\right) = B \cdot A(t) \cdot \exp(jm(t)) \tag{3}$$

It is well known that the leading order laser phase noise is modeled as a Brownian motion i.e. it has a Gaussian probability density function with a white frequency noise power spectral density, see e.g [28]. This leads to a phase noise spectral density (in the case of no signal phase modulation) which is proportional to f^{-2} (the inverse frequency squared). In the case of signal

#148326 - $15.00 USD Received 27 May 2011; revised 21 Jun 2011; accepted 22 Jun 2011; published 13 Jul 2011

modulation, the power spectral behavior taking into account phase noise as well as the phase modulation is more complicated, but it may still be anticipated that a major part of the phase noise is situated near DC. On the other hand, the signal modulation spectrum is concentrated around the $1/T_s$ frequency (T_s is the symbol time) and extending towards DC for long identical symbol modulation symbol sequences. Thus, it appears that filtering the received modulation signal phase by a discrete high pass filter will potentially take away major parts of the phase noise (and slightly distort the modulation signal). The remaining phase noise and distorted phase modulation is denoted $\overline{m(t)}$. As a result, an Rx extracted RF pilot tone can now be generated as (see Fig. 1):

$$\overline{E_{RF}(t)} = B \cdot \exp\left(j\left(\varphi(t) + m(t) - \overline{m(t)} \right) \right) \tag{4}$$

and this signal can be used for phase noise compensation (equivalently to the ideal RF pilot tone in Eq. (3)) by generating the signal:

$$E_s(t) \cdot \overline{E_{RF}^{*}(t)} = B \cdot A(t) \cdot \exp\left(j\overline{m(t)} \right) \tag{5}$$

So far, we have not considered that the modulated signal, as well as the RF pilot tone, is influenced by additive noise e.g. from amplifiers in the transmission path. Taking into account additive noise and using the modulated signal in Eq. (1), one can specify the bit-error-rate (BER) for the considered nPSK or nQAM system in a situation without correcting the phase noise. With Eq. (3) or (5), the BER is specified using optically generated and Rx extracted RF pilot tones to correct (as much as possible) the phase noise influence.

Implementing the HPF filtering and generation of an RF carrier is equivalent to filtering away the phase noise by a mirror LPF filter.

2.2 Phase noise analysis

It is adequate to discuss the total phase noise influence in the system (EEPN). The EEPN scales linearly with the accumulated chromatic dispersion and the linewidth of the LO laser. The variance of the additional noise due to the EEPN can be expressed as follows, see e.g [13]:

$$\sigma_{EEPN}^2 = \frac{\pi\lambda^2}{2c} \cdot \frac{D \cdot L \cdot \Delta f_{LO}}{T_S} \equiv 2\pi\Delta f_{EE} \cdot T_s \tag{6}$$

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. This enables a definition of the effective intermediate frequency (IF) linewidth [21] - which defines the phase noise influence in the receiver:

$$\Delta f_{Eff} \approx \frac{\sigma_{Tx}^2 + \sigma_{LO}^2 + \sigma_{EEPN}^2}{2\pi T_S} = \Delta f_{Tx} + \Delta f_{LO} + \Delta f_{EE} \tag{7}$$

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 and $\sigma_{LO}^2 = 2\pi\Delta f_{LO} \cdot T_S$ is the LO laser phase noise variance. Equation (7) 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 [21].

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

#148326 - $15.00 USD Received 27 May 2011; revised 21 Jun 2011; accepted 22 Jun 2011; published 13 Jul 2011

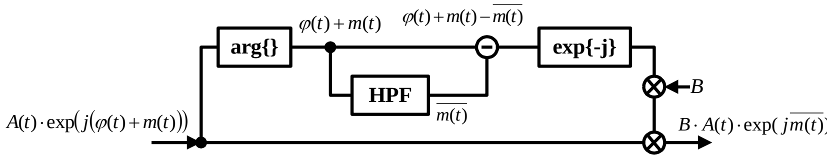

Fig. 1. Structure of RF pilot carrier extraction and the complex conjugation operation in the general n-level PSK/QAM Rx employing a combination of amplitude and phase modulation. The signal specification in the notation of section 2 (Eq. (1) – Eq. (5)) is indicated. Figure abbreviation: HPF - High-Pass Filter.

