TDM-PON with 30 Gb/s D8PSK downstream and 10 Gb/s OOK upstream based on a digital incoherent receiver

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Abstract: In this paper, we propose the use of multilevel modulation formats with differential detection to enable Next-Generation Time-Division Multiplexing Passive Optical Networks (TDM-PONs). Bidirectional transmission of 30 Gb/s Differential 8 Phase-Shift Keying (D8PSK), on the downstream, and 10 Gb/s On-Off Keying (OOK), on the upstream, over a TDM-PON has been demonstrated experimentally. Furthermore, some of the functionalities that can be implemented in Digital Signal Processing (DSP) in the receiver, namely wavelength misalignment compensation, IQ imbalance mitigation and data-aided multiple symbol phase estimation, are explored. Results indicate that DSP-based incoherent multilevel formats are an attractive option for providing the high bit rates required for future TDM-PONs.

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1. Introduction

In the last decade, the emergence of bandwidth-hungry, video-centric applications over the Internet has fueled the widespread deployment of broadband access networks and new services like telepresence, 3D HDTV and cloud computing will require even higher bit rates [1]. Fiber-based Passive Optical Networks (PONs) have been deployed to meet this increased bandwidth demand, with recent standards specifying 10 Gb/s operation [2] and it is expected that higher line rates will be required soon [1].

A number of alternatives have been proposed for enabling higher than 10 Gb/s operation in PONs. 40 Gb/s can be achieved by multiplexing four 10 Gb/s OOK signals operating on different wavelengths [3]. This approach requires, however, colored components in the user premises, which is undesirable. Another possibility for scaling the bit rate is moving to advanced modulation formats, like OFDM. 40 Gb/s OFDM-PON in a single wavelength have been demonstrated with both coherent [4] and direct detection [5]. Very good receiver sensitivity is achieved in the coherent case, but for direct detection there is significant power penalty.

In this paper, to enable very high speed PONs, we propose using optical multilevel modulation formats, specifically Differential 8 Phase-Shift Keying (D8PSK) for the downstream channel whilst a simpler modulation format is employed for the upstream. With D8PSK, three bits are encoded in every symbol, enabling 30 Gb/s transmission with 10 GHz components. Incoherent (differential) detection is employed, simplifying the receiver. In comparison to the coherent case, a low-linewidth local oscillator and phase and carrier recovery are not required at the ONU. With this configuration, very high-speed TDM-PONs with colorless Optical Networking Units (ONUs) are possible, enabled also by using a Directly Modulated Laser (DML) at 10 Gb/s as a cost-effective upstream channel.

Moreover, a DSP-based receiver is proposed for the detection of the D8PSK signal, as it simplifies the optical part and enables functionalities to be implemented in the digital domain [6]. Specifically, in this paper an algorithm that corrects the constellation rotation caused by the misalignment of the wavelength of the incoming signal with respect to the periodic function of the delay-line demodulator is examined. Additionally, the performance of an orthogonalization procedure for compensating potential imbalance between the in-phase and quadrature components of the signal, based on the Gram-Schmidt algorithm, is evaluated on D8PSK. Finally, receiver sensitivity enhancement through means of data-aided Multiple-Symbol Phase Estimation (MSPE) is explored with experimental data.

This paper is organized as follows. In Section 2, the D8PSK/OOK PON is presented and in Section 3 the experimental set-up and results are described. In Section 4, the DSP functionalities for the receiver are discussed and simulation and experimental results are shown. Finally, Section 5 concludes the paper.

2. D8PSK/OOK TDM-PON

DPSK with incoherent detection has been proposed in the literature as a way to increase spectral efficiency in the metro and core networks without requiring the increased complexity associated with coherent detection [7]. In these application areas, however, the superior sensitivity and the straightforward implementation of impairments mitigation, such as
Chromatic Dispersion (CD) - as the optical signal is linearly mapped in the electronic domain meant that coherent detection was adopted. In the access domain, however, the complexity of coherent detection is undesirable, while the performance requirements are not as strict due to the shorter reach. Incoherent formats are, therefore, an interesting option for the scaling of the bit rates in future TDM-PONs.

With DPSK, information is encoded in the phase difference between consecutive symbols. In the receiver, the phase reference is provided by a delayed (by one symbol period) version of the signal. There are a number of options regarding D8PSK transmitters and receivers [8], depending on whether the complexity is placed in the optical or the electrical domain. In this paper, a parallel-serial configuration for the transmitter is used, where a nested pair of Mach-Zehnder (MZ) modulators creates a DQPSK signal and a phase modulator in series introduces a $\pi/4$ phase shift to create the D8PSK signal. All modulators are driven with binary electrical signals. Note that the phase modulator could be omitted, if multilevel driving signals are employed. With the advent of high speed A/D and D/A converters [9], DSP-based transmitters are an attractive option to reduce optical complexity and add functionalities (e.g. transmitter-side CD compensation for Long-Reach PONs). However, the available Arbitrary Waveform Generator (AWG) bandwidth is limited to 6 GHz, so the binary-signal approach was selected.

