

Experiments on Bipolar Transmission with Direct Detection

Thomas Wiegart^{(1),†}, Daniel Plabst⁽¹⁾, Tobias Prinz⁽¹⁾, Talha Rahman⁽²⁾, Maximilian Schädler⁽²⁾,
Nebojša Stojanović⁽²⁾, Stefano Calabrò⁽²⁾, Norbert Hanik⁽¹⁾, Gerhard Kramer⁽¹⁾

⁽¹⁾ Institute for Communications Engineering, Technical University of Munich, Germany, [†tw@tum.de](mailto:tw@tum.de)

⁽²⁾ Huawei Technologies Duesseldorf GmbH, Munich Research Center, Germany

Abstract Achievable information rates of bipolar 4- and 8-ary constellations are experimentally compared to those of intensity modulation (IM) when using an oversampled direct detection receiver. The bipolar constellations gain up to 1.8 dB over their IM counterparts. ©2022 The authors.

Introduction

Short-reach fiber-optic communication systems usually use direct detection (DD) receivers to reduce hardware cost, system complexity, and energy consumption as compared to coherent receivers^{[1]–[3]}. A DD device outputs the intensity of its input signal and thus short-reach systems with DD usually apply single polarization intensity modulation (IM), i.e., information is modulated onto the intensity and the transmit constellation is real and non-negative, e.g., on-off keying (OOK) or 4-/8-ary pulse amplitude modulation (PAM).

However, the signal phase can be detected with a DD receiver by employing oversampling^[4], and when optical noise dominates one loses at most one bit per channel use (bpcu) as compared to coherent detection^{[5],[6]}. This motivates using bipolar or even complex-valued modulation formats. Two oversampled receivers for bipolar and complex-valued modulation formats were proposed in^{[7],[8]}. They recover the phase from limited inter-symbol interference (ISI) in the received signal. More sophisticated receivers for bandlimited channels were developed in^[9] and numerical simulations showed significant energy gains of bipolar modulation formats over IM.

In this paper, we experimentally demonstrate that bipolar transmission improves IM by using the tools and methods in^[9]. We perform measurements with optical back-to-back (B2B) transmission and with 20 km of standard single-mode fiber (SSMF) in C-band. We observe gains of up to 1.3 dB and 1.8 dB, respectively, for 4-ary and 8-ary bipolar constellations as compared to unipolar 4- and 8-PAM.

System Model

We adapt the system model from^[9] and transmit a block of n uniform independent and identically

distributed (i.i.d.) symbols X_i , $i \in \{1, \dots, n\}$, from the alphabet $\mathcal{X}_{4\text{-PAM}} = \{0, 1, 2, 3\}$ for 4-ary PAM or from $\mathcal{X}_{4\text{-ASK}} = \{-3, -1, 1, 3\}$ for 4-ary amplitude shift keying (ASK), and analogously for 8-PAM and 8-ASK. The transmit symbols are pulse shaped, modulated, and transmitted through the channel. A bandlimited DD receiver outputs the received signal intensity and the receiver uses two-fold oversampling.

Consider the upsampled transmit sequence $\mathbf{X}' = [X_1, 0, X_2, 0, \dots, X_n, 0]$ and the channel matrix \mathbf{H} which has Toeplitz structure and is constructed from a M -tap impulse response $\mathbf{h} = [h_1, \dots, h_M]$. The matrix maps $2n$ inputs to $2n$ outputs, i.e., we discard border samples. The channel matrix includes all filters and linear transmission effects, i.e., pulse shaping, bandwidth limitations, chromatic dispersion (CD), and attenuation. We model the time-discrete oversampled baseband system by:

$$\mathbf{Y} = |\mathbf{H}\mathbf{X}' + \mathbf{N}_1|^{\circ 2} + \mathbf{N}_2 \in \mathbb{R}^{2n} \quad (1)$$

where $|\cdot|^{\circ 2}$ denotes the element-wise modulus squared, and where \mathbf{N}_1 and \mathbf{N}_2 are additive noise before and after the photodetector (PD), respectively. The entries of \mathbf{N}_1 are modelled as independent circularly-symmetric complex Gaussian (CSCG) and they include noise impairments of the transmitter, e.g., laser phase noise or amplifier noise. The entries of \mathbf{N}_2 are modelled as zero-mean independent real Gaussian and they include noise impairments of the receiver after the PD (e.g., thermal noise). Comparing to the model from^[9], we added the noise \mathbf{N}_1 before the PD because we observed significant transmitter noise in our experiments.

