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Multi-level modulation formats for optical access networks

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There is growing demand for higher bit rates at the access domain. The most promising and future-proof technology for providing end users with high bandwidth is Passive Optical Networks (PON). In order to provide these higher bit rates, the use of multi-level modulation has been proposed. By moving to multi-level signals, low speed electronics can be used, with some added complexity to the optical part. This paper investigates the performance of incoherent multi-level modulation formats (in particular QAM and DQPSK) in bidirectional PONs. The simulation results indicate that incoherent QAM is a strong candidate for future PONs.

Introduction

The explosive growth of the Internet has led to an increased demand for broadband access by business and home users. This demand has been met up to now using a variety of transmission media, but there is a consensus that the only ‘future-proof’ solution is Passive Optical Networks (PON). The most important types of PONs are Time Division Multiplexing (TDM) PON and Wavelength Division Multiplexing (WDM) PON. In TDM PON, a common feeder fiber is split in individual fibers close to the users’ premises, who are granted access to the fiber for a fraction of the time. Contrary to a TDM PON, in a WDM PON there is no bandwidth sharing, since each user uses a different pair of wavelengths, separated and combined in an Arrayed Waveguide Grating (AWG) (de)multiplexer [1].

In the physical layer, there is a resurgence of interest on multi-level modulation formats. In multi-level modulation using M levels, each symbol carries $\log_2 M$ bits. This means that for a given bit rate, the symbol rate will be $\log_2 M$ times lower. For access networks, this reduction of the symbol rate allows the use of cheaper electronic and optoelectronic components, helping to realize cost-effective PONs, and lowers the congestion probability. Multi-level formats can be demodulated either coherently or incoherently. In the first case, a local oscillator (a laser) is used in the receiver to track the phase of the received signal. In incoherent detection, no local oscillator is used and only the phase difference between the received symbols is known. In this case, the transmitted data must be differentially coded. Since complexity should be kept at a minimum we have focused on incoherent modulation formats.

The two most popular multi-level modulation formats are Differential Quaternary Phase Shift Keying (DQPSK) and Quadrature Amplitude Modulation (QAM). In DQPSK, two bits are encoded in one of the four possible phase differences between two consecutive symbols. Combined with Polarization Multiplexing (POLMUX), four bits can be transmitted during each symbol period. In incoherent 16QAM, four bits are encoded in the amplitude and in the phase difference between consecutive symbols. In Sections II and III of the paper, the transmitter and receiver configurations that can produce and detect DQPSK and QAM signals are examined, respectively. In Section IV, the results from simulations regarding bidirectional transmission of DQPSK and QAM signals are shown. Finally, Section V provides some conclusions.

Transmitter structures

The basic building block of a DQPSK/QAM transmitter is an I/Q modulator [2]. The most straightforward implementation is a nested pair of Mach-Zehnder modulators, followed by a $\pi/2$ phase shift in the Quadrature phase component. With this method, NRZ signals are created. If RZ signals are preferable, an extra MZ modulator driven by a sine wave with 50% duty cycle can perform the RZ carving.

As already mentioned, incoherent communication requires differential coding of the transmitted data. The coding is performed in the electrical domain and is different for the two modulation formats in question. For DQPSK, the differential coding can be implemented with digital logic directly at the output bit stream of the PRBS. Then, NRZ pulses are created by the coded bit sequence, which are used to the drive the MZ modulators. For incoherent QAM, the encoding is implemented in the analog domain [3]. Every four consecutive bits are mapped into a 16QAM symbol, denoted $a_k e^{j\phi_k}$. To enable differential detection, the phase pre-integration technique is used, adding the phase of the previous symbol to the current one. The transmitted symbol, therefore, becomes $a_k e^{j(\phi_k+\phi_{k-1})}$. The QAM symbol is then split and into the I and Q components and is predistorted, to compensate for the nonlinear transfer function of the MZ modulator. The resulting I and Q optical components in each case are then combined to form the optical QAM or DQPSK signal. The schematic of the DQSK transmitter configuration used can be seen in Fig. 1, and the QAM transmitter in Fig. 2.

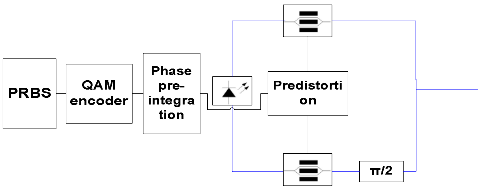

Figure 1 QAM transmitter

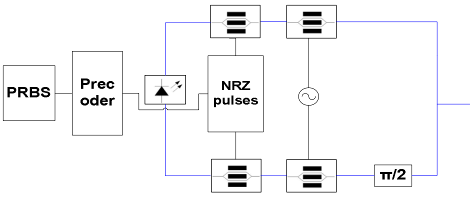

Figure 2 DQPSK RZ transmitter

Receiver structures

Incoherent modulation formats use interferometric-based demodulation ([2], [3]). An interferometric receiver consists of two asymmetric Mach-Zehnder interferometers, followed by two balanced detectors. Each MZ interferometer has a time delay equal to one symbol period and a phase shift of $\theta, \theta-90^o$ respectively, with θ depending on the modulation format. For QAM, a separate photodiode is needed to produce an estimate of the amplitude of the received signal. If the received signal is denoted as $r(t)e^{j\phi(t)} + n(t)$, the outputs of the balanced detectors are:

$$i_I(t) = \frac{r(t)r(t-T)}{4}\cos[\phi(t) - \phi(t-T) - \theta] + n_I(t)$$

$$i_Q(t) = \frac{r(t)r(t-T)}{4}\cos[\phi(t) - \phi(t-T) - \theta + 90^o] + n_Q(t)$$

