

Demonstration of 2.5-Gslot/s optically-preamplified M-PPM with 4 photons/bit receiver sensitivity

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Abstract:

Photon-efficient optical communications using variable-duty-cycle M-ary pulse-position modulation (M-PPM) with coding is investigated experimentally using a simple, multi-rate nearly quantum-limited receiver with throughputs ranging from 1.25 Gbit/s in the binary case, to 78Mbit/s for M=256.

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1. Introduction

High-sensitivity optical communications has received significant interest recently by the telecommunications industry as a means of reducing nonlinear impairments and long term interest from the free-space community due to the potential for providing cost-efficient high-rate communications with reduced size, weight, and power constraints [1-15]. Free-space applications include future long-range networks [16], with particular benefit to deep-space exploration, i.e., links to the Moon, Mars – which are actively being pursued [3], and beyond. Also of interest are terrestrial links such as high-rate links with aircraft, ship-to-shore, and inter-building. In such links, the channel bandwidth is generally not a limitation, and therefore, spectral efficiency can readily be traded for photon-efficiency.

While photon-counting receiver architectures have been proposed that show great potential to reach the ultimate sensitivity of multiple bits-per-photon [3], here we demonstrate an optically-preamplified receiver based design, with unsurpassed sensitivity that leverages mature telecom technologies that are readily available today, that incorporates a single high-sensitivity multi-rate architecture capable of near optimum performance at all rates [7, 8,17]. Combining this with use of high-constellation M-ary PPM with forward error correction (FEC) enables the investigation of receiver performance into the low photon-per-bit (PPB) regime. This approach is particularly well suited for high-rate background-limited links where a high degree of spatial filtering (single-mode operation) and nearly-matched spectral filtering can be attained, and offers an extended dynamic range of operation in excess of 30 dB by varying data rate, allowing for fall-back modes of operation. Further, EDFAs have been shown to have a useful ~20 year lifetime in space-based environments constrained by radiation [18, 19], which may limit the useful lifetime of certain photon-counting detectors [20].

2. Experimental setup

The experimental setup is shown in Figure 1. The multi-rate architecture allows the same transmit/receive hardware (including RF and optical filtering) to be used for all bit-rates ranging from 1244 Mbps to 78 Mbps, corresponding to $M = \{2, 4, 8, \dots, 256\}$. The master oscillator power amplifier (MOPA) transmitter generates a modulated stream of 400psec pulses. Representative variable duty cycle waveforms at the output of the modulator are shown in the upper left for symbol rates ranging from 1244 Msym/s to 155 Msym/s (binary through 16-ary PPM). The pattern generator drives the modulator with preprogrammed M-PPM symbols representing an FEC encoded pseudo-random sequence at a slot-rate of 2.5 Gslots/sec.

There are three major constraints that can impact the MOPA transmitter performance for large constellation size M-PPM: 1) modulator extinction ratio (ER = power off/power on) must be small relative to the duty cycle (DC = $\sim 1/M$), 2) SNR degradation due to ASE buildup, and 3) nonlinear spreading of signal energy due to self phase modulation (SPM) or stimulated Raman scattering (SRS), or scattering due to stimulated Brillouin scattering (SBS). The last two constraints can be neglected for sub-nanosecond pulsed waveforms if the EDFA power amplifier remains saturated (due to sufficient input signal) and the peak output power is $< \sim 200W$. Emerging amplifier

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designs with larger mode areas may enable operation with even higher peak powers. The peak output power from the saturated, average-power-limited EDFA [21] is given by

$$P_{peak} = \frac{P_{avg}}{DC + ER(1 - DC)}, \quad (\text{Eq. 1})$$

where P_{avg} is the average output power. As shown in the measured waveforms in upper right of Fig. 1, as the duty cycle is reduced, the peak power at the EDFA output increases. In order to prevent transmitter peak power loss [21] due to seepage into the “off” state, a high modulation extinction ratio (ER) is required for large M. For $ER > DC + 15$ dB, the reduction in peak power due to the finite extinction ratio of the modulator is less than 0.1 dB. A cascade of two Mach-Zehnder modulators (MZMs) in the transmitter provides more than ~50 dB ER, and enables > 1024-ary PPM with negligible penalty.

There are also technical challenges that impact the receiver. Clock recovery becomes more difficult for high-constellation M-PPM; the slot clock and the symbol clock must both be recovered. Also high-constellation M-PPM can lead to challenging electronic bandwidth requirements as the slot rate is typically much higher than the data rate.

The experimental receiver consists of an optical preamplifier followed by a 3-GHz Fabry-Perot filter (FP) [23] and a 5-GHz Fiber Bragg grating filter (FBG) matched to the signal. The filter output is detected by a high-speed high-current photodetector, which directly feeds a 10 Gsample/sec analog-to-digital converter (ADC) with ~5 to 6 bit effective resolution. The 4x oversampled ADC output is buffered in memory and processed to extract slot and symbol clocks, by iteratively minimizing BER. Alternatively, with phase-locking clock recovery, the slot rate could be extended to 10 Gslot/sec, allowing data-rates to increase by a factor of four.