Achievable Information Rates

The mutual information (MI) rate $\frac{1}{n}I(\mathbf{X}'; \mathbf{Y})$ is an achievable information rate (AIR) for reliable communication. We follow the algorithm described

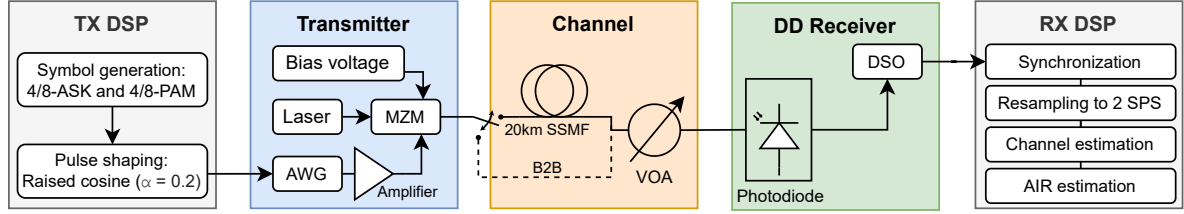


Fig. 1: Experimental setup: raised cosine pulses with roll-off $\alpha = 0.2$ and 4- and 8-ary ASK and PAM constellations.

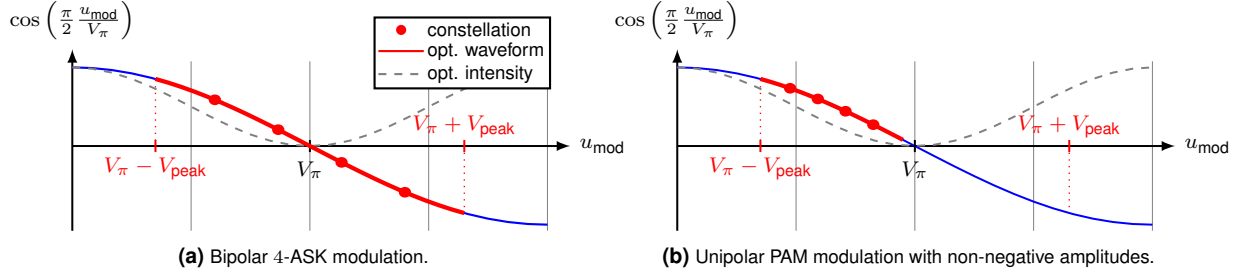


Fig. 2: Visualization of bipolar and unipolar modulation using a MZM with 4-ASK and 4-PAM. Red dots denote constellation points and red lines show all possible values of the waveform. The gray dashed curve depicts the intensity of the modulated signal.

in^[9] to compute the MI for channels with ISI in the oversampled receive sequences. For spectrally-efficient pulses, e.g., raised cosine pulses with small roll-off factors, there is significant ISI. However, the algorithm in^[9] has an exponentially growing complexity in the number of considered ISI taps. We thus compute lower bounds on the MI through an auxiliary channel with L taps where L is smaller than the actual system memory M (see^[10] and Sec. III in^[9]). The resulting rates can be achieved by mismatched decoding, i.e., the receiver uses the auxiliary model to decode.

Experimental Setup

The experimental setup is shown in Fig. 1. The transmitter generates symbols at symbol rate $R = 30$ GBd and performs differential precoding as in^[9]. A raised cosine pulse with roll-off $\alpha = 0.2$ is used and the oversampled signal is loaded into an arbitrary waveform generator (AWG) operating at 120 GSa/s. The AWG signal is amplified and fed to a Mach-Zehnder modulator (MZM) that is driven by a C-band laser operating at a wavelength of $\lambda = 1550$ nm. The bias point of the MZM is tuned depending on the constellation as described in the next section. The optical signal is either transmitted in a B2B setup with a variable optical attenuator (VOA) or over 20 km of SSF (attenuation 0.2 dB/km, group velocity dispersion $D = 17$ ps/(nm · km)) followed by a VOA. This allows for measurements with and without CD.

