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Phase Noise Influence in Coherent Optical DnPSK Systems with DSP based Dispersion Compensation

Abstract: We present a comparative study of the influence of dispersion induced phase noise for n-level PSK systems. From the analysis, we conclude that the phase noise influence for classical homodyne/heterodyne PSK systems is entirely determined by the modulation complexity (expressed in terms of constellation diagram) and the analogue demodulation format. On the other hand, the use of digital signal processing (DSP) in homodyne/intradyne systems renders a fiber length dependence originating from the generation of equalization enhanced phase noise. For future high capacity systems, high constellations must be used in order to lower the symbol rate to practically manageable speeds, and this fact puts severe requirements to the signal and local oscillator (LO) linewidths. Our results for the bit-error-rate (BER) floor caused by the phase noise influence in the case of QPSK, 16PSK and 64PSK systems outline tolerance limitations for the LO performance: 5 MHz linewidth (at 3-dB level) for 100 Gbit/s QPSK; 1 MHz for 400 Gbit/s QPSK; 0.1 MHz for 400 Gbit/s 16PSK and 1 Tbit/s 64PSK systems. This defines design constrains for the phase noise impact in distributed-feed-back (DFB) or distributed-Bragg-reflector (DBR) semiconductor lasers, that would allow moving the system capacity from 100 Gbit/s system capacity to 400 Gbit/s in 3 years (1 Tbit/s in 5 years). It is imperative at the same time to increase the analogue to digital conversion (ADC) speed such that the single quadrature symbol rate goes from today's 25 GS/s to 100 GS/s (using two samples per symbol).

Keywords: coherent systems, n-level PSK systems, phase noise

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1 Introduction

Coherent optical transmission is currently being implemented in the core telecom network in terms of 100 Gbit/s QPSK systems that are homodyne with modulation in two polarizations and two quadratures. Thus, the base modulation rate is 25 GS/s with two bits per symbol. Next generation systems could be 400 Gbit/s QPSK systems with base modulation rate of 100 GS/s or 400 Gbit/s 16PSK/16QAM systems with a base rate of 50 GS/s (four bits per symbol). The ongoing research trend in a 3 to 5 year time frame is towards systems operating at 1 Tbit/s in the core network. Key parameters to increase the capacity is further improvement of the linewidths of transmitter (Tx) and Local Oscillator (LO) lasers, and required analogue-to-digital conversion (ADC) speed in the frontend of the receiver (RX). In the discussion to follow we will assume ADC using 2 samples per symbol.

The experimentation around coherent optical communication systems based on semiconductor lasers as transmitter (Tx) and local oscillator (LO) was initiated around 1980 with lab tests using two level modulation: amplitude shift keying (ASK); frequency shift keying (FSK); phase shift keying (PSK) or polarization shift keying (PolSK), in one quadrature heterodyne detection [1]. Homodyne systems implementation were problematic because they should rely on analogue phase locked loops, that was very difficult to realize with semiconductor lasers even using optical injection locking to generate the carrier reference phase of the receiver (Rx) [2]. The heterodyne systems were influenced by the laser phase noise originated from the transmitter (Tx) and local oscillator (LO) lasers. The laser phase noise degraded the bit-error-rate (BER) performance resulting in BER-floors (constant BER for increasing optical signal-to-noise ratio). The degradation was entirely dependent on the modulation format and the implementation of analogue receivers. For larger phase noise values (laser 3-dB linewidths in the order of the bit-rate), so-called weakly coherent systems were build (ASK, large frequency deviation FSK or PolSK systems) where the BER-floor position was specified in the 10^{-9} BER range in terms of the sum of laser linewidths relative to the intermediate frequency band pass filter bandwidth in the Rx [1, 3, 4]. For smaller laser linewidths – in the order of 1% of the bit-rate – narrow deviation FSK (continuous phase FSK, CPFSK) systems or differential PSK (DPSK) systems could be build width the BER-floor position in the 10^{-9} range [1, 5, 6]. A practical system BER for operation in the telecom network was in the 10^{-9}–10^{-12} range since no BER improvement could be obtained using digital methods of the detection, i.e. in terms of forward-error-correction (FEC) coding of the signal [7]. The research on two-level heterodyne systems with analogue Rx was terminated in the beginning of the 1990's when commercial optical amplifiers appeared, and only direct detecting system were actual for the following decade.

