Comparison of Modulation Formats in Fiber-Optic Transmission Systems

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Abstract. In this paper we compare the most important modulation formats, which are used in optical communications, in terms of bit error rate, Q-factor and optical reach. Simulations are primarily performed for transmission rates 10 Gbps and 40 Gbps per channel. The main purpose of these simulations is to find out their limitations, benefits and discuss about the capabilities of these formats to satisfy future network needs and handle data traffic growth. The intensity modulation formats we investigate are Non Return to Zero, Return to Zero, Carrier-Suppressed Return to Zero and duobinary. Subsequently these formats are compared to phase-based formats like Differential Phase-Shift Keying and Differential Quadrature Phase-Shift Keying for the same transmission system and given parameters. We use for simulation purposes the Time Domain Split Step method in OptSim software environment.

Keywords

Optical systems, intensity modulation formats, phase modulation formats, Q-factor, bit error rate.

1. Introduction

The current trends of data traffic growth are creating an urgent necessity for increased system capacities in the existing fiber infrastructures. For this reason, other cost effective solutions have to be proposed to fulfill these requirements and future needs. One of the key solutions is the proper choice of modulation format, which directly affects the overall system performance. For this reason, we compare in this paper the most important formats currently used in optical transmission systems in terms of bit error rate (BER), Q-factor and optical reach. The intensity modulation formats which have been investigated are: Non Return to Zero (NRZ), Return to Zero (RZ), Carrier-Suppressed Return to Zero (CSRZ) and DuoBinary (DB). Subsequently, phase-based formats such as Differential Phase-Shift Keying (DPSK) and Differential Quadrature Phase-Shift Keying (DQPSK) are simulated and compared to intensity formats. Simulation setups are built in OptSim software environment version 5.2 from RSoft Design Group [1]-[4].

2. State of the Art

NRZ, RZ and CSRZ are the three most popular formats we deal with in optical communications [5]. Although On-Off Keying (OOK) is the simplest modulation type, it remains the almost exclusively deployed format up to 10 Gbps per optical channel [6]. Upgrade of the existing fiber infrastructures to higher bit rates would deal with many physical layer constraints, such as chromatic dispersion (CD), polarization mode dispersion (PMD), fiber nonlinearities, accumulated amplified spontaneous emission noise and filter spectral narrowing [7]. For 10 Gbps Dense Wavelength Division Multiplexing (DWDM) systems, the major sources of signal degradation are mainly cross-phase modulation and four-wave mixing [8]. On the other hand, phase-based formats have proved to be more robust especially at 40 Gbps. In this paper we investigate DPSK and DQPSK. Similarly as OOK, they can be implemented in NRZ and RZ formats. The main benefit of DPSK with balanced detection is its 3 dB sensitivity improvement over OOK [7][9]. DQPSK halves the symbol rate at fixed bit rate. As a results, its spectrum will be compressed in frequency by a factor of two although its shape looks the same to that of DPSK. This allows DQPSK to enable higher spectral efficiencies and increased CD tolerance. Its long symbol duration makes DQPSK to be more robust to PMD [10]. In section 3.3, we discuss the transceiver design of all above mentioned formats and the way how they are realized in OptSim. Other advanced modulation formats are becoming commercially available for 100 Gbps and other solutions are being under development for higher transmission rates however the main issues these transponders are facing with are their requirements for complex and high-speed digital signal processing circuits, high power consumption, etc. A description of these formats and a vision to the future can be found in [11] and [12].

3. Methods

For comparison purposes we primarily use Q-factors and BER. Simulation results in OptSim are obtained using the Time Domain Split Step method, which is used to
calculate in the time domain the linear effects in a fiber optic transmission system such as dispersion, from the convolution product in sampled time. This method benefits in full band simulation, aliasing errors immunity, accurate differential group delays, parallel computing, etc, at the cost of implementation complexity [2].