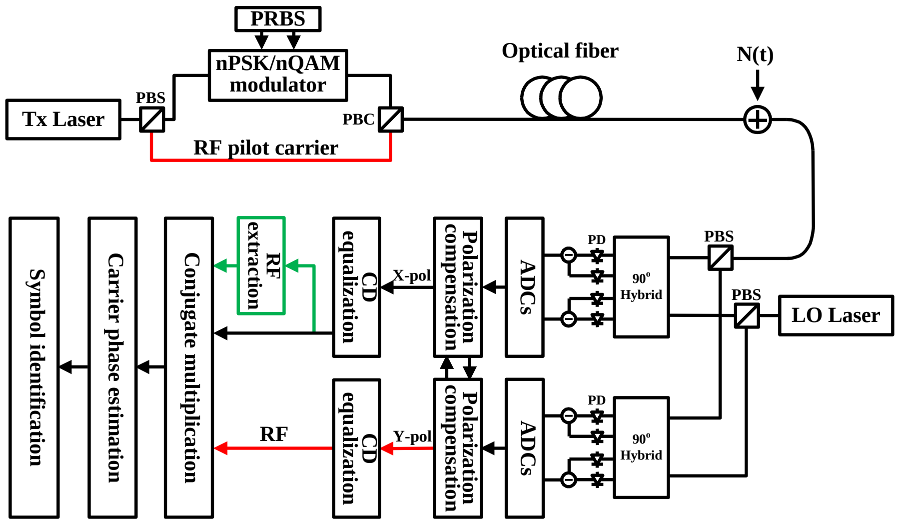

Fig. 2. Block diagram for single polarization nPSK/nQAM system using an optical RF pilot tone for phase noise correction (including red system parts) or using an Rx extracted RF pilot tone for phase noise correction (including green system parts). *N(t)* shows the added optical noise which is used to measure the bit error rate (*BER)* as a function of optical signal-to-noise ratio (*OSNR)*. Figure abbreviations: Tx – transmitter; PBS – polarizing beam splitter; RF – radio frequency; PRBS – pseudo random bit sequence ; LO – local oscillator; ADC – analogue to digital conversion; CD – chromatic dispersion.

3. Simulation results

An example of a complete single polarization coherent system is schematically shown in Fig. 2 including an optical RF signal tone or an Rx extracted RF signal tone for eliminating the phase noise. We will consider an FDE filter for the chromatic dispersion compensation and carrier phase extraction using the normalized LMS (NLMS) method [27]. The FDE filter is selected as commonly used in most practical system demonstrations at this time.

In the simulations, we consider a QPSK system with a symbol frequency of 28 GS/s i.e. the single polarization system capacity is 56 Gb/s. One polarization state is used to either transmit an RF carrier or left empty in the case of an Rx based RF pilot tone extraction. We note that it is straightforward to double the system capacity using the Rx generated RF pilot tone by using also the orthogonal polarization state for QPSK signal transmission whereas this is more complicated using the optically transmitted RF pilot tone (see e.g. the discussion in [25]). We utilize the software tool from VPI [29] for the system simulations, and we evaluate the bit-error-rate versus optical signal-to-noise ratio (OSNR).

#148326 - $15.00 USD Received 27 May 2011; revised 21 Jun 2011; accepted 22 Jun 2011; published 13 Jul 2011

