Performance of Stereo Multiplexing in Single Channel and DWDM Systems Using Direct Detection with Optimum Dispersion Maps

Oscar Gaete, Leonardo Coelho, Bernhard Spinnler∗  
Institute for Communications Engineering, Technische Universität München, Germany  
∗Nokia Siemens Networks GmbH & Co. KG, München, Germany  
Email: {Oscar.Gaete, Leonardo-Coelho}@tum.de and Bernhard.Spinnler@nsn.com

Abstract—We present Stereo Multiplexing, a novel technique that permits simultaneous direct detection of two modulated optical carriers. This is accomplished by modulating the optical carriers with the difference and the sum of two signals. The linear performance of Stereo-multiplexed DQPSK signals is compared to single-carrier DQPSK and dual-carrier DQPSK. Subsequently, by means of simulations, the robustness of each format is compared for single channel and DWDM transmission of 55.5 Gb/s through 1040 km of SMF. This is done by searching the optimum dispersion map and input powers for each format and looking at the stability of the performance around the optimum. We show that the best performance and robustness is obtained by sharing the information between two carriers, and that Stereo is only 1dB below dual-carrier NRZ-DQPSK. We discuss the penalty associated with designing a DWDM system based only on the optimization of transmission of single channel.

Index Terms—modulation formats, direct detection, DQPSK, optimum dispersion maps

I. INTRODUCTION

The increasing capacity requirements in optical networks demand the use of spectrally efficient transmission formats at very high data rates. This supposes a big challenge concerning both transmission performance and hardware requirements. Lately, much interest has been put in schemes that reduce the symbol rate by sharing the transmitted data in two optical wavelengths [1]–[4]. By doing so, not only the bandwidth requirements of the components are relaxed, but it is also expected a gain in robustness against impairments that scale with the symbol rate, e.g., dispersion. In dual-carrier transmission using coherent detection, demultiplexing is carried out electrically, resulting in good performance but at expense of increased complexity in the receiver structure [1]. On the other hand, complexity can be kept low in direct detected systems; however, the optical carriers must be detected and demodulated separately, which increases the receiver hardware and the overall cost [2].

In [5] we proposed Stereo Multiplexing, a novel transmission format that allows the simultaneous reception and electrical demultiplexing of two optical carriers using direct detection. In [6] we compared the performance of Stereo-multiplexed DQPSK signals against its single-carrier and dual-carrier equivalent, using RZ-50% and NRZ pulse shaping. This was done for DWDM signals regarding the linear performance in back-to-back configuration, and after 1040 km of transmission in standard single-mode fiber (SMF). For a fair comparison the optimum dispersion map of each modulation format was found using the global optimization algorithm introduced in [7] and [8]. Subsequently, we analysed the robustness of the dispersion maps for each format.

In this contribution, we are interested in the optimization process that led to the mentioned results. Optimization of dispersion maps for DWDM requires a significant effort regarding simulation time, and often, the process is simplified by analysing the transmission of a single channel, either simulating it or using approximated models for the performance of the system [9]. Here we look at the penalty involved between optimization of single channel versus optimization of a DWDM system. For this purpose, we compare in detail the optimum dispersion maps and overall performance of single channel transmission with DWDM transmission of 7 optical channels.

In section II, a brief introduction to Stereo Multiplexing is given and section III shows the system design for the compared formats. In section IV, the algorithm for optimizing the dispersion maps is described and the results of the simulations are discussed.

II. STEREO MULTIPLEXING

In a conventional dual-carrier transmission system, two data streams modulate two optical carriers independently. In Stereo Multiplexing, the sum and the difference of two modulated signals are conveyed in two optical carriers respectively. Taking on-off keying (OOK) as example, the Stereo-multiplexed optical signal can be described as

\[ x_o(t) = (A + B) e^{j(\omega_1 t + \phi_1)} + (A - B) e^{j(\omega_2 t + \phi_2)} \]  

where \(A\) and \(B\) are OOK base-band signals that modulate two complex optical fields at angular frequencies \(\omega_1\) and \(\omega_2\), and phases \(\phi_1\) and \(\phi_2\) respectively. After direct detection, the electrical signal is directly proportional to the squared magnitude of the complex optical signal

\[ x_e(t) = (|A|^2 + |B|^2) + (|A|^2 - |B|^2) \cos(\Delta \omega t + \Delta \phi) \]  

(2)
By recovering the band-pass part of the electrical signal and combining it with the base band, the intensities of the original data signals can be demultiplexed and used for decision or further processing in the electrical domain. Figure 1a illustrates one possible realization of the Stereo-multiplexed signal at the transmitter side. The two optical carriers OC1 and OC2 can be generated using a Mach-Zehnder modulator (MZM) driven by a sinusoidal signal with half the frequency of the desired sub-carrier separation, followed by a Mach-Zehnder interferometer-based filter used to separate both of them [3]. After being generated, the optical carriers must be added with a phase shift of 90° between them, for example by means of a 3 dB optical coupler. Then, both sub-carriers are simultaneously modulated with two different data patterns and the signals at the output of the modulators are added again using a coupler. The receiver is shown in Fig. 1b. Figure 2a depicts the optical spectrum of a 10 Gb/s OOK-Stereo-multiplexed signal and the spectrum of the received electrical signal. In this example, the frequency deviation of the optical carriers from the center frequency is twice the symbol rate.