3.1 Q-factor and Bit Error Rate

Q-factor can be calculated as follows [13]:

\[
Q \left[ \right] = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}
\]

where \( \mu_0, \mu_1 \) are the mean log.0, log.1 level values, and \( \sigma_0, \sigma_1 \) are their standard deviations. Essentially, Q-factor denotes the minimum required optical signal to noise ratio to obtain a certain BER. It is possible to evaluate BER from Q-factor as follows [13]:

\[
BER \left[ \right] = \frac{1}{2} \cdot \text{erfc} \left( \frac{Q}{\sqrt{2}} \right)
\]

3.2 Simulation Setup

In the figure below we show the basic idea of the simulation scheme we have used to compare the modulation formats. For measurement purposes we use spectrum analyzers and electrical scopes to measure Q-factors and BER as well as eye diagrams. The optical path consists of a standard single mode fiber with 0.2 dB/km loss. We do not deploy any dispersion compensation techniques or optical amplifier. The output power of transmitters was set to 0 dBm for comparison purposes. The operational wavelength is set to 1550 nm.

On the receiver’s side we include filters with optimized parameters based on the modulation type so they could achieve the best result, i.e. the lowest BER. We consider in the simulations the optical and electrical noise as well.

3.3 Transceiver Design

In this section, we describe the design of transceivers we used in OptSim [3]. Transmitters of the main intensity formats are given in Fig. 2. The simplest transmitter is that of NRZ, which is based on a continuous wave (CW) laser and an amplitude modulator. The other components within the transmitter are a pseudorandom binary sequence (PRBS in the figure) generator and a NRZ raised cosine electrical driver. The main parameters we set up in the transmitter include bit rate, CW laser frequency, output power of the laser, etc. As can be seen from Fig. 2, RZ’s transmitter is identical to that of NRZ, except of the driver type. For CSRZ, a second modulator is used to achieve the carrier-suppression effect. The frequency of the sinusoidal signal generator is set to half of the bit rate to obtain a \( \pi \) phase shift between any two adjacent bits.

Fig. 2. Transmitter design of NRZ, RZ and CSRZ.

DB transmitter is shown in Fig. 3. Its main component is the amplitude dual-arm Mach-Zehnder modulator (MZM). The binary sequence of one of the ‘arms’ is inverted using a NOT gate. Low-pass filters (LPF) are included in the scheme to consider the impact of a non-ideal binary-to-electrical signal conversion.

Moving on to phase-based formats, the transmitter’s complexity increases. In Fig. 4 we show the transmitters of NRZ-DPSK and RZ-DPSK, which are relatively simple compared to that of DQPSK which will be described later on. MZM is core component in a DPSK transmitters which basically generates the phase-modulated output signal. Again, a LPF is used for the same purpose as in DB transmitter. The driver must be carefully set up with the proper maximum and minimum values of the electrical signal. The RZ-DPSK transmitter contains in addition a second MZM driven by an electrical signal to generate the RZ pulses, as schematically shown in the figure below.

In Fig. 5 we schematically show the transmitters of NRZ-DPQSK and RZ-DPQSK formats. As DPQSK deals with the in-phase (I) and quadrature (Q) components, it is necessary to work with each of them separately. Both

Fig. 3. Transmitter design of DB format.

Fig. 4. Transmitter design of NRZ-DPSK and RZ-DPSK.

Fig. 5. Transmitter design of NRZ-DPQSK and RZ-DPQSK.
binary signals for I and Q signal parts are firstly encoded so that the signals on the receiver's side will match the transmitted ones. Subsequently their corresponding electrical signals are generated through the use of drivers to drive MZMs, one per each component. LPFs are included as well in DQPSK transmitters, similarly as in previous formats to consider a real binary-to-electrical signal conversion. As shown in Fig. 5, to one of the optical outputs it is applied an additional phase shift of 90°, which is required for the Q part. This is realized by deploying a phase modulator, which is driven by properly setting a bias wave generator. The output from the phase modulator is then combined with the I component to create a single NRZ-DQPSK modulated signal. Similarly as in RZ-DPSK transmitters, RZ-DQPSK contains in addition to NRZ-DQPSK another MZM to generate the RZ output pulses.

