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LINEWIDTH PENALTY ON OPTICAL ACCESS NETWORKS USING DPSK MODULATION FORMAT

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Resumen

En este artículo se analiza el impacto del ancho de línea en el desempeño de una red de acceso óptica en la que se emplea el formato de modulación DPSK. Se demostró, mediante simulaciones, el efecto del ancho de línea sobre la BER (Bit Error Rate). Se analizó el desempeño para diferentes velocidades de transmisión y valores de dispersión en la fibra óptica. DPSK es un formato simple y de menor costo comparado con el uso de detección coherente, DPSK. Se encontró que puede emplearse un mayor ancho de línea al incrementar la tasa de bits, lo que significa un menor costo de implementación. Se propone a DPSK como el siguiente paso en la actualización de la red de acceso actual que emplea modulación en intensidad.

Palabras clave: Modulación de fase diferencial, red óptica pasiva, penalidad del ancho de línea.

Abstract

In this paper we analyze the impact of the linewidth over the performance of an optical link in an optical access network that employs the DPSK modulation format. We use simulations to measure the BER when the linewidth of the optical transmitter changes. We analyze the link performance with different data bit rates and different dispersion values of the optical fiber. DPSK is a cheaper and simpler solution compared with coherent detection. We found that is required a higher linewidth when the bit rate increases. This implies a lower cost of implementation of the access network. In this case, DPSK could be the next stage to upgrade the intensity modulation format used in the access networks.

Keywords: Differential Phase Shift Keying (DPSK), Linewidth Penalty, Passive Optical Network (PON).

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1. Introduction

The increasing bandwidth demand for both fixed and mobile services has motivated the deeper penetration of optical fiber in access networks due to its superior performance, related to the bandwidth-distance product. However, reducing the implementation cost is a continuous challenge for optical access networks. In this sense, Passive Optical Network (PON) architecture has been introduced in access segment, because it does not require any power supply. In Time Division Multiplexing PON (TDM-PON) an optical line terminal (OLT) located in central office (CO) is shared over several optical network units (ONU) located in the customer premises. One wavelength per sense, down and up stream, is used in this network [1]. One alternative to increase the capacity of TDM-PON is enhancing the spectral efficiency through multilevel modulation. Examples of low complexity modulation techniques are OOK (*On-off shift keying*), duobinary, DPSK and DQPSK [2]. DPSK modulation format is an excellent option, since it offers better tolerance to chromatic dispersion and fiber nonlinearities than OOK [3], [4], increasing the spectral efficiency and improving the coverage and capacity of the access network [5].

In [4] is presented a performance comparison of different modulation formats like DPSK, FSK, IRZ and OOK with Manchester encoding. In this case, DPSK presents the best performance in a dispersive channel.

Recently, the evolution of PON was proposed including DPSK [6]. It includes modulations formats such as DSPK and ASK combined with DPSK. This solution provides low cost and compatibility with previous PON.

Migration alternatives from TDM-PON to WDM-PON include DPSK in the downlink channel and ASK [7] or OOK [8], [9], [10], [11], [12] in the uplink channel. This alternative allows to reduce the receiver cost and improve power consumption in the overall system.

Efforts to reduce the costs of the overall system are focused on the design of the ONU. However, some strategies could be applied in the optical transmitter at OLT.

In this paper we use simulations to analyze the impact of the linewidth of the OLT transmitter over the system performance, when DPSK is used as a modulation format. We conclude that wider linewidth sources can be used between 10 Gb/s and 40 Gb/s. These linewidth values are wider than the values reported in [13]- [14]. They obtained around 30 MHz and we obtain around 270 MHz for 10 Gbps.

We analyze the linewidth penalty to achieve a specified BER value, in order to estimate the impact of linewidth over the system. We define the linewidth penalty as the increment in the required linewidth in the OLT laser, with respect to the case when a zero dispersion fiber (D∼0 ps/nm- km) is employed, in order to obtain the same BER value. The results are obtained with simulations using VPI simulation software.

The paper is organized as follows. In section 2, the main characteristics of the DPSK transmitter and receiver are presented, including an analysis of the linewidth and its impact in the DPSK signal. In section 3, the linewidth penalty and its impact on the BER in a WDM-PON architecture, that uses a DPSK modulation format, is analyzed at different bit rates. Finally, in section 4 the conclusions are presented.