The proposed technique can also be implemented with phase modulation. In this case interferometric detection must be performed first. Thanks to the periodicity of the transfer function of the delay interferometer (DI), it is possible to demodulate the two carriers simultaneously [4], provided that the frequency separation between them is an integer number of the free spectral range of the DI. In any case, the multiplexing stage in the transmitter is independent of the modulation format. Hence, with single ended MZM (as depicted in Fig.1a) OOK or DPSK can be generated. Optical IQ modulators would be required to generate DQPSK.

III. SYSTEM DESIGN AND LINEAR PERFORMANCE

Figure 3 depicts a block representation of the three simulated systems. The DQPSK modulation is accomplished by using nested Mach-Zehnder modulators. The demodulators consist of Mach-Zehnder delay interferometers followed by balanced detection and a 5th order Bessel low pass filter (B = 0.75*symbol rate) before final symbol decisions. In each case a PRQS of length 40 is used to modulate the optical carriers. The total data rate is 55.5 Gb/s. The transmitters generate 7 WDM channels in a 50 GHz grid. The center channel is extracted by means of a 42 GHz optical band pass filter (2nd order, Gauss) and the required OSNR for a BER of 10^-4 is calculated. The BER is calculated in all cases with the Karhunen-Loève method [10]. RZ-50% and NRZ pulses are simulated for each modulation format. When two optical carriers are used to convey the data (dual-carrier and Stereo), they have a frequency separation of twice the symbol rate. In dual-carrier DQPSK, band pass optical filters are used to separate the optical carriers. It was found that the optimum bandwidth of the filters for the single channel case is 25 GHz for RZ-50% and 19.4 GHz for NRZ; and for the DWDM case is 13.8 GHz for RZ-50% and 20.8 GHz for NRZ. In Fig. 4 the BER curves and the dispersion tolerance for the back-to-back configuration are shown. It is possible to observe, that single-carrier and dual-carrier NRZ share the best back-to-back sensitivity and that Stereo-NRZ is only half decibel away, and as expected, Stereo-NRZ and dual-carrier-NRZ have an increased tolerance to dispersion. Formats with two carriers and RZ-50% pulses have a degraded sensitivity due to the cross-talk between carriers and they will not be considered for the rest of the simulations.
IV. OPTIMIZATION OF DISPERSION MAPS

A. The Optimization Algorithm

In optimizing a communication system, we are concerned with the problem of finding the best suitable set of parameters that leads to the best performance in the transmission, e.g., the lowest required OSNR. In this paper we do this by independently varying four parameters of the transmission link (see Fig. 3): average input power levels into the SMF and DCF ($P_{\text{SMF}}, P_{\text{DCF}}$), amount of pre-compensation ($D_{\text{PRE}}$) and residual dispersion per span ($D_{\text{RES}}$). Post-compensation ($D_{\text{POS}}$) sets the accumulated dispersion back to zero. The usual approach is to carry out a grid search, in other words, to simulate every possible combination of parameters and choose the one that gives the best result. However, due to the long transmission distances and the extremely large bandwidth of the signals, the simultaneous optimization of several parameters often translates into prohibitive simulation times. In such scenarios advanced optimization algorithms prove to be an attractive alternative to the conventional grid search.

In [7] and [8] we have presented a novel algorithm especially appropriate for the optimization of optical communication systems. It is independent of external parameters and converges rapidly to the global optimum of the system, drastically reducing the number of required simulation. The algorithm works as follows: After an interval for each parameter is set (thus defining the search space), the algorithm starts by simulating the $2^4$ boundary points. Then it divides the search space into a set of simplexes. For each simplex, the unknown objective function (the required OSNR after 1040 km) is modeled as a Gaussian stochastic process and its mean and variance are used to find the next set of input parameters, which will most probably improve the currently best solution already found. After a certain number of iterations the global optimization algorithm determines the lowest required OSNR and the set of parameters that defines the optimum dispersion map.

B. Simulation results

The algorithm is set to find the optimum dispersion map for each modulation format in 75 iterations (plus the initial 16 boundary points). The link is depicted in Fig. 3. The total field transmission is simulated using the non-

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linear Schrödinger equation and the symmetrized split-step Fourier method. Only dispersion, attenuation and Kerr nonlinearities are investigated. Polarization mode dispersion and nonlinear phase noise are not considered. The nonlinearity of the pre- and post-compensation fibers is neglected, but their attenuations are taken into account. EDFA’s have a noise figure of 6 dB.