Around year 2000, research efforts on coherent systems were revived. The reason for that was multifold. First of all, it was driven by the fact that higher fiber capacities in the trunk network can be achieved with frequency stacked coherent system solutions operating with high constellations rather than using direct detecting systems. Secondly, the performance of semiconductor lasers allowed higher signal power and lower laser phase noise than before, with feasible laser linewidth in the 100 kHz range. (This implies smaller phase noise influence but it should be noted that a leap from two- to multi-level constellations generates the opposite trend, so that the phase noise influence is still a very important design factor.) Finally, the Rx now allow digital signal processing (DSP) which has significant practical advantages: homodyne systems can now be digitally implemented, i.e. the free-running Tx and LO lasers can operate in close proximity in frequency (as intradyne systems), and the phase-locking is done using DSP; DSP can be used to implement system parts which otherwise must be implemented in analogue form in the optical domain, i.e. polarization line-up in the Rx or dispersion compensation [8]. This means that current research for trunk network coherent systems mainly deal with two quadrature, two polarization implementations of QPSK and 16-64QAM/PSK systems for system capacities of 100–1000 Gbit/s. A special DSP design deals with the equalization enhanced phase noise (EEPN) which is generated from the LO-laser phase noise when the dispersion influence from the fiber transmission is digitally equalized in the Rx [9]. This gives a length-dependent phase noise influence which is novel compared to systems without DSP. The DSP technology enables the practical use of FEC that brings BER floor positions from around 10^{-2} down to the 10^{-12} level.

The aim of this paper is to give some practical design constraints regarding the phase noise influence of current distributed-feed-back (DFB) lasers in relation to current and near-future coherent systems intended for use in the trunk network. We will exemplify by looking at the BER performance of normal differential n-level PSK systems and will include the influence of EEPN which can be seen as specifying the limiting performance for BER in the trunk network.

2 Theory

It is relevant to discuss the total phase noise influence in a coherent system. We will use DSP (a digital filter) to compensate for chromatic dispersion (CD) equalization [8]. In this configuration, the EEPN scales linearly with the accumulated chromatic dispersion and the linewidth of the LO laser [9]. The LO laser that contributes to the generation of EEPN in the digital CD compensation process is described via the variance

$$\sigma_{EEPN}^2 = \frac{\pi\lambda^2}{2c} \cdot \frac{D \cdot L \cdot \Delta\nu_{LO}}{T_S} \equiv 2\pi\Delta\nu_{EE} \cdot T_s \tag{1}$$

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, $\Delta\nu_{EE}$ 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. (1) has 2/3 contribution from the phase noise of EEPN and 1/3 from the amplitude noise [9, 10] showing that EEPN is not a pure phase noise, and in this way differs from intrinsic laser phase noise. Equation (1) enables a definition of the effective intermediate frequency (IF) linewidth [9, 10, 11] – which defines the phase noise influence in the receiver:

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

where $\Delta\nu_{Tx}$ is the 3-dB transmitter laser linewidth, $\sigma_{Tx}^2 = 2\pi \cdot \Delta\nu_{Tx} \cdot T_S$ is the intrinsic transmitter laser phase noise variance, $\Delta\nu_{LO}$ is the 3-dB local oscillator laser linewidth, and $\sigma_{LO}^2 = 2\pi \cdot \Delta\nu_{LO} \cdot T_S$ is the intrinsic LO laser phase noise variance. (2) 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) [11]. The BER-floor position which is defined from the phase noise influence is specified as (for a DnPSK Rx) [12, 13]:

$$BER_{floor} \approx \frac{1}{\log_2 n} erfc\left(\frac{\pi}{n\sqrt{2}\sigma_{Eff}}\right) \quad (3)$$

Simulation results will be considered in Section 3 of this paper.

3 Results and discussion

We will now consider the influence of laser phase noise including EEPN for three generations of PSK systems by evaluating Eq. (3) as a function of transmission length, L. The systems under consideration are DQPSK (2 bits/symbol), D16PSK (4 bits/symbol) and 64PSK (6 bits per symbol). We will consider total system capacities of 100 Gbit/s, 400 Gbit/s and 1 Tbit/s for double quadrature and double polarization transmission. This means that the basic symbol rate in one quadrature is 25 GS/s, 100 GS/s and 250 GS/s for DQPSK systems under consideration; it is 12.5 GS/s, 50 GS/s and 125 GS/s for D16PSK and 8.33 GS/s, 33.33 GS/s and 83.33 GS/s for D64PSK. We will consider equal linewidth for the Tx and LO lasers (operating at a wavelength of $\lambda = 1.55$ µm) and examplify by choosing the three 3-dB linewidths of 5 MHz (standard DFB lasers of modern technology), 1 MHz (good quality DFB lasers today) and 0.1 MHz (good DFB lasers in 3 to 5 years time perspective). We consider a normal single mode transmission fiber with dispersion coefficient $D = 16$ ps/nm/km and zero dispersion slope.