2. Differential binary phase modulation

2.1. DPSK modulation format

The DPSK modulator consists of a differential encoder and a phase modulator. The bit sequence is differentially coded in the phase difference between two successive bits using a XOR. The differentially coded signal modulates the phase of a continuous wave (CW) laser. A Mach-Zehnder Modulator (MZM) may be used as phase modulator. The electrical field of the optical signal at the output of the transmitter is represented by [2]:

$$E_S(t) = \sqrt{P_s}.\, e^{j(\omega_s t+\varphi_s)}.\, e^{j\frac{u(t)}{V_\pi}\pi} \tag{1}$$

where $\sqrt{P_s}$ is the amplitude, ω_s is the angular frequency and φ_s is the initial phase of the electrical field of optical signal; and V_π is the voltage at the input of the MZM that causes a change of π in the phase of the optical signal. The electrical control signal $u(t)$ is defined as (2),

$$u\left(t\right) = V_\pi * \sum\nolimits_k \left(d_k * p\left(t - KT_S\right)\right) \tag{2}$$

where the subscript k is the number of a specific bit of a bitstream, d_k is the bit value $\in \{0,1\}$, T_S is the symbol time and $p(t)$ is the pulse shape. The value of $u(t)$ may change between 0 and V_π depending on the d_k value. Whereas in intensity modulation the control signal changes in the amplitude of the electrical field, in DPSK the control signal modifies the phase of the electrical field.

At the DPSK receiver, the optical signal is demodulated using a delay line interferometer (DLI). The DLI may be a Mach Zehnder interferometer (MZI) or based on a Michelson interferometer. The DLI has a 1:2 splitter that divides the optical signal. Each signal takes a different path into the DLI and the path difference is adjusted to obtain a delay equal to T_S. The two signals are combined to produce constructive and destructive interference depending on the phase changes. After the DLI the optical signal may be detected using a PIN or a balanced photodetector. With the balanced photodetector the sensibility of the receiver is increased in 3 dB, compared with the PIN.

2.2. Linewidth in differential phase modulation

Laser phase and amplitude noise have their origin in spontaneous emission of photons [2], inducing power fluctuations $\delta P(t)$ and phase fluctuations $\varphi_{n_s}(t)$. With these considerations, the electrical field at the output of the transmitter, presented in (1), is modified as:

$$E_s(t) = \sqrt{P_s + \delta P(t)}.\, e^{j(\omega_s t + \varphi_S + \varphi_{n_s}(t))}.\, e^{j\frac{u(t)}{V_\pi}\pi} \quad (3)$$

The variance of the phase change $\Delta\varphi_{n_S}(\tau)$ within a time interval τ is:

$$\langle \Delta\varphi^2_{n_S}(t)\rangle = W_{\varphi_{n_S}} * |\tau| = 2|\tau|/t_c \quad (4)$$

where $\Delta\varphi_{n_S}$ is the constant power spectral density of the frequency noise and t_c represents the coherence time, which denotes the maximum delay difference up to which two components of emitted optical field can stably interfere [2]. If the intensity noise is neglected, the power spectral density of optical field has a Lorentzian shape spectrum. In this case, the linewidth of the laser $\Delta\upsilon_s$ is defined as the full-width half-maximum (FWHM) of the power spectral density of the laser, and is specified by [15]:

$$\Delta\upsilon_s = W_{\varphi_{n_S}}/2\pi = 1/(\pi t_c) \quad (5)$$

Replacing the power spectral density from (5) in (4), the variance of the phase noise may be calculated by:

$$\langle \Delta\varphi^2_{n_S}(\tau)\rangle = 2\pi\Delta\upsilon_S|\tau| \quad (6)$$

From (6) it is possible to observe that the phase uncertainty increases with the laser linewidth $\Delta\upsilon_S$, and with the time interval τ.

The penalty of the communication system due to fluctuations of the laser depends on the modulation format. For DPSK format, the coherence time t_c in function of the bit time T_b is $t_c \gg 2T_b$ because DPSK is a differential modulation and the minimum value of coherence time in function of the data bit rate R is:

$$t_c = 2/R \quad (7)$$

The maximum linewidth value in terms of the bit rate is expressed as:

$$\Delta\upsilon_S = R/(2\pi) \quad (8)$$

The initial linewidth of the transmitter is modified by the dispersion and the nonlinearities in the propagation of the signal through the optical fiber. However, DPSK modulation format is more robust against nonlinearities as well as chromatic dispersion compared with intensity modulation [16].