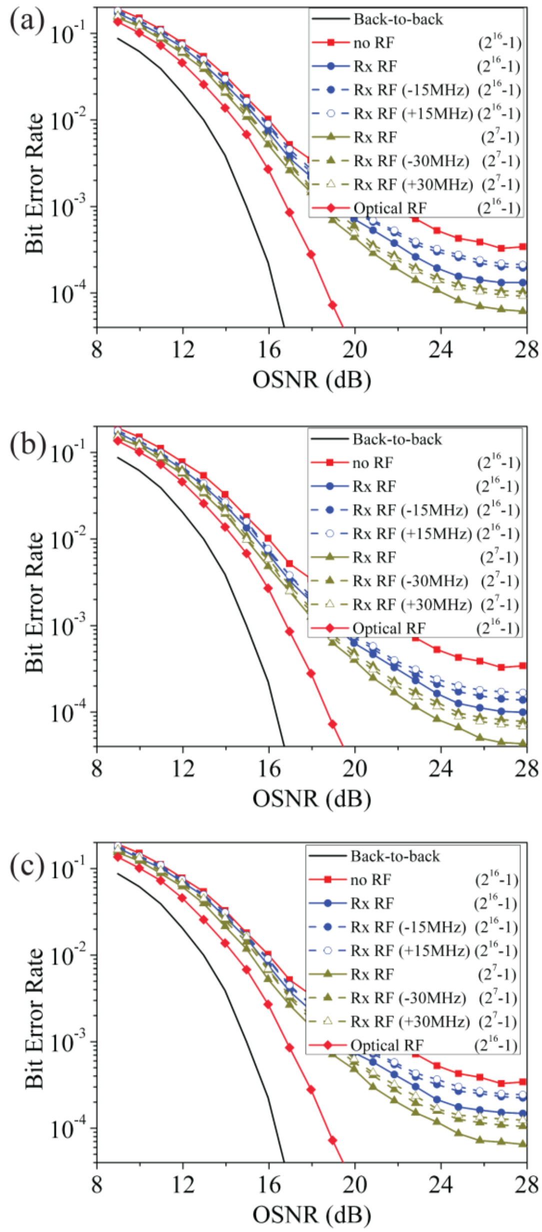

Fig. 3. BER for single polarization QPSK coherent system of Fig. 2. The transmission distance is 10 km; Tx and LO laser linewidths are 85 MHz and the PRBS leghths are 2^{16}-1 and 2^{7}-1 as indicated. The HPF filter is of Butterworth type with order 3 (a), 5 (b) and 7 (c). The 3-dB filter bandwidth is 170 MHz in the Rx RF cases (filled blue and green curves). Dashed curves are for 3-dB bandwidths that deviate ± 15 and ± 30 MHz as indicated. Figure abbreviations: OSNR - optical signal-to-noise ratio; Rx – receiver; RF – radio frequency.

Figure 3 shows the system performance for 10 km distance of a normal transmission fiber with dispersion coefficient of $D = 16$ ps/nm/km. The equalization enhanced phase noise (EEPN) is negligible when we consider Tx and LO linewidths of 85 MHz - which exemplifies the use of distributed feed-back (DFB) lasers diodes of poor quality. The figure compares the performance of 3rd, 5th and 7th order HPF filters of Butterworth type with 3-dB cut-off frequency of 170 MHz (filled green and blue curves for the Rx RF cases). Also shown are

#148326 - $15.00 USD Received 27 May 2011; revised 21 Jun 2011; accepted 22 Jun 2011; published 13 Jul 2011

results (dashed curves) for 3-dB cut-off values that deviate ± 15 MHz for the 2^{16}-1 PRBS sequence and ± 30 MHz for the 2^7-1 sequence. The 5th order Butterworth HPF filter with a 3-dB cut-off of 170 MHz is observed to have the best performance (gives the lowest BER floor position). As one sees from the figure, without phase noise compensation the phase noise generates an BER floor slightly below the 10^{-3} level and this is moved well below 10^{-4} by the use of an optical RF carrier. This result is in good qualitative agreement with [27] where a 10 GS/s 16QAM system with an optical RF pilot tone was considered. The use of an Rx generated RF pilot tone is slightly less efficient but for a short modulation (PRBS) sequence of 2^7-1 it moves the BER floor below 10^{-4}. It should be noted that it may be possible to improve the result by considering a more carefully designed HPF for the purpose of most efficient removal of the phase noise. Our simulation results in Fig. 3 indicate that the efficient extraction of an RF carrier will require an IF stability in the Rx of about ± 50 MHz for a 2^7-1 modulation sequence and about ± 20 MHz for a 2^{16}-1 sequence. These values are quite demanding for lasers with 85 MHz linewidth but may be possibly obtained using carefully designed IF frequency tracking schemes.