Fig. 5. NRZ-DQPSK and RZ-DQPSK transmitters.

As per receivers, all intensity formats were detected and measured by using an optical filter, PIN photodiode and electrical scope. We select the band-pass filter type and we set the center wavelength of this filter with its corresponding bandwidth, which was optimized by running a scan test with variable values to find out for which bandwidth we obtain the lowest bit error rate for a given modulation format. Meanwhile, the design of receivers for phase-based formats differs. The core component of a DPSK receiver is a balanced 2DPSK component which consists of a tunable Mach-Zehnder interferometer with two output paths delayed to each other by a bit time duration. Each of these optical outputs is detected by a PIN photodiode and the output electrical signal of the 2DPSK receiver is given by the difference between the detected currents [3]. In case of DQPSK, two 2DPSK receivers were used, one for the in-phase and the second for the quadrature component. Similarly as for intensity formats, we include optical filters with optimized bandwidth settings in the input of phase-based receivers. In the next section we discuss about the simulation results. For DQPSK formats we show only the average BER, respectively Q-factor value for both I and Q components.

4. Results

In this section we discuss the simulation results we obtained from comparing modulation formats in terms of BER, Q-factor and optical reach for transmission rates 10 Gbps and 40 Gbps per channel. Fig. 6 shows the BER evaluation of the formats at 10 Gbps. The optical reach varies from 50 km to 150 km.

The corresponding Q-factors are given in Fig. 7.

Fig. 6. Bit error rates of the investigated modulation formats for 10 Gbps systems as a function of fiber length.

Fig. 7. Q-factors of the investigated modulation formats for 10 Gbps systems with different fiber lengths.

OptSim can measure very high Q-factor values however we have limited the values of y-axis because such high values would not be relevant in reality from the required measurement time point of view. As can be seen from the graphs, RZ-DQPSK enables at transceiver’s complexity cost the lowest BER, respectively the highest Q-factor for each length of fiber path. DB offers the best performance compared to other intensity formats. From the graphs we can also observe that till 150 km fiber length only DB, NRZ-DQPSK and RZ-DQPSK can offer at least BER of 10^{-10}, respectively Q-factor of approx. 6.36. RZ format is mainly limited due to its broader spectrum which can significantly limit its implementation in DWDM systems. We continue the comparison of formats at 40 Gbps. All OOK formats did not perform well at this transmission rate therefore we have included in the results shown in Fig. 8.
and Fig. 9 only DB, DPSK and DQPSK formats to better distinguish their physical reach limitations.

The corresponding Q-factors are given in the graph below.

The system performance of DB, NRZ-DQPSK and RZ-DQPSK is quite similar. Up to certain point, DB can perform even better, and as the fiber length increases the DQPSK starts to take over and offers a lower BER, respectively a higher Q-factor. The performance of NRZ-DPSK and RZ-DPSK is very similar with a slight reach improvement of RZ-DPSK for shorter distances.

5. Conclusion

In this paper we have compared different modulation formats for optical communications. Results show that the best system performance is achieved by RZ-DQPSK at both 10 Gbps and 40 Gbps transmission rates. However, simpler and less expensive implementations of a particular modulation format may be sufficient to fulfill the requirements for a give optical transmission system, although other more advanced formats could perform better at the cost of transmitter’s complexity. In this context, a typical example with respect to results from simulations would be the DB format and DQPSK. DB could achieve the lowest bit error rate, respectively the highest Q-factor value from the intensity formats and it was comparable to DQPSK’s performance even at 40 Gbps. DB, NRZ-DQPSK and RZ-DQPSK could enable 150 km at 10 Gbps. At 40 Gbps, the optical reach of these formats was not exceeding 12 km to obtain at least $10^{-10}$ BER, without applying any dispersion compensation technique, or deploying any optical amplifier, etc.

References


About Author...

Rajdi AGALLIU was born in 1989. He received the Master’s degree in communications engineering from the Czech Technical University in Prague in 2013. He is currently a Ph.D. student at the same faculty and his research interests include optical communications and network design.