3. Linewidth penalty in DPSK

Several simulations, using VPI simulation platform, were carried out to measure the linewidth penalty for different data bit rates in a WDM-PON architecture. DPSK modulation format was applied to the laser in the transmitter side. The laser was configured in 1540 nm with 0 dBm power and variable linewidth. The linewidth was chosen to guarantee a specified BER value at different data bit rates. The electrical signal was provide by a PRBS (Pseudo-Random Binary Sequence), which is differentially encoded and then NRZ (Non-Return to Zero) encoded. The signal at the output of the coder was filtered by a low pass Bessel filter of order 3, and then, electrically amplified with a MZM driver. Finally, the electrical signal modulated the phase of the optical signal using the MZM. The MZM had a V_π of 4 V, insertion loss of 3.5 dB and extinction ratio of 22 dB. The diagram with the components of the transmitter is shown in Figure 1.

In the receiver a DLI demodulates the optical signal, and it is direct detected by a PIN balanced photodetector with responsivity 1.6 A/W, dark current 10-6 A and thermal noise of 10^{-12} A/Hz$^{1}/_{2}$. At the output of the balanced photodetector the electrical signal is filtered by a low pass Bessel filter of order 3, and then the signal is analyzed by a BERT (bit error rate tester).

The diagram with the components at the receiver side is shown in Figure 2.

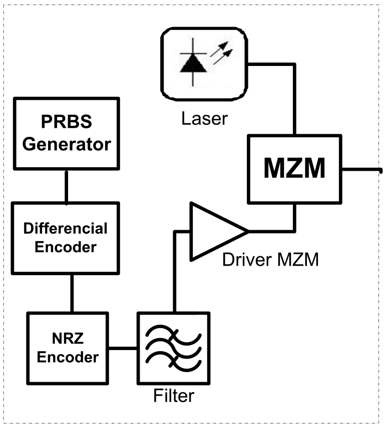

Figure 1. Components of the DPSK transmitter used in the simulations.

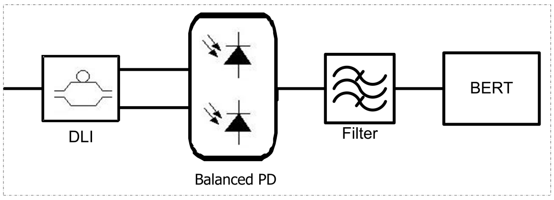

Figure 2. Components of the DPSK receiver used in the simulations.

Figure 3 shows the BER as a function of the laser linewidth for data bit rates from 1,25 Gb/s up to 40 Gb/s, at the output of 20 km of a single mode zero dispersion fiber (DSF).

For high data bit rate is possible to observe that the linewidth requirements decrease, allowing the use of less exigent optical sources.

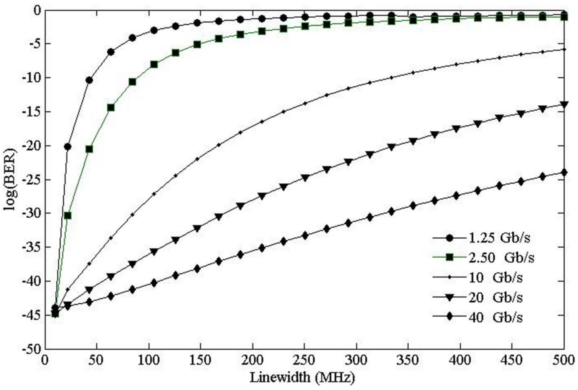

Figure 3. BER in function of the linewidth for different data bit rates, in a 20 km zero dispersion fiber using DPSK as a modulation format.

In order to guarantee a BER value lower than 10^{-12}, the linewidth requirements for different data bit rates are presented in Table 1.

Table 1. Maximum Linewidth for Several Data Bit Rates with Zero Dispersion Fiber.

Bit rate [Gb/s]	Maximum linewidth [Mhz]
1,25	22,2
2,5	64,1
10	278,1
20	2675,4
40	Higher than 5000,0

Then, an optical link to calculate the BER in function of the laser linewidth for data bit rates from 1,25 Gb/s to 20 Gb/s with a dispersive SSMF (Standard Single Mode Fiber) was simulated. The dispersion value of the SSMF at 1550 nm was set to 17 ps/nm-km.

Figure 4 and Figure 5 present the BER curve in function of the linewidth for data bit rates of 10 Gb/s and 20 Gb/s respectively. The BER curves with data bit rates at 1,25 and 2,5 Gb/s, are not presented in those figures because the difference between the BER in function of the linewidth with and without dispersion is not significant for those data bit rates.

