High-Rate Photon-Efficient Laser Communications with Near Single Photon/bit Receiver Sensitivities

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Abstract: Optical communication systems with sensitivities approaching a single photon/bit can be realized by combining near-quantum-limited optically-preamplified receiver performance with energy-efficient modulation and coding. Potential applications include average-power-limited photon-starved links where channel bandwidth is readily available.
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1. Introduction

Tremendous technology advances in optical communications have occurred over the past decade leading to wide-band fiber-optic networks that span the planet. Demonstrations of multiple Tbit/s capacities comprised of 10 Gbit/s and 40 Gbit/s WDM channels over 10,000km class fiber-based links have been achieved with spectral efficiencies approaching ~1 bit/s/Hz [1, 2, 3], yielding an impressive distance-rate product, $\Gamma_{D\text{-}R} = \sim 10^{16}$ km-bit/s. Recent gains in receiver sensitivity, enabled by photon-efficient DPSK modulation and powerful high-speed forward error correction (FEC) electronics [2, 3, 4, 5, 6], have been instrumental in these demonstrations. DPSK has been of particular interest since it is both energy-efficient and spectrally-efficient as illustrated in Fig. 1. For a quantum-limited optically-preamplified DPSK receiver with optimal coding, Shannon-limited performance approaches 3 photons/bit (PPB) with ~0.5 bit/s/Hz efficiency. High rate demonstrations using 24.6% and 7% low-overhead FEC (with 0.8 and 0.935 bits/s/Hz efficiencies) achieving 7 and 9 PPB receiver sensitivities have been achieved at 10 and 40 Gbit/s data rates, respectively [4, 6].

While spectral-efficiency has long been a key design parameter in the telecom industry, in some optical communication links excess channel bandwidth is available, and the technologies just described can be applied to improve performance where photon efficiency is the design driver. In such links, the available bandwidth can be used to improve receiver sensitivities by ~5 dB by using, for example, coded M-ary orthogonal modulation formats such as pulse-position modulation (PPM). In M-PPM, information is encoded by the pulse-position within an M-slot symbol, enabling each symbol to carry $\log_2 M$ bits. As shown in Fig. 1, the quantum-limited sensitivity (pre-amplified, direct detection) for uncoded 1024-PPM in which each symbol carries 10 bits of information, is ~6 dB-PPB (~4 PPB), with 100x ($M/\log_2 M$) bandwidth expansion. With the addition of ~50% overhead (OH) hard-decision FEC, ~1.5 PPB sensitivity can be achieved, and this can be extended to nearly 1 PPB by implementing

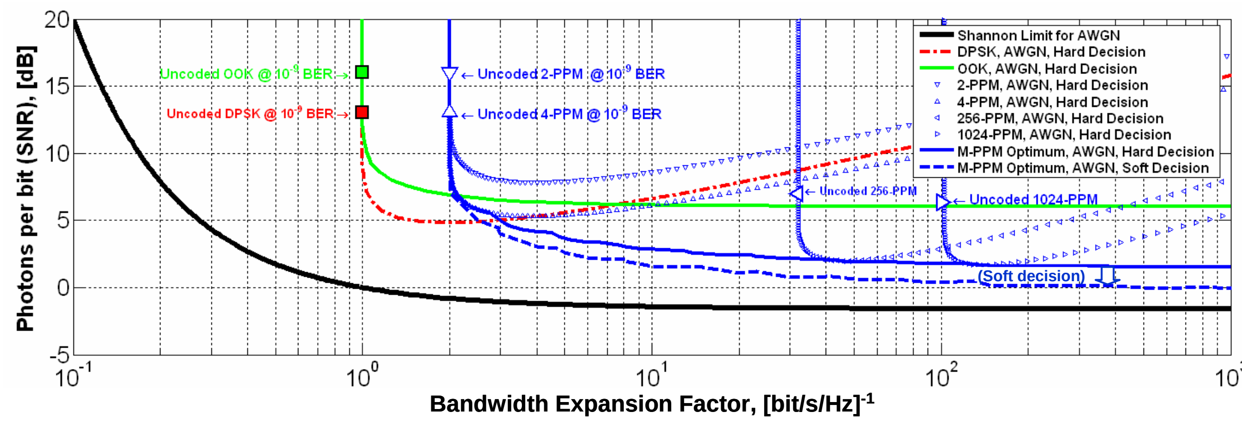

Fig. 1 The tradeoff between sensitivity (photon-efficiency) in photons/bit, and bandwidth expansion (spectral-efficiency) for OOK, DPSK, M-PPM, and the Shannon limit for additive white Gaussian noise (AWGN) systems (hard decision). For high-constellation orthogonal modulation formats such as M-PPM with soft-decision decoding, ~0dB photon/bit (~1 photon/bit) sensitivity can be achieved in principle.

