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Error-rate Floors in Differential n-level Phase-shift-keying Coherent Receivers employing Electronic Dispersion Equalisation

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Abstract: An analytical model for the phase noise influence in differential n-level phase shift keying (nPSK) systems and 2n-level quadrature amplitude modulated (2nQAM) systems employing electronic dispersion equalization and quadruple carrier phase extraction is presented. The model includes the dispersion equalization enhanced local oscillator phase noise influence. Numerical results for phase noise error-rate floors are given for dual polarization DQPSK, D16PSK and D64PSK system configurations with basic baud-rate of 25 GS/s. The transmission distance in excess of 1000 km requires local oscillator lasers with sub MHz linewidth.

Introduction: Coherent optical communications research activities focuses currently on achieving system bit-rates of 100 – 1000 Gb/s and to apply electronic dispersion equalization to account for several thousand kilometers of transmission [1,2]. Practical high capacity system configurations have been polarization multiplexed n-level phase shift keying (nPSK) and quadrature amplitude modulation (nQAM) systems (n = 4, 8, 16, 32, 64,…) with differential detection. The demodulation in the receiver is coherent (with an optical transmitter (Tx) and local oscillator (LO) laser) and effectively homodyne since homodyne detection provides the closest possible channel stacking in wavelength division multiplexed (WDM) system implementations as well as the best system sensitivity. Phase noise becomes a prime system design parameter for high-constellation coherent systems since it affects the electronic carrier phase extraction [3,4] and furthermore the LO phase noise influence is enhanced by electronic dispersion compensation [5]. It is possible (and straightforward) to extend the analytical derivation for the enhanced LO phase noise in [5] to specify the BER floor for nPSK and 2nQAM systems - with and without practical *n*-power carrier phase extraction by generalizing results from [3,4]. In [6] a similar study including the Viterbi-Viterbi carrier phase extraction has been presented. The purpose of our paper is to provide practically important system design considerations based upon simple and physically insightful system models.

Theory outline: In [5] a theoretical treatment of the equalization enhanced phase noise influence from the Local Oscillator laser caused by electronic dispersion compensation in the receiver (Rx) is given. This derivation assumes that perfect carrier phase extraction is used. Furthermore, the electronic dispersion is implemented by optimal fixed configuration electrical filtering (such as a time domain Finite Impulse Response (FIR) filter or a frequency domain Blind Look-Up (BLU) filter [2]) meaning that adaptive (time domain) Least Mean Square (LMS) filters [2] are not covered by the treatment. Adaptive (LMS) filters may be expected to lead to enhanced phase noise penalty because the adaptive filter tap optimization is strongly dependent upon the laser coherence over many symbol time periods and this coherence is destroyed by the laser phase noise. The dispersion equalisation enhanced laser phase noise influence is due to the LO laser only and using [5] the total phase noise variance is specified as $\sigma^2 = {\sigma_{Tr}}^2 + {\sigma_{LO}}^2 + {\sigma_{EE}}^2$ with ${\sigma_{Tr}}^2 = 2\pi\Delta\nu_{Tr}T$, ${\sigma_{LO}}^2 = 2\pi\Delta\nu_{LO}T$ and ${\sigma_{EE}}^2 = (\pi\lambda^2 DL\Delta\nu_{LO})/(2cT)$. Here $\Delta\nu_{Tr}$ and $\Delta\nu_{LO}$ denotes the transmitter and Local Oscillator laser linewidths, λ the laser wavelength, D the dispersion coefficient of the fiber, L the fiber length, T the symbol period and c the free space velocity of light.

Based upon [3,4] the BER influenced by phase noise can be specified. The BER is the sum of errors caused by detecting in-phase and quadrature components in error, respectively [3,4]. The error-rate floor caused by detection between PU's including phase unwrapping gives the dominating contribution to the *BER*:

$$BER \approx \frac{1}{N \log_2 n} erfc\left(\frac{\pi}{n\sqrt{2}\sigma} \sqrt{\frac{3N}{2N^2+1}} \right) \qquad (1)$$

where *erfc* denotes the complementary error function and *N* is the length (measured in numbers of considered symbols) for the *n*-power carrier phase Processer Unit (PU). For *N>1* (1) is accurate for BER-values less than the order of 10^{-2}. For N=1 (1) specifies the *BER* for ideal carrier phase extraction.

From (1) it can be concluded that transmission systems should operate with small block sizes (low *N*-values). However, practical systems are influenced by significant amounts of additive noise as well originating from amplified spontaneous emission (ASE) noise from in-line optical amplifiers and from thermal receiver noise. The system penalty attributed to the additive noise is in inverse proportion to *N*. Thus the system BER has to be optimized by selecting an optimum value of *N*.