Differential detection is usually implemented through a number of MZ delay interferometers (MZDIs) and balanced photo detectors (BPD) pairs, the number of which again depends on whether multilevel electrical signals are preferable [8]. In this paper, the approach that involves the minimum optical components is chosen, since the complexity of the ONU receiver should be as low as possible. Two MZ interferometers with phase shifts of 0 and 90°, followed by two BPDs, demodulate and detect the D8PSK signal. The detected multilevel signals are proportional to $\Re\{s_n \cdot s_{n-1}\}$, $\Im\{s_n \cdot s_{n-1}\}$, where $s_n$ is the transmitted symbol at instant $n$. The multilevel electrical signals are then sampled and transferred to the digital domain to be processed off-line. The main DSP functions are the reconstruction of the D8PSK symbols and decoding of the information bits according to the decision of which symbol has been received. Besides that, further functionalities can be included, which will be discussed in Section 4.

Regarding the complexity of a downstream channel based on D8PSK, the transmitter and receivers are quite sophisticated, compared to traditional PON transceivers. For the transmitter, the added complexity is not so critical, since it is equipment shared by all the PON users. On the other hand, the receiver will be located in every ONU; therefore it is necessary to be low-cost. In that respect, optical integration is instrumental in developing low-cost incoherent multilevel receivers [10].

For the upstream channel, a 10 Gb/s OOK signal at 1310 nm is selected as the most cost-efficient choice. The bit rate selected is moderately asymmetric, as is the case historically with most standards for access networks. Transmitters and receivers specified for the 10 Gb/s PON standards can be used, lowering costs. Transmission at 1310 nm eliminates the need for dispersion compensation, even for distances longer than 20 km, and reduces interference with the downstream channel.

3. Experimental set-up and results

An experimental set-up, based on the transmitter and receiver structures described in the previous section, was built in order to investigate the performance of the proposed scheme and is shown in Fig. 1. In the Central Office (CO), a Pulse Pattern Generator (PPG) creates the binary signals with bit pattern of $2^{13}-1$. The signals are decorrelated through different cable lengths, aligned and amplified, and then drive the D8PSK modulators. An External Cavity Laser (ECL) set at 1550 nm functions as the low-linewidth CW light source. The D8PSK signal passes through 4km of DCF that compensates for the dispersion over the transmission fiber and is then amplified. After a 1550/1310 nm diplexer, the signal is launched into 25 km of standard single-mode fiber. An attenuator introduces 15 dB of splitting losses (that
corresponds to a splitting ratio of 32 users). In the ONU, the downstream signal is separated through a diplexer and is pre-amplified, before being detected and sampled by a Digital Phosphor Oscilloscope (DPO), with a sample length of 100k symbols. Optical pre-amplification was necessary in this case, as the balanced photo detectors did not have integrated Trans-Impedance Amplifiers (TIAs). The EDFA operates at constant output power mode, with the power fixed at +7 dBm. A detected constellation diagram is shown in Fig. 2a. No degradations from imperfect generation, detection processes or fiber transmission are observed.

![Fig. 1. Experimental set-up](image)

For the upstream channel, a PPG creates a 10 Gb/s signal with a pattern of $2^{23}-1$ that drives a DML at 1310 nm. The NRZ OOK upstream signal, after passing through the splitter and 25 km of fiber, is pre-amplified in the CO by a Semiconductor Optical Amplifier (SOA) to boost the signal before being detected by a PIN-TIA receiver, which has a nominal sensitivity of -19 dBm. If a more sensitive APD-TIA were available at the CO, the SOA would be unnecessary. A detected OOK eye is shown in Fig. 2b, also exhibiting no sign of degradation.

The BER curves as a function of the received power for bidirectional transmission of the downstream and upstream channels can be seen in Figs. 3 and Fig. 4. For the D8PSK signal, error-free transmission with Forward Error Correction (FEC), introducing 7% overhead, is possible. Observed sensitivity is -33.5 dBm and a small power penalty of around 0.5 dB is measured. The results validate the very good generation and detection of the multilevel signal. A power budget of 34 dB is available which means that up to 512 users can be accommodated. In an actual PON deployment, optical amplification in the ONU is not feasible. With balanced photo detectors incorporating TIAs, however, the optical amplifier in the ONU can be removed. For the OOK upstream channel, receiver sensitivity is -24 dBm, with very low power penalty due to fiber transmission and no error floor. If a commercial APD receiver is used, similar power budgets with the downstream signal will be achieved for the upstream channel, therefore the splitting ratio of the system is not affected.

