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Performance evaluation of multilevel modulation formats using partial response for capacity upgrade in access network with limited electronic bandwidth

Peter Madsen *, Lau Frejstrup Suhr, Juan Sebastian Rodriguez, Idelfonso Tafur Monroy, Juan José Vegas Olmos

Technical University of Denmark, Department of Photonics Engineering Ørsted Plads, Building 343, Kgs. Lyngby 2800, Denmark

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ABSTRACT

We present a successful experimental evaluation of 4 level Pulse Amplitude Modulation (4-PAM) and Duobinary modulation. An experimental performance evaluation is presented for Duobinary 4 PAM and other modulation formats. All modulation formants used, may be considered to be implemented in future Passive Optical Network (PON) class access networks with limited electrical bandwidth. We compared NRZ, Duobinary, 4-PAM and Duobinary 4-PAM operating at 9 Gbaud over 20 km single mode fiber. The results provides an insight and guidelines on the utilization of these advanced modulation formats.

1. Introduction

Today access networks are being stressed, by the constant increasing number of equipment that needs a connection to the Internet [1]. Currently, the Internet traffic grows with exponential rate. There is a confirmed demand for upgrading the capacity of optical access networks as the metro network-only traffic surpassed the long haul network traffic in 2014 [2]. The main bandwidth limit in optical access equipment is the electronic bandwidth. Higher capacity standards propose the employment of advanced modulation formats to overcome this limit [3]. Among the advanced modulation formats that have been considered for access networks is, Discrete Multi Tone (DMT) and Orthogonal Frequency Division Multiplexing (OFDM). As both DMT and OFDM require a large amount of Digital Signal Processing (DSP) at the receiver side these modulation formats are assessed to be costly to implement [4,5]. Multilevel modulation formats, as 4-level Pulse Amplitude Modulation (4-PAM) and Duobinary, can be handled by analog solutions; in form of Digital to Analog Converters (DAC) and electrical filters respectively, and these solutions require reduced DSP [6]; for example only in the form of a modulo operation for Duobinary modulation schemes [7]. Duobinary modulation over PON systems have been implemented before [4], but the performance has not been directly compared to more advance modulation formats as 4-PAM. Recent research shows that the adoption of 4-PAM in standardization bodies has led to the real time implementation [8]. As such it is relevant to investigate and evaluate the performance of even more advanced modulation formats including Duobinary 4-PAM [7,9]. This paper reports on an experimental comparison of the performance of Non Return to Zero (NRZ), Duobinary, and Duobinary 4-PAM, modulation formats. We performed transmission through a Passive Optical Network (PON) like system using a directly modulated Distributed Feedback (DFB) laser and a minimal amount of DSP. A typical PON access network scenario is seen from Fig. 1. The experimental setup used in this work carries some of the same features and parameters as the PON scenario from Fig. 1. The selected symbol rate is below 10 Gbaud and the electrical bandwidth of the transmitter, receiver is limited at 10 GHz and the maximum transmission distance is 20 km. The maximum optical power measured in the experiment is below todays standard split ration loss for a PON Optical Distribution Network (ODN) [10]. Therefore, the system presented in the experimental setup should be consider only in Point-2-Point (P2P) connection or PON type systems with no or very low split ratio. The results show that the modulation formats under test

* Corresponding author.

E-mail addresses: petma@fotonik.dtu.dk (P. Madsen), lasu@fotonik.dtu.dk (L. Frejstrup Suhr), juse@fotonik.dtu.dk (J. Sebastian Rodriguez), idtm@fotonik.dtu.dk (I. Tafur Monroy), jjvo@fotoniik.dtu.dk (J.J. Vegas Olmos).

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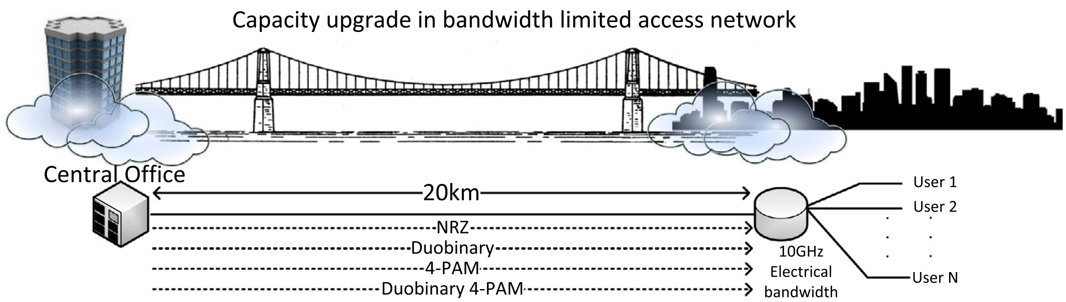

Fig. 1. Scenario for partial response multilevel formats in bandwidth limited PONs. All four modulation formats are transmitted from the central office, over the same 20 km fiber, to an urban location where the electrical bandwidth is limited at 10 GHz.

are compatible with already implemented access networks while offering the capability of doubling the system capacity.