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optimal soft-decision decoding. Recent M-PPM demonstrations have illustrated the feasibility of this approach: one at 2.5 Gslot/sec using 256-PPM, 7% OH RS(255/239) coding, achieving ~10 Msymbols/s (74 Mbit/s) with ~4 PPB sensitivity [7]; and another at 10 Gslot/sec using 32-PPM, rate-1/2 (100% OH) serially-concatenated PPM turbo code, achieving ~312 Msymbol/s (781 Mbit/s) with ~20 PPB sensitivity [8]. While these demonstrations incorporated non-real-time decoding, the electronics needed for real-time implementation are less complex than those that have already been demonstrated at 10 Gsym/s [4], due to the significantly lower symbol rates. It is worth noting that there is potential to improve receiver sensitivities further by using photon-counting receivers [8, 12, 13] based on emerging detector technologies, but we focus here on the use of established optically preamplified designs.

2. Applications: to the Moon and beyond

While there may be applications for such high-sensitivities in fiber-optic networks, there are clear applications in free-space optical (FSO) communications such as in future terrestrial and air links, optical satellite networks, and deep-space exploration [9, 10, 11, 12, 13 14]. FSO links have some notable advantages over radio-frequency (RF) and fiber-optic links, potentially allowing for great flexibility in transmitter (Tx) and receiver (Rx) design and optimization. These include (especially in space-based applications where atmospheric effects are nonexistent) the absence of channel dispersion and nonlinearities, virtually unlimited and unregulated channel bandwidth, and extremely high antenna gains from modest apertures. In such links, this high gain directly translates to reduced size, weight, power, and cost. Renewed interest in manned missions to the moon and beyond would require robust bidirectional high-rate links to support the human infrastructure, telemetry, science data, diagnostics, remote monitoring and control, and, of course, web-based connectivity. Example Earth-moon link budget estimates utilizing M-PPM modulation and coding are given in Table 1, which include some assumptions for link implementation penalties and four potential configurations.

	Key Parameters for Earth ↔ Moon link	#1 M=1024, W=1		#2 M=128, W=1		#3 M=1024, W=8		#4 M=256, W=120	
	Communication System Parameters:								
1	Constellation size (M)	1024		128		1024		256	
2	Coding Overhead (η_{FEC})	50%		50%		50%		50%	
3	Number of WDM channels (W)	1	channel	1	channel	8	channel	120	channels
4	**Data Rate/channel, R_{ch} = S*log$_2$(M)/[M*(1+η_{FEC})]**	**0.065**	**GBit/sec**	**0.365**	**GBit/sec**	**0.065**	**GBit/sec**	**0.208**	**GBit/sec**
	Transmitter:								
5	Tx diameter (D_T)	0.16	m	0.16	m	0.16	m	0.2	m
7	Average Tx Power/channel (P_{Tx})	0	dBW	0	dBW	-9.0	dBW	-7.8	dBW
8	Peak Tx Power/channel = P_{Tx}*M/W	33	dBW	24	dBW	24	dBW	19	dBW
9	**Net Tx Power = W*P_{Tx}**	**0**	**dBW**	**0**	**dBW**	**0**	**dBW**	**13**	**dBW**
	Channel: Link distiance L = 400,000km								
10	**Space Diffraction Loss, η_{space} = ~[$\pi D_T D_R/(4\lambda L)]^2$**	**-89.8**	**dB**	**-89.8**	**dB**	**-89.8**	**dB**	**-85.9**	**dB**
	Receiver:								
11	Rx diameter (D_R)	0.16	m	0.16	m	0.16	m	0.2	m
12	Approximate Uncoded Rx sensitivity M-PPM, (PPB_{QL})	6.0	dB-PPB	7.6	dB-PPB	6.0	dB-PPB	7.0	dB-PPB
13	Coding Gain, with 50% overhead, (G_{code})	5	dB	5	dB	5	dB	5	dB
14	Net Rx sensitivity @ Data Rate (S_{Rx})	-107.8	dBW	-98.7	dBW	-107.8	dBW	-101.7	dBW
15	**Received Power/channel at EDFA input (P_{Rx})**	**-97.8**	**dBW**	**-97.8**	**dBW**	**-106.8**	**dBW**	**-101.7**	**dBW**
	Performance								
16	**Net Distance-Rate Product: $\Gamma_{D\text{-}R}$ = R_{ch}*W*L**	**2.6E+13**	**km-bit/sec**	**1.5E+14**	**km-bit/sec**	**2.1E+14**	**km-bit/sec**	**1.0E+16**	**km-bit/sec**
17	**Implemented Receiver Sensitivity**	**3.0**	**dB-PPB**	**4.6**	**dB-PPB**	**3.0**	**dB-PPB**	**4.0**	**dB-PPB**
18	**Net Bandwidth Required = 2*S*W*(1+η_{FEC})/125E9**	**0.24**	**nm**	**0.24**	**nm**	**1.92**	**nm**	**28.8**	**nm**
19	**Net Rate: Rnet = R_{ch}*W**	**0.065**	**GBit/sec**	**0.365**	**GBit/sec**	**0.521**	**GBit/sec**	**25.0**	**GBit/sec**
20	**Margin**	**10.0**	**dB**	**0.9**	**dB**	**0.9**	**dB**	**0.0**	**dB**