Table I summarizes the results for the optimization of each transmission format. Subsequently, the robustness of each optimum dispersion map is investigated. This is done by fixing the optimal input powers and varying the pre-compensation and residual dispersion per span around the optimum values shown in the previous table. Results are shown in Fig. 5 for the single channel case and Fig. 6 for DWDM. The contour plot represents the required OSNR in dB, for a BER of $10^{-4}$.

By optimizing the dispersion maps, a fair comparison can be done regarding the overall performance of a transmission format. From Table I, one can observe that by optimizing the dispersion map, the performance of the transmission after 1040 km is comparable to the back-to-back case. Results show that the required OSNR for single-carrier and for dual-carrier are approximately the same, and for Stereo is about 1 dB more than the rest of the formats. The results depicted in Fig. 5 and 6 show the robustness of each modulation format to variations in the optimum parameters of the dispersion map.

As expected RZ-50% is more robust than NRZ to variations in the amount of residual dispersion per span, and pre compensation. It is also possible to observe that by sharing the transmitted data in two optical carriers, the robustness of the dispersion map is greatly improved. This is true for dual carrier and for Stereo. Robustness to input power in the SMF seems to increase as well. Dual-carrier-DQPSK using NRZ pulses has the best performance and greatest robustness. However, this comes at the expense of doubling the required hardware. Stereo-multiplexed signals, on the other hand, trade around 1 dB in performance against increased robustness in the dispersion map and reduced hardware requirements at the receiver side.

It is worth mentioning that the values in Table I are compared to single-carrier and dual-carrier DQPSK, with NRZ and RZ-50% pulses. With the help of an algorithm for the global optimization of the dispersion maps, we have found that dual-carrier DQPSK has the best performance and the most robust dispersion map of all,

**V. Conclusion**

In this paper, Stereo-multiplexed-DQPSK has been introduced and its performance has been analysed and compared to single-carrier and dual-carrier DQPSK, with NRZ and RZ-50% pulses. With the help of an algorithm for the global optimization of the dispersion maps, we have found that dual-carrier DQPSK has the best performance and the most robust dispersion map of all,
<table>
<thead>
<tr>
<th>Back-to-back</th>
<th>Single-Carrier NRZ</th>
<th>Single-Carrier RZ-50%</th>
<th>Dual-Carrier NRZ</th>
<th>Stereo NRZ</th>
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<td>Single-Channel</td>
<td>DWDM</td>
<td>Single-Channel</td>
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<td>17.5</td>
<td>18.5</td>
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<tr>
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<td>17.7</td>
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<td>$P_{\text{DCF}}$ (dBm)</td>
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<td>$D_{\text{PRE}}$ (ps/nm)</td>
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<tr>
<td>$D_{\text{RES}}$ (ps/nm)</td>
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<td>-26.56</td>
<td>0.0</td>
<td>13.28</td>
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</tbody>
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Figure 5: Robustness of optimum dispersion maps for single channel

Figure 6: Robustness of optimum dispersion maps for DWDM

but at the expense of doubling the required hardware at the transmitter and receiver. On the other hand, Stereo-DQPSK using NRZ pulses is an alternative if robustness of the dispersion map needs to be increased, and costs must be kept low.

We also verified that optimizing single channel transmission, is a good starting point for transmission of DWDM channels, and that in the case of the investigated formats, a penalty of less than one decibel can be expected.

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Oscar Gaete was born in Viña del Mar, Chile, in 1981. He received the Dipl.-Ing. degree in Electrical Engineering from the Pontificia Universidad Catolica de Valparaíso, Chile in 2005 and the M.Sc. degree from the HTW-Aalen in 2007, Germany working on indoor optical communications.

He was a visiting researcher at the University of Melbourne, Australia, in late 2010 and is currently working toward the Ph.D. degree at the Technische Universität München. His main research interests include optimization of fiber-optic communication systems, robust modulation formats for high speed transmission and equalization of system impairments.

Leonardo D. Coelho was born in Recife, Brazil, in 1979. He received the B.Sc. degree in Electrical Engineering from the Universidade Federal de Pernambuco, Recife, Brazil in 2003, the M.Sc. and Ph.D. degree from the Technische Universität München (Munich, Germany) in 2005 and 2010, respectively, studying advanced modulation formats for high-speed optical transmission systems.

He currently holds a postdoctoral position at the Institute for Communicaitons Engineering, Technische Universität München. His main research interests include simulation and optimization of optical communication systems, transmitter and receiver modeling for new modulation formats and nonlinear signal propagation in fiber-optic transmission systems.

Bernhard Spinnler was born in Erlangen, Germany, in 1968. He received the Dipl.-Ing. degree in communications engineering and the Dr.-Ing. degree with a thesis on noncoherent detection of continuous phase modulation from the University of Erlangen-Nurnberg, Germany, in 1994 and 1997, respectively.

Since 1997, he worked on low-complexity modem design of wireless radio relay systems at Siemens AG, Information and Communication Networks. In 2002, he joined the optical networks group of Siemens Corporate Technology, which later merged into Nokia Siemens Networks. There he is working on robust and tolerant design of optical communications systems. His interests focus on advanced modulation, forward error correction, and equalization.