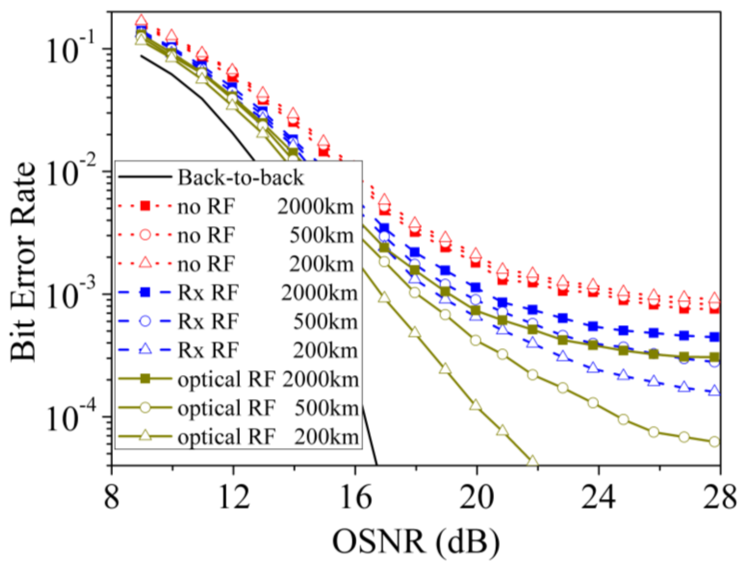

Fig. 4. BER for single polarization QPSK coherent system of Fig. 2. Results are for transmission distances of 200 km, 500 km and 2000 km using an optical RF pilot tone and an RF pilot tone generated in the Rx for phase noise mitigation. Different cases are indicated in the figure. Tx and LO laser linewidths are 44 MHz (200 km), 19 MHz (500 km) and 5 MHz (2000 km). The PRBS length is 2^{16}-1. Figure abbreviations: OSNR - optical signal-to-noise ratio; Rx – receiver; RF – radio frequency.

In Fig. 4 we have 3 situations with an effective IF linewidth (Eq. (7)) of 216 MHz. We have chosen a slightly larger value than the 170 MHz in the case of Fig. 3 because this assures a bit-error-rate-floor position (without phase noise compensation) above 10^{-3}. The data display important trends for BER-values above the order of 10^{-4} where the simulation results are reliable. In this case, the optimum HPF filter is the 5th order Butterworth with a 3-dB cut-off of 216 MHz. We consider transmission distances of 200 km ($\Delta f_{Tx} = \Delta f_{LO} = 44$ MHz, $\Delta f_{EE} = 128$ MHz), 500 km ($\Delta f_{Tx} = \Delta f_{LO} = 19$ MHz, $\Delta f_{EE} = 178$ MHz) and 2000 km ($\Delta f_{Tx} = \Delta f_{LO} = 5$ MHz, $\Delta f_{EE} = 206$ MHz). When the transmission distance is increased the phase noise in the Rx is dominated by EEPN. Figure 4 shows that RF pilot tone phase noise reduction is gradually less efficient when the EEPN part of the phase noise increases. For 2000 km transmission distance the reduction of the bit-error-rate floor is less than one order of

#148326 - $15.00 USD Received 27 May 2011; revised 21 Jun 2011; accepted 22 Jun 2011; published 13 Jul 2011

magnitude even using optical RF tone generation and the Rx generated pilot tone gives slightly poorer performance. This behavior is attributed to the well known fact that EEPN results in a complex combination of pure phase noise, amplitude noise and time jitter [13–21], and neither the amplitude noise nor the time jitter is compensated using the RF pilot tone.

4. Conclusions

A novel method for extracting an RF pilot carrier signal in the coherent Rx is presented. The method is based on high pass filtering the received signal phase in order to remove the phase noise and to use the filter output for generation of the RF pilot tone. In a contrast to an (ideal) optical RF pilot tone, the use of an Rx generated RF pilot tone simplifies the design of the optical part of the transmission system and allows straightforward and efficient use of dual polarization modulation. The RF pilot tone carrier is used to eliminate the phase noise influence in high constellation n-level PSK and QAM systems by complex conjugation prior to the signal detection and error-rate specification. The performance is compared to the use of an optically transmitted RF pilot tone. As expected, it is found that the electronically generated RF carrier provides slightly less efficient phase noise mitigation than the optically transmitted one, but still it improves the phase noise tolerance by about one order of magnitude when a short modulation sequence is used. It is also found – as a novel study result - that equalization enhanced phase noise which appears as correlated pure phase noise, amplitude noise, and time jitter in the received signal, cannot be efficiently mitigated by the use of an (optically or electrically generated) RF pilot tone.

The suggested method for electronic RF pilot tone generation is – to our knowledge - a first idea demonstrating the potential of electronic phase noise compensation using DSP techniques in the optical receiver. Future work may consider elimination of the amplitude noise part and the time jitter caused by the equalization enhanced phase noise. Here, other techniques have to be implemented since RF pilot tones are not efficient.

#148326 - $15.00 USD Received 27 May 2011; revised 21 Jun 2011; accepted 22 Jun 2011; published 13 Jul 2011