Receiver decoding was implemented via post-processing software. In addition, for the binary case, the post-processed results were validated using a real-time receiver demodulator described in reference [8]. Once clock and symbol boundaries are established, the maximum-likelihood M-PPM decoding algorithm determines which slot within the symbol contains the most energy, and the “winning” slot is then passed on to the FEC decoding and error analysis, which can in turn, be used to update slot and symbol clock boundaries until the BER is minimized. Standard Reed-Solomon 255/239 forward error correction (FEC) coding with low (7%) overhead was used in these experiments, although up to 5 dB additional sensitivity is expected with the use of more powerful FEC.

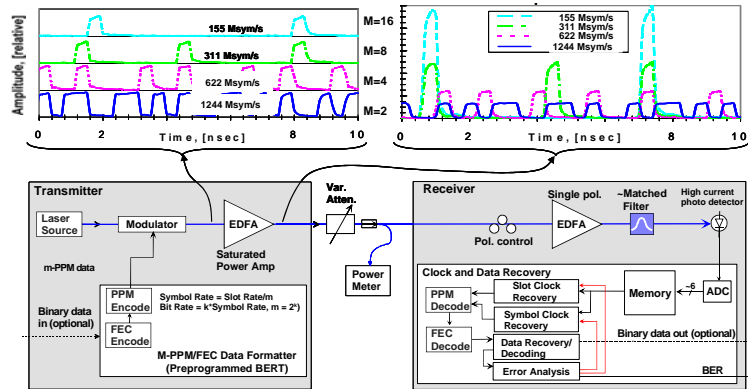


Fig.1. Setup of M-PPM experiments. The transmitter is average power limited (APL), which causes the peak output power to vary inversely with the average duty cycle (~1/M). The basic transmitted pulse shape is constant allowing the single receiver filter to be matched to all rates [7, 17]. Modulation information is imparted on the pulse-position within the M-slot symbol. Peak power and energy-per-pulse vary as 1/M.

3. Results

The multi-rate M-PPM transceiver experiments yielded comparable receiver sensitivities each falling about 1.8 dB from uncoded theory [22]. Measured BER performance with and without the FEC coding along with theoretical BER curves are shown in Fig. 2, for the bounding binary and 256-ary PPM constellation sizes. For the binary case, uncoded BER of 10^{-6} was achieved for -50.1 dBm (10 nW), corresponding to ~60 PPB. For 256-PPM, the uncoded BER of 10^{-6} was achieved for -72 dBm (63 pW), corresponding to ~6 PPB, and coded 10^{-6} BER was attained for -74.5 dBm (35 pW) corresponding to ~3.5 PPB. It’s interesting to note that the received power levels and SNR were so low that in the initial experiments that the control electronics used to align the FP to the signal where unable to maintain a stable lock and needed to be replaced with an externally stabilized open-loop tunable FP [23].

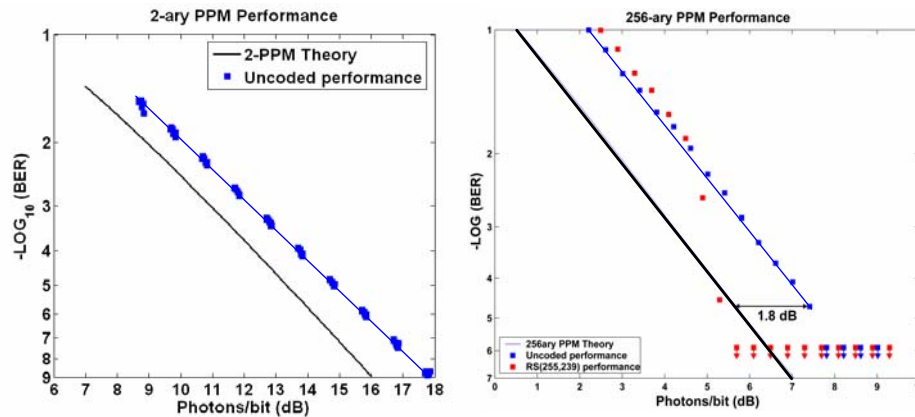


Fig. 2. Measured 2.5 Gslot/sec M-PPM receiver performance, for $M=2$ (left) and $M=256$ (right). Blue and red markers indicate uncoded and coded performance, respectively. Solid black lines show uncoded theory.

4. Summary/Discussion

A photon-efficient laser communication system employing a flexible multi-rate variable M-PPM transmitter and optically preamplified receiver operating at 2.5 Gslot/s is demonstrated with near quantum-limited performance approximately 1.8 dB from theory at data rates ranging from 1244 Mbps to 78 Mbps. This performance combined with 256-PPM modulation gain yielded ~ 6 PPB sensitivity @ 10^{-6} BER, which extrapolates to ~ 9 PPB @ 10^{-9} BER, and compares favorably with all previous high sensitivity demonstrations [4-13]. The addition of RS(255/239) FEC further improved the 10^{-9} performance to better than 4 PPB, which to our knowledge, is the most sensitive optical communication demonstration published to date. Furthermore, in contrast with PSK homodyne demonstrations [5], the optically-preamplified receiver is scalable in that aggregate bit-rates can be easily augmented using standard WDM approaches.

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