Results and discussion: Distributed Feed Back (DFB) lasers have 3 dB linewidths in the order of 0.1 to 10 MHz where sub-MHz linewidths may in practice require external-cavity lasers. In Fig. 1 eq. (1) has been plotted for $\Delta\nu_{tr} = \Delta\nu_{LO} = 2$, 0.5 and 0.1 MHz in the case of a D16PSK dual-polarization 200 Gb/s system with a baud rate of 25Gb/s. The phase noise sensitivity is similar for a D32QAM system in a circular constellation configuration [5] which yields a capacity of 250 Gb/s. Results are shown as a function of transmission distance up to 3000 kilometers for ideal carrier phase extraction and using practical *n*-power carrier phase extraction with PU size of *N=5*. A standard single mode fiber (G.652) with dispersion coefficient of *D*=17 ps/km/nm is considered. A BER-value of 10^{-4} may be considered the maximum values for the use of forward error correction (FEC) to improve the BER performance. From the figure it appears clearly that this requirement in the of practical carrier phase extraction (*N=5*) is only L<17 km for $\Delta\nu_{LO} = 2$ MHz whereas for $\Delta\nu_{LO} = 0.5$ MHz it is met for L<349 km. In the case of ideal carrier phase extraction the transmission distances increases to 193 and 1051 km. The obtainable transmission distance for an error-rate floor of 10^{-4} is summarized in Table 1 for DnPSK systems with *n* = 4, 16, 64. The results emphasize the strong influence of equalization enhanced phase noise for higher constellation schemes. The results are in qualitative agreement with the ones obtained for the Viterbi-Viterbi carrier phase extraction algorithm that are presented in [6].

It has to be observed that the use of hardware based dispersion compensation (using e.g. Dispersion Compensation Fibers, DCFs) is an alternative to software based methods with the advantage that no equalization enhancement of the phase noise influence is present and that dispersion compensation may be performed in one-shot over the whole C-band. Then the phase noise influence specified in [3] for 25 GS/s baud-rate applies and using *n*-power carrier phase extraction with about 1 MHz laser linewidth constellations up to 64PSK (128QAM) gives a BER floor below 10^{-4}. For real applications the design of DCFs that should match the detailed transmission fiber dispersion profile over the whole C-band is very demanding. However, DCFs can more easily be designed to leave a small (less than 1 ps/km/nm, say) residual dispersion over the C-band and using added adaptive (Least Mean Square (LMS) based [3]) electronic residual dispersion compensation a very small equalization enhancement effect results from this.

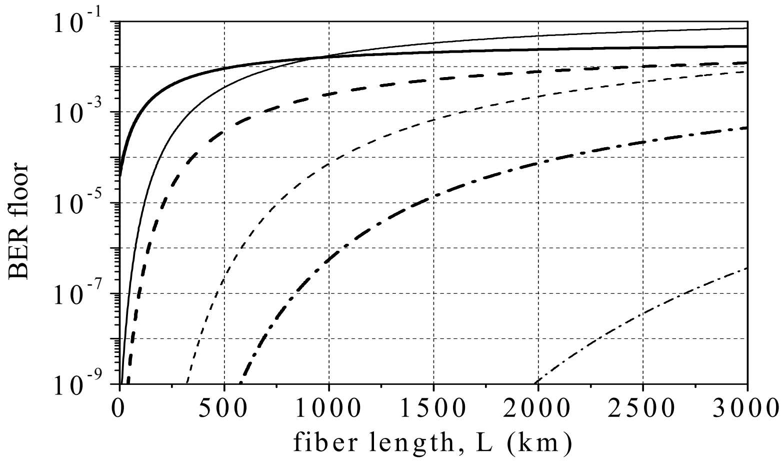

Figure 1. BER as a function of transmission length, *L* using ideal carrier phase recovery (thin curves) and using n-power carrier recovery (thick curves) with Processor Unit block size of $N = 5$ for a D16PSK constellation.

—— $\Delta\nu_{LO} = \Delta\nu_{tr} = 2$ MHz; – – – $\Delta\nu_{LO} = \Delta\nu_{tr} = 0.5$ MHz; ——— $\Delta\nu_{LO} = \Delta\nu_{tr} = 0.1$ MHz

Table 1. Transmission distance (in km) to have BER floor of 10^{-4} for DQPSK/D8QAM and D16PSK/D32QAM systems capacity with baud-rate 25 GS/s. Results are for different laser linewidths and for ideal (and *n*-power) carrier phase extraction.

$\Delta\nu_{LO} = \Delta\nu_{tr}$ [MHz]	5	1	0.1	0.01
QPSK/8QAM	530(1567)	3026(8209)	$>10^4(>10^4)$	$>10^4$ $(>10^4)$
16PSK/32QAM	0(21)	127(479)	2117(5634)	$>10^4$ $(>10^4)$
64PSK/128QAM	0(0)	0(0)	56(287)	1405(3716)

Conclusion: A model for the equalization enhanced phase phase noise influence in differential n-level phase shift keying (nPSK) and differential 2n-level QAM systems using *n*-power based carrier phase extraction is presented. Results for the phase noise sensitivity are given for a dual polarization system configuration with basic baud-rate of 25 GS/s and n ranging from 4 to 64. Results emphasize the need for highly phase stable optical signal sources with sub-MHz linewidths in higher constellation configurations and for transmission distances beyond the order of 1000 km over normal (G.652) fiber. The use of Viterbi-Viterbi carrier phase extraction provides similar phase noise influence as the *n*-power method [6]. The use of hardware based rather than electronic based dispersion compensation will eliminate the equalization based phase noise enhancement. It will be a subject of future research to investigate the phase noise properties using electronic dispersion compensation with decision-directed carrier-phase estimation – see e.g. [7].

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