For DQPSK demodulation, $\theta = 45^o$ and $r(t) = r(t-T) = A$. That means that the signs of the two output currents can be directly mapped to the detected pair of bits. The DQPSK receiver is shown in Fig. 3. For QAM, $\theta = 0^o$ and the output currents are proportional to $\cos\Delta\phi, \sin\Delta\phi$, where $\Delta\phi$ is the phase difference between the current and the previously received symbol. Using these two metrics, the inverse tangent is computed and an estimation of the phase difference is produced, which is an estimation of the phase of the original QAM symbol, before the pre-integration operation. Since amplitude estimation is also available, from the single photodiode, the transmitted symbol can be reconstructed at the receiver. A QAM decoder then maps the complex symbol into the four corresponding bits. The QAM receiver can be seen in Fig. 4.

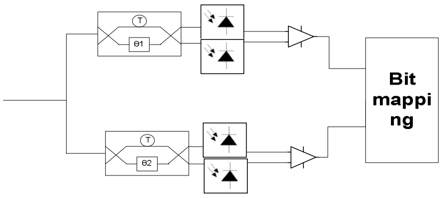

Figure 3 DQPSK receiver

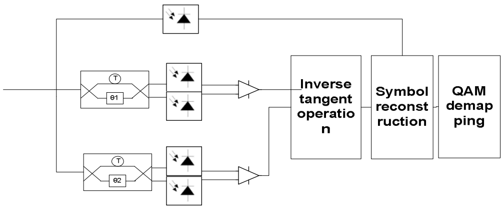

Figure 4 QAM receiver

Simulations

In order to evaluate the performance of multi-level modulation formats in the context of access networks, VPI was used to model bidirectional transmission over 20 km of fiber in hybrid TDM/WDM topology. The system model can be seen in Fig. 5. The modulated signal is multiplexed with an unmodulated carrier, which is modulated at the Optical Network Unit (ONU). After transmission over 20 km of SSM fiber and a WDM demultiplexer, an attenuator models the losses caused by the TDM splitter. In the ONU, a demultiplexer separates the data signal from the unmodulated carrier. The data signal is then demodulated and the BER is estimated. The unmodulated carrier is amplified, filtered and modulated by the upstream data. The upstream signal undergoes the same operations as the downstream data signal and is received at the Central Office (CO). In the DQPSK-POLMUX case, the transmitter and receiver indicated in Fig. 5 consist of two identical (de)modulators who use two orthogonal polarizations. Polarization splitters and combiners and polarization control are also necessary for this scheme.

The performance of the two modulation formats was evaluated by constructing the BER vs. the received power curves. For the DQPSK-POLMUX format, a preamplifier was used only in the CO for the upstream data, so in order to directly compare the two signals the received power was measured after the preamplifier. The results are shown in Fig. 6.

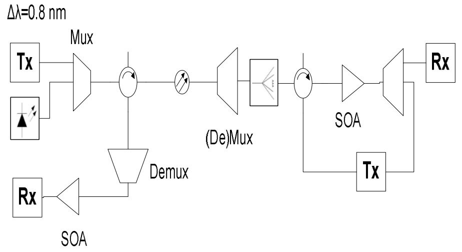

Figure 5 PON schematic

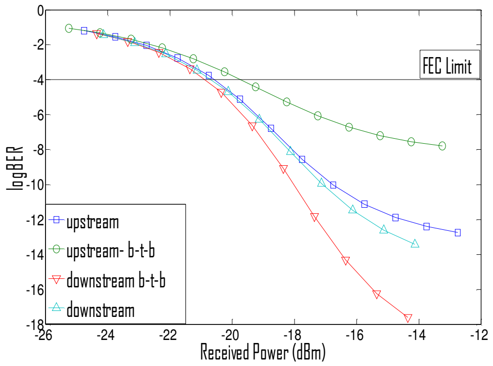

Figure 6 BER curves for DQPSK-POLMUX

The respective BER curves for incoherent 16QAM are shown in Fig. 7. In the QAM case, preamplifiers are used in both directions, so the received power is measured before the amplifiers.

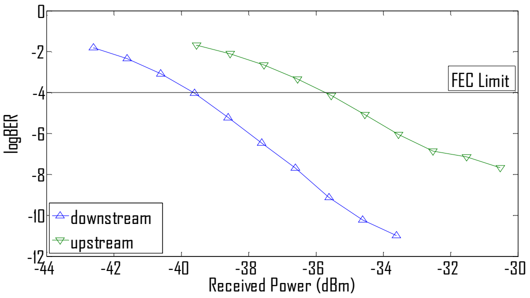

Figure 7 BER curves for incoherent QAM

Conclusions

Simulations indicate that incoherent multi-level modulation formats are promising candidates for next generation PONs, especially QAM, which does not require the additional complexity associated with polarization multiplexing. Future work will include more simulations and experimental validation to fully evaluate the performance of incoherent QAM. Moreover, ways to improve the performance of the receiver (e.g. Maximum Likelihood detection) will be investigated.

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