In Figure 1 we show BER performance in the range of $10^{-3} < BER < 10^{-1}$. This represent the BER-range where the use of FEC and Viterbi-Viterbi based compensation of the phase noise effect may be used to decrease the effective BER to below 10^{-12} level [14, 15, 16].

From the figure, a number of observations are pertinent. First of all, the influence of EEPN is becoming stronger for increasing transmission distance. Also, the influence of EEPN is stronger for increasing LO laser linewidth and for increasing number of constellation points (going from DQPSK to D64PSK for the same capacity).

It is interesting to compare performance for the different system constellations. For DQPSK systems (Fig. 1(a)) the EEPN influence increases with the system capacity. For 100 Gbit/s and 5 MHz linewidth; the BER performance is below 10^{-2} for a transmission distance of 4400 km. Going to 400 Gbit/s and 1 Tbit/s, the distance decreases to 400 km. For D16PSK systems (Fig. 1(b)) the effect is more pronounced, and here one can observe that the 5 MHz linewidth for 100 Gbit/s capacity causes an error rate floor

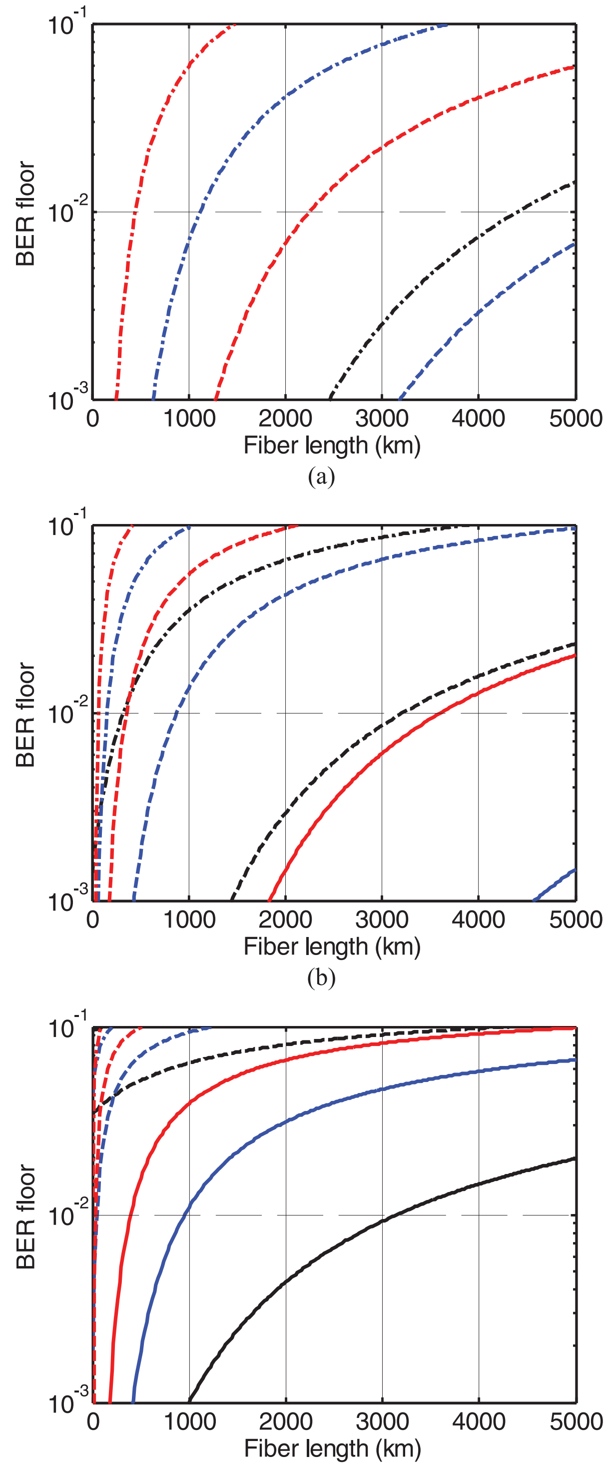

Fig. 1: BER_{floor} (Eq. (3)) as a function of transmission distance (fiber length L, km) for dual polarization DQPSK (a), D16PSK (b), and D64PSK (c) systems. Total systems capacities are indicated by colors: 100 Gbit/s (black), 400 Gbit/s (blue) and 1 Tbit/s (red). Linewidths of transmitter (Tx) and local oscillator lasers are equal and shown by line styles: 5 MHz (dash-dotted), 1 Mhz (dashed) and 0.1 MHz (solid).