Table 1 Earth – moon link budgets for various configurations of PPM constellation size (M), number of channels (W), and aperture diameter. Changes between adjacent configurations are highlighted in red-boxed entries. Common to each of the four configurations is the slot rate S=10 Gslot/s, coding overhead, wavelength (λ = 1550nm), link distance, and assumptions for implementation penalties. These include losses in theTx (η_{Tx} = -3 dB) and Rx (η_{Rx} = -3 dB) optics, pointing and tracking (η_{PAT} = -2 dB) and Rx deviation from theoretical performance (η_{QL} = -2 dB).

A representative Tx and Rx pair suitable for long-term use in space [14, 19, 20, 22] that can achieve the performance in the budget above is a Master-Oscillator-Power Amplifier (MOPA) transmitter with an optically preamplified receiver [5, 14, 7]. Quasi-Gaussian pulse-shaping in the transmitter is used to ensure a robust match between the Tx-waveforms and the Gaussian optical filter in the Rx [21], with demonstrated performance within ~0.5 dB of the quantum limit [17]. Furthermore, fixing the pulse shape for all M and varying the modulated format allows a single optimized optical receiver to be used at a wide range of data rates while maintaining optimized performance [18, 15, 16, 7].

Configuration #1 highlights a low-rate 65 Mbit/s link achieved with 10 dB margin using a 1W transmitter, 16cm Tx and Rx apertures, and 1024-PPM. Of course, the margin could be traded to reduce aperture size or net output power. Alternatively, by simply changing the PPM alphabet size to M= 512, 256, or 128 as in configuration #2, the excess margin could be used to increase the data rate up to 365 Mbit/s with ~1 dB margin, providing the option for bandwidth-on-demand or fall-back modes of operations as needed. Another option would be to include additional WDM channels with 0.2nm spacing as in configuration #3, which can provide up to 521 Mbit/s with 0.9 dB margin. Relative to #2, the increase in net data rate is enabled by the 1.6 dB improvement in Rx sensitivity due to the larger alphabet size. Although more hardware is required to support the additional WDM channels, #3 provides similar flexibility in net data throughput as #1 and #2 with additional redundancy. In addition, having multiple channels share a common power amplifier effectively reduces the peak Tx power, which can limit the range of M that can be used due to peak power nonlinearities [14, 7]. Such effects start to impact communication performance at 24 to 30 dBW peak levels, and could necessitate a change of design parameters in #1. However, emerging amplifier designs with higher doping concentrations, shorter fiber lengths, and larger core areas have demonstrated much higher nonlinear thresholds in excess of 10 kW (40 dBw) peak levels [e.g., reference 23], which extends design options considerably. By increasing the aperture to 0.2m, Tx power to 13 dBW, and WDM channel count to 120 in configuration #4, a link with up to ~25 Gbit/s throughput can be achieved.

3. Summary

Mature technologies developed for the telecom industry can be leveraged to implement scalable photon-efficient optical communication capabilities over photon-starved links where adequate channel bandwidth is available. Example lunar link budgets, based on an average-power-limited MOPA Tx and a near-quantum-limited M-PPM optically-preamplified Rx with coded performance about 3 dB from the Shannon limit, show the potential for high-capacity free-space optical links at rates ranging from 65 Mbit/s for a single-channel to 25 Gbit/s for 120 WDM channels. The latter requires ~29nm of bandwidth, which corresponds to only 0.007 bit/s/Hz spectral efficiency, but the resultant improvement in receiver sensitivity to 2.5 PPB enables a respectable distance-rate product $\Gamma_{D\text{-}R} = \sim 10^{16}$ km-bit/s — comparable to the best fiber-based demonstrations, without the need for ~4000 regenerators.

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