![Fig. 2. (a) received constellation diagram, D8PSK (b) detected eye, OOK](image)
4. Algorithms for incoherent receivers

In the experiment presented in Section 3, the alignment of the signal to the transfer functions of the MZDIs and the orthogonality of the I and Q components were controlled manually. In a real-time system, these functions should be performed automatically, preferably without increasing the complexity of the optical and analog electronic part of the receiver. DSP-based receivers allow these functions to take place in the digital domain, as well as enhance receiver sensitivity, by implementing suitable algorithms. By moving to DSP solutions, the added complexity to the receiver is minimal. Three such algorithms are presented in this Section, verified with simulations and experimental data.

4.1 Wavelength misalignment compensation

Incoherent receivers are based on delay-line MZ interferometers, as the one used in the experiment presented in this paper, or 90° hybrids with a splitter and a delay line. The transfer function of both devices is a periodic function of the wavelength of the incoming signal. That means that in order for the detected signals to be proportional to $\text{Re}\{s_n \cdot s_{n-1}\}, \text{Im}\{s_n \cdot s_{n-1}\}$, the wavelength of the signal has to be aligned to the maximum CW transmission point at the upper interferometer and at minimum CW transmission at the lower interferometer. This can be achieved by tuning the phase shifters of the interferometers. As the phase will drift over time, an analog feedback loop needs to be implemented to keep the signals aligned. In a 90° hybrid, the phase relations between the outputs are fixed based on the geometry of the device, so such tuning is difficult. However, this misalignment can be dealt with in the digital domain, as it has been proposed in [11]. In mathematical terms, assuming that the orthogonality between I and Q is kept, the misalignment results in a phase shift in the electrical signals after...
balanced detection, which will be $\text{Re}\{s_n \cdot \overline{s_{n-1}} \cdot e^{j\phi}\}$, $\text{Im}\{s_n \cdot \overline{s_{n-1}} \cdot e^{j\phi}\}$. This phase shift creates a rotation of the reconstructed constellation diagram.

The most important characteristic of the induced phase shift is that it is slowly-varying over time. That means that during every burst of data that is to be received by each ONU, the phase shift can be considered constant. That means that there it can be estimated once per transmission cycle. To simplify the processing required and to avoid cycle slips associated with blind estimation methods [12], a simple algorithm based on estimation of the phase shift using pilot symbols is proposed. More specifically, the algorithm uses N known symbols in the start of every transmission to estimate the phase shift. This is performed by computing the phase error between the received symbols and the pilot symbols and averaging it over the training length to reduce the influence of noise. The phase shift estimation $\hat{\phi}$ can thus be expressed as:

$$\hat{\phi} = \frac{1}{N} \sum_{n=1}^{N} [\arg(r_k) - \arg(y_k)],$$  \hspace{1cm} (1)

where $r_k$, $y_k$ are the received and pilot symbols, respectively. The receiver in the ONU can always keep track of the rotation by calculating the phase shift during the reception of traffic bursts that contain data of other users, but to reduce power consumption a sleep mode is envisioned during off-times [13]. That means that the phase shift estimation must take place every time that a burst of data is to be received by the ONU. Therefore, the number of pilot symbols that are required for a reliable estimation of the phase shift is important, to determine the overhead of the algorithm. To evaluate the performance of the algorithm, a model was developed in Matlab, simulating the detection of a D8PSK signal with Additive White Gaussian Noise (AWGN) and a random phase fluctuation on every symbol, to account for the effect of the laser phase noise. A random phase shift, between $(-\pi, +\pi)$ was inserted in both in-phase and quadrature components to model the constellation rotation. Three values for the length of the pilot sequence, 10, 50 and 100 symbols, are used in the simulations to estimate the phase shift as a function of the channel SNR. Two scenarios for the random phase fluctuation are chosen, a low one with a range of $(-3^\circ, +3^\circ)$ and a high one, with a range of $(-10^\circ, +10^\circ)$. Translating these numbers into linewidth and assuming a symbol rate of 10 Gsym/s, the corresponding values are 1.44 MHz and 16.2 MHz, for the low and high scenario, respectively. The simulation results giving the error of the phase estimation normalized over the actual phase shift are shown in Figs. 5 and 6. The SNR ranges from 15.5 dB, which corresponds to a BER of $5 \cdot 10^{-3}$, to 20.5 dB, which corresponds to a BER of $10^{-5}$.

![Fig. 5. Phase error, low phase noise](image-url)
For the low phase noise case, it can be seen that for 50 and 100 symbols, the phase error is kept below 1% even for low SNR values. For short pilot lengths of 10 symbols, the phase error approaches 1% at higher SNR values, but in any case it remains below 2%. For the high phase noise case, for 50 symbols-long sequences the phase error is around 0.8%. For 10 symbols, phase error converges at around 1.2% at high SNR values. The longest sequence, 100 symbols, has a phase error of around 1% at high SNR. The reason that the longest sequence performs worse than the medium one at high phase noise values is a result of phase noise accumulation, which affects long sequences more [14]. On the other hand, very short sequences are more affected by Amplified Spontaneous Emission (ASE) noise. For both phase noise cases, however, it has been shown that the phase error can be kept below 1% without introducing significant overhead in the data transmission.