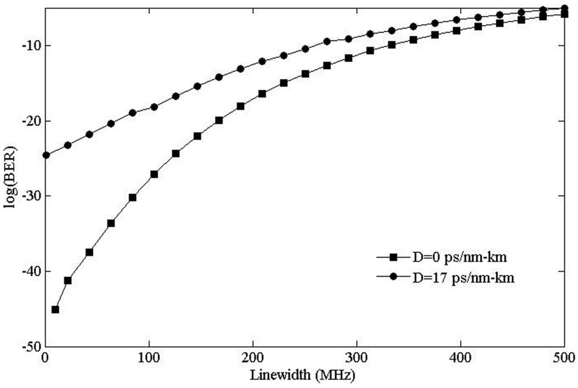

Figure 4. BER in function of the linewidth for 10 Gb/s in a 20 km fiber with and without dispersion.

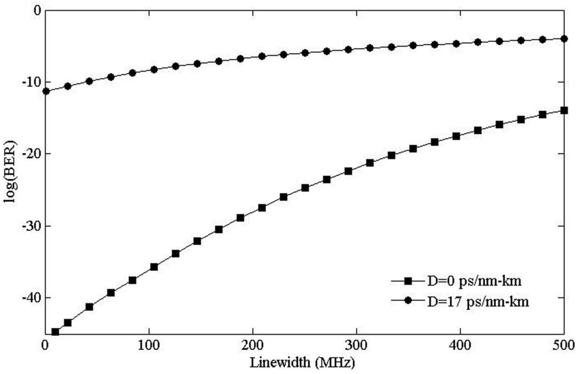

Figure 5. BER in function of the linewidth for 20 Gb/s in a 20 km fiber with and without dispersion.

As it can expected, the performance of the link decreases due to the chromatic dispersion, and the requirement of the laser linewidth is restricted to keep the BER at lower values. Comparing DPSK applied to SSMF and DSF, we obtained better BER values for SSMF when the data bit rate decreases, whereas, for a zero dispersion fiber we obtained better BER values when the data bit rate increases. With a data bit rate of 10 Gb/s, when the laser linewidth increases, the effect of the linewidth over the chromatic dispersion is less significant. We can observe this behavior in Figure 4 with linewidth values higher than 500 MHz obtaining a minimum BER value around 10^{-5}. Instead with 20 Gb/s the chromatic dispersion impacts the BER in all the range of simulated linewidth values (see Figure 5).

The linewidth penalty due to the chromatic dispersion for a BER of 10^{-12} is presented in Table 2. The linewidth penalty when a dispersive fiber (D>0 ps/nm-km) is used, is measured as the increment in the required linewidth with respect to the case when a zero dispersion fiber (D∼0 ps/nm-km) is used, for getting 10^{-12} BER. Also, Table 2 presents the maximum linewidth allowed for the transmitter laser to keep the BER lower or equal to 10^{-12}.

Table 2. Linewidth Penalty for Several Data Bit Rates with BER=10^{-12}.

Bit rate [Gb/s]	**Linewidth Penalty [Mhz]**	**Maximum linewidth [Mhz]**
1,25	22,2	22,188
2,5	64,1	64,09
10	278,1	210,34

In Figure 6 is presented the minimum values of the transmitter laser linewidth in function of the data bit rate in order to achieve BER values at 10^{-9}, 10^{-12} and 10^{-15}, with 20 km of SSMF. As it was discussed previously, the laser linewidth required to obtain a specific BER value can be greater than the linewidth required for lower bit rates.

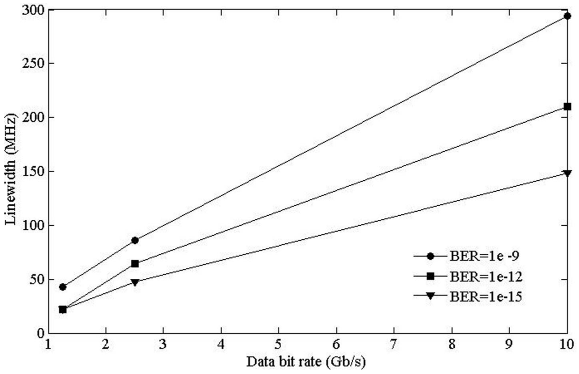

Figure 6. Linewidth vs. data bit rates at different BER values with 20 km of SMF.

4. Conclusions

In this work, we analyze the linewidth penalty in the BER, for an access network scenario employing the DPSK modulation format. We conclude that, for an optical fiber with zero dispersion, the laser linewidth requirements decrease when the data bit rate is increased, decreasing the cost and the complexity of the access network. When a fiber with dispersion higher than zero is used, the linewidth requirements increase to guarantee the same BER values. We measured, using simulations, the laser linewidth penalty for different data bit rates with a SSMF. We found for data bit rates of 1,25 and 2,5 Gb/s, a not significant linewidth penalty.

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