2. Duobinary modulation principles of NRZ and 4-PAM

Duobinary modulation is a partial response signal format that exploits known Intersymbol Interference (ISI). Through heavy filtering of an NRZ signal, the spectral efficiency is increased by inducing controlled ISI when the upper part of the spectra is removed by the filter. On the transmitter side, the NRZ needs to be precoded, as the ISI creates a correlation between adjacent bits in the NRZ otherwise the receiver will experience error propagation. The precoding is easily done in hardware following the method proposed by Lender in 1963 [11]. The precoding method creates a two level signal $b_k = a_k \oplus b_{k-1}$, where a_k is the original NRZ signal. By knowing that the ISI from the filter will correlate the adjacent bits in b_k we get $c_k = b_k + b_{k-1}$. c_k becomes a thee level signal which is easily demodulated with DSP through $a_k = c_k \ mod\ 2$. It is clear that the symbol rate in duobinary signaling does not change from that of the original NRZ, but due to the induced ISI the spectrum becomes smaller and the bandwidth is less than that of NRZ. The principles of Duobinary modulation can be combined with 4-PAM, by using a 4-PAM seed signal into a Duobinary filter. This results in a $4 + 3 = 7$ level signal. In terms of encoding and decoding, the Duobinary formulas are extended to include a modulo 4 operation. Encoding a 4-PAM signal into Duobinary is done through $b_k = a_k - b_{k-1} \ mod\ 4$. The ISI from the filter remains the same $c_k = b_k + b_{k-1}$ and on the receiver side, the original signal is recovered by also including a modulo 4 operation as in $a_k = c_k \ mod\ 4$. Duobinary 4-PAM utilize advantages from both 4-PAM and Duobinary modulation. Operating at twice the symbol rate of the NRZ used as seed for the 4-PAM signal and having halve the spectral width of the 4-PAM signal used as seed for the Duobinary filter. These advantages are gained while the transmitter and receiver only requires simple DSP [12,13]. The drawback of Duobinary 4-PAM lies in reduced receiver sensitivity, as the 7 level signal needs higher extinction ratio and is more prone to noise at the receiver. Duobinary 4-PAM is also more sensitivity to fiber dispersion. It creates a timing skew in the 7 levels and the process of sampling the signal requires more complex DSP [14].

3. Experimental setup

This section presents the experimental setup that was used to evaluate and compare the performance of NRZ, Duobinary, 4-PAM and Duobinary 4-PAM signals.

In Fig. 2 a Pulse Patten Generator (PPG) is set to output a Pesudo Random Bit Sequence, with a length of 15 (PRBS15), at two different outputs, with a bitrate of 9 Gbps. The first output has a peak-to-peak voltage at 250 mV and the second output has a peak-to-peak voltage at 896 mV. At the first output, an electrical delay line is used to adjust the timing of the two outputs to each other. The two adjusted signals are fed to a 4-bit DAC. The 4-PAM signal from the DAC has a maximum peak-to-peak voltage of 123 mV. The signal from the DAC is amplified to 2 V peak-to-peak. The DFB laser is powered with 70 mA driving current, providing an optical output power of 4 dBm. The DFB laser has a bandwidth of 10 GHz and an optical extinction ration of 9 dB and is directly modulated with the 4-PAM signal at a wavelength of 1550 nm. A Variable Optical Attenuator (VOA) is implemented to do Bit Error Rate (BER) measurements. The fiber span consists of different types of fiber, Standard Single Mode Fiber (SSMF), Dispersion Shifted Fiber (DSF) and Non-Zero Dispersion Shifted Fiber (NZDSF) each fiber has the length of 5 km and 20 km. The optical signal is received by a 10 GHz Receiver module implementing a PIN photo diode. The signal is received by a 40 GSa/s Digital Storage Oscilloscope (DSO) where traces are stored for later offline DSP. The setup in Fig. 2 is modified to measure Duobinary and Dubinary 4-PAM signals by implementing a 4 GHz Bessel filter before the DSO. When measuring NRZ signals, only one output from the PPG is used. The NRZ signal from the PPG is adjusted so that the voltage is 2 V peak-to-peak.

4. Results

This section presents the results from work done on the experimental setup described in Section 3.

Fig. 3 shows the BER on a y-scale of $-log_{10}(BER)$ and the x-scale shows optical received power in *dBm*. The Forward Error Correction (FEC) limit corresponds to a "Beyond Bound Decoding" with 7% overhead [15]. The receiver sensitivity varies with 12 dB at the FEC limit between the different modulation formats. From the BER curves presented by Fig. 3 it is clear that, the performance of NRZ and Duobinary is indistinguishable, this could be due to an unfiltered high frequency component from DFB laser, which limits the performance of the NRZ signal. It is also clear that the system reaches an error floor around a BER of 10^{-3} for Duobinary 4-PAM. Due to effects of dispersion in SSMF the system was not able to get a receiver sensitivity below the FEC limit for Duobinary 4-PAM at 20 km of SSMF. From Fig. 3 we see that the BER of NRZ and Duobinary follow straight lines with a steep slope, indicating that these two signal types can reach low BER values with little receiver power penalty. At 4-PAM we see that the BER is also straight, but with a different, less steep, slope. Reaching low BER values punishes the receiver power penalty much more then for NRZ and Duobinary. The average difference in receiver power, at the FEC limit, from NRZ and Duobinary to 4-PAM is around 6 dB which makes sense, as the total extinction ration of the NRZ