4.2 IQ imbalance compensation

In the previous analysis, it was assumed that the orthogonality between I and Q components is maintained. However, it may be the case that due to imperfections of the demodulator, there might be deviations from the orthogonality. To alleviate this problem, orthogonalization algorithms can be used. A popular algorithm is the Gram-Schmidt procedure [15]. The Gram-Schmidt procedure creates two orthonormal signals from two nonorthogonal signals by finding the correlation between them. Specifically, with \( I_r(t), Q_r(t) \) denoted as the received components and \( I_o(t), Q_o(t) \) denoted as the new orthogonal components, the algorithm works as follows:

\[
I_o(t) = \frac{I_r(t)}{\sqrt{P_1}}
\]

\[
Q_o(t) = Q_r(t) - \frac{\rho \cdot I_r(t)}{P_1}
\]

\[
Q_o(t) = \frac{Q_r(t)}{\sqrt{P_2}}
\]

where \( P_1, P_2 \) are the means of the power of the received components and \( \rho = E[I_r(t) \cdot Q_r(t)] \) is the correlation coefficient between them.

To evaluate the performance of the Gram-Schmidt orthonormalization procedure for D8PSK signals, the simulation model developed in the previous Section is used, where the phase between the I and Q components is varied. A random phase shift in the constellation is still assumed and it is estimated using 50 pilot symbols. In addition, phase noise is present. The BER of the uncompensated and the orthonormalized signals as a function of the deviation
from orthogonality is shown in Fig. 7. The reference signal has a BER of $10^{-4}$ and the length of the sequence for the calculation of the correlation coefficient is 1000 symbols. It can be seen that if the imbalance is left uncompensated, a phase deviation of $10^0$ can incur significant power penalty. If the Gram-Schmidt algorithm is used, the power penalty of deviations as large as $15^0$ can be reduced to 0.5 dB. Taking into account that the Optical Internetworking Forum (OIF) has a guideline of allowed phase errors in the $90^0$ hybrid in the range of $\pm5^0$ [16], it can be seen that the degradation due to IQ imbalance can be minimal. Two simulated constellation diagrams, before compensation, with random phase rotation and $10^0$ IQ imbalance, and after compensation, are shown in Fig. 8. It can be seen that the compensated constellation has orthogonal IQ components and has been rotated back to the correct position.

![Fig. 7 BER vs. IQ imbalance](image)

![Fig. 8. Simulated constellation diagrams: (a) before compensation (b) after compensation](image)

### 4.3 Multiple symbol phase estimation

The sensitivity of the receiver can be enhanced if the decision variable takes into account previous symbols to improve the available phase reference. A generalized MSPE algorithm for DPSK modulation formats has been presented at [17]. In this algorithm, the phase modulation of previous received symbols is removed and the symbols are used to create a more reliable phase reference. In mathematical terms, the improved decision variable $x(n)$ will be:

$$ x(n) = u(n) + w \cdot u(n) \cdot x(n-1) \cdot \exp[-j\Delta\phi(n-1)] \cdot \exp(-j\pi / m), $$  

where $u(n)$ is the received symbol, $w$ is a forgetting factor, $\Delta\phi(n)$ is the decoded phase for symbol $n$ and $m$ is the order of the DPSK format used. Implementing this algorithm to the received data of the 30 Gb/s D8PSK experiment, the improved BER curve is obtained and shown in Fig. 9. An improvement in the receiver sensitivity of around 1 dB at a BER of $10^{-4}$
can be seen. Due to the algorithms simplicity, it can be used in differential receivers to provide an increased power margin in multilevel-based access networks.

![Graph showing BER vs. received power for conventional and MSPE detection]

**Fig. 9.** BER vs. received power for conventional and MSPE detection

5. Conclusion

We have proposed the use of multilevel modulation with differential detection as an efficient way of increasing the downstream bit rate in TDM-PONs. Bidirectional transmission of a 30 Gb/s D8PSK downstream and a 10 Gb/s OOK upstream channel has been experimentally demonstrated over 25 km of fiber, with very good receiver sensitivity observed for the D8PSK signal. Moreover, DSP functionalities that can reduce the complexity of the receiver, increase its robustness to component imperfections and improve the system margin were examined through simulations and experimental data. Results indicate that incoherent multilevel formats with DSP-based transceivers are an attractive and potentially cost-efficient option for scaling the line rate in Next-Generation TDM-PONs.

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