The receiver has a 70 GHz PD followed by a digital storage oscilloscope (DSO) operating at 256 GSa/s. Offline processing is performed for synchronization and resampling to 2 SPS (sam-

ples per symbol) and channel estimation. Afterwards, the achievable rate is computed using the method from^[9] with 10000 samples per rate point.

Generation of ASK and PAM Constellations

The experimental comparison of ASK and PAM constellations is performed as follows. For both constellations, the AWG is loaded with the same bipolar (mean-free) transmit sequence.

For ASK transmission, the MZM is tuned to the null point V_π and modulated with a signal with a peak-to-peak voltage span of $2V_{\text{peak}}$ as depicted in Fig. 2a. The output signal thus uses both positive and negative amplitudes.

For PAM transmission, the peak-to-peak output voltage of the AWG is halved compared to ASK transmission and the bias point of the MZM is adjusted so that the PAM constellation has the same average optical launch power as in the ASK case. For the considered scenario (raised-cosine pulse with $\alpha = 0.2$) this also leads to almost the same peak power for both scenarios (ASK had a peak power which is only 0.05 dB larger). Thus the two constellations are comparable under average or peak power constraints. The launch power into the SSF or the VOA was -3.2 dBm for 4-ary constellations and -5.0 dBm for 8-ary constellations.

Auxiliary Channel Optimization

To consider additional effects occurring in the experiments, we slightly modify (1) to

$$\tilde{\mathbf{Y}} = |\mathbf{H}\mathbf{X}' + \mathbf{N}_1 + \boldsymbol{\mu}_1|^{\circ 2} + \mathbf{N}_2 + \boldsymbol{\mu}_2 \quad (2)$$

to include the MZM bias $\boldsymbol{\mu}_1 = (\mathbf{1}_n \otimes [\mu_{11}, \mu_{12}])^T$, where $\mathbf{1}_n$ is the length n all-ones vector, \otimes de-

notes the Kronecker product and μ_{11}, μ_{12} are design parameters. Furthermore, (2) includes $\mu_2 = (\mathbf{1}_n \otimes [\mu_{21}, \mu_{22}])^T$ which models DC-free measurements at the oscilloscope. The model (2) has independent CSCG noise N_1 and zero-mean real Gaussian noise N_2 with covariance matrices $C_{N_1} = \text{diag}(\mathbf{1}_n \otimes [\sigma_{11}^2, \sigma_{12}^2])$ and $C_{N_2} = \text{diag}(\mathbf{1}_n \otimes [\sigma_{21}^2, \sigma_{22}^2])$, respectively. This allows to individually adjust the means μ_{ij} and the variances σ_{ij}^2 for samples at and between symbol times.

The parameters $(\mu_{11}, \dots, \mu_{22}, \sigma_{11}^2, \dots, \sigma_{22}^2, \mathbf{h})$, including the length L impulse response \mathbf{h} , in the auxiliary model (2) are estimated using the experimental measurements. We remark that these parameters must be carefully chosen to ensure satisfactory performance. We use the approach described in Sec. III C of [9] to optimize the parameters to maximize the AIRs. The optimization is carried out numerically using 5000 pilot symbols from the experiments.

Experimental Results

Fig. 3a compares AIRs with 4-ASK and 4-PAM transmission for different optical attenuation values in a B2B setting. We consider different detector memory values L (note that L taps in the oversampled model correspond to $(L-1)/2$ symbols). PAM significantly outperforms ASK for $L = 3$ (1 symbol, green curves). Both schemes perform almost equally well for $L = 7$ (3 symbols, red curves). ASK outperforms PAM by 0.8 dB at a rate of 1.8 bpcu for $L = 11$ (5 symbols, blue curves).