even for zero transmission distance of around $2 \cdot 10^{-3}$, i.e. the floor is caused by the sum of intrinsic Tx and LO laser linewidths (see Eq. (2) and (3)). For the D64PSK system (Fig. 1(c)) the only feasible system for longer transmission distance with BER < 10^{-2} is the system with 0.1 MHz LO laser linewidth and a capacity of 1 Tbit/s. This system operates up to a transmission distance of 3200 km.

We can conclude from Fig. 1, that a feasible long distance transmission system today is the 100 Gbit/s dual polarization DQPSK system using lasers with a linewidth of 5 MHz, quadrature symbol rate of 25 GS/s, and providing 4400 km transmission distance for BER < 10^{-2}.

A feasible system in a 3 year time frame could be either a 400 Gbit/s D16PSK system with lasers having 0.1 MHz linewidth, a quadrature symbol rate of 50 GS/s, and providing more than 5000 km transmission distance for BER < 10^{-2}; or a 400 Gbit/s QPSK system with lasers having a linewidth of 1 MHz, a quadrature symbol rate of 100 GS/s, and providing 2200 km transmission distance for BER < 10^{-2}.

A feasible system in a 5 year time frame could be a 1 Tbit/s D64PSK with lasers having 0.1 MHz linewidth, quadrature symbol rate of 62.5 GS/s, and providing 3200 km transmission distance for BER < 10^{-2}.

From the discussion above, it is to be emphasized that strong requirements on the BFB/DBR laser phase noise (3-dB laser linewidth) is a key to obtaining the high system capacities of 400 Gbit/s and 1 Tbit/s in a 3–5 year time perspective. Another crucial factor is the available analogue-to-digital conversion (ADC) speed in the Rx. Here, typical designs today require 2 samples per symbol time for DSP operation of chromatic dispersion compensation algorithms. This makes DQPSK single quadrature speeds of about 25 GS/s possible with state of the art ADC circuits with speeds up to 80 GSamples/s [17]. In a 3–5 year time, it should be possible to increase this speed to about 100 GS/s (following Moore's law of doubling the electronic circuit speed every 18 month).

For 16–64 QAM systems, no simple analytical prediction of the BER_{floor} caused by laser phase noise including EEPN is available as in the case for PSK based systems. However, QAM systems can be implemented in circular rather than square constellations, where such analytical predictions are available [13] showing similar phase noise performance as for PSK based systems. From [13] it is anticipated that high constellation QAM systems of any constellation pattern will have similar phase noise performance as PSK systems with equal constellation level. Thus, our conclusions for PSK constellation based systems are expected to hold at least qualitatively also for QAM systems with the same constellation level.

4 Conclusions

Our comparative study of the influence of dispersion induced phase noise in n-level PSK systems demonstrates that the phase noise influence for classical homodyne/heterodyne PSK systems is entirely determined by the complexity of modulation and the analogue demodulation format. The use of digital signal processing in homodyane/intradyne systems renders a fiber length dependence originating from the generation of equalization enhanced phase noise. Systems with advanced modulation format (of high constellations) must be used in order to lower the symbol rate to practically manageable speeds. This imposes stringent requirements to the signal and local oscillator linewidths. We present example results for the bit-error-rate floor caused by the phase noise influence in the case of QPSK, 16PSK and 64PSK systems.

It is clear, that 100 Gbit/s QPSK systems may tolerate a LO-laser 3-dB linewidth of 5 MHz, a 400 Gbit/s QPSK system – a linewidth of 1 MHz, whereas a linewidth of about 0.1 MHz is required for 400 Gbit/s 16PSK and 1 Tbit/s 64PSK systems. Thus, stringent phase noise tolerances are required for future LO-lasers in the form of distributed-feed-back (DFB) or distributed-bragg-refector (DBR) semiconductor lasers.

In order to move from 100 Gbit/s system capacity to 400 Gbit/s in 3 years and 1 Tbit/s in 5 years it is also imperative to increase the analogue to digital conversion (ADC) speed in the Rx. Using two samples per symbol the single quadrature symbol rate must increase from today's 25 GS/s to 100 GS/s. This should be possible following Moore's law.

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