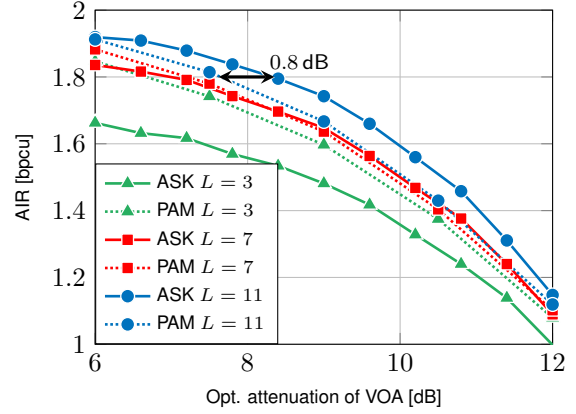
The curves in Fig. 3b show results with 20 km SSMF followed by a VOA. As observed in [9], CD may help the receiver to recover phase information and especially ASK benefits from CD. In this setting, ASK and PAM perform similarly for $L = 3$ and ASK outperforms PAM for larger memory. For $L = 11$, ASK gains about 1.3 dB over PAM at an AIR of 1.8 bpcu.

Fig. 3c shows results for 8-ary transmission in a B2B scenario. The results are in line with the 4-ary ones, but the gains of bipolar transmission increase for higher order constellations. For $L = 11$ we see gains of 1.8 dB at an AIR of 2.7 bpcu and an AIR gain of 0.12 bpcu without attenuation.

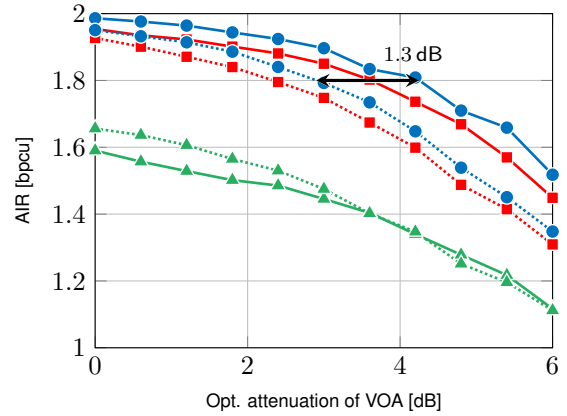
For all setups we observe that ASK outperforms PAM if the receiver is capable of handling enough memory. For very low memory, however, PAM might be beneficial.

Conclusions

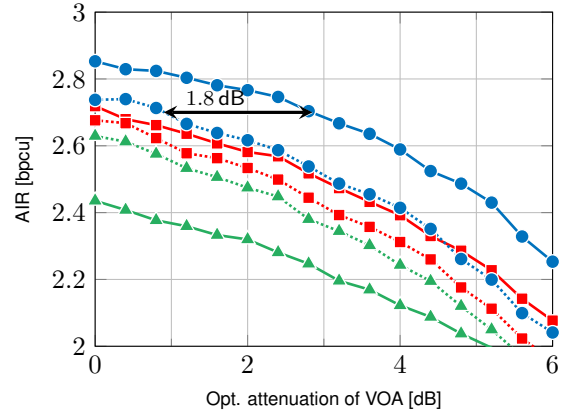
We experimentally verified the simulation results of [9], where bipolar transmission for oversampled



(a) 4-ASK vs. 4-PAM in optical B2B setup.



(b) 4-ASK vs. 4-PAM with 20 km SSMF followed by VOA.



(c) 8-ASK vs. 8-PAM in optical B2B setup.

Fig. 3: AIRs for Q -ASK (solid) and Q -PAM (dotted) for (a) $Q = 4$, optical B2B, (b) $Q = 4$ and 20 km of SSMF followed by a VOA, and (c) $Q = 8$, optical B2B. Colors (marks) correspond to different memory lengths L considered at the receiver, see the legend in subplot (a).

DD receivers was proposed. We showed gains of up to 1.8 dB using bipolar constellations as compared to their unipolar IM counterparts.

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