STRATEGIC WHITE PAPER

DEMONSTRATION OF RECORD SENSITIVITY IN AN OPTICALLY PRE-AMPLIFIED RECEIVER BY COMBINING PDM-QPSK AND 16-PPM WITH PILOT-ASSISTED DIGITAL COHERENT DETECTION

Xiang Liu[1], T. H. Wood[2], R. W. Tkach[1], and S. Chandrasekhar[1]

1: Bell Labs, Alcatel-Lucent
791 Holmdel-Keyport Road
Holmdel, NJ 07733, USA

2: LGS Innovations, Government Communication Lab
15 Vreeland Road
Florham Park, NJ 07932, USA

e-mail: xiang.liu@alcatel-lucent.com

Abstract: We propose a power-efficient modulation/detection scheme that combines PDM-QPSK and 16-ary-pulse-position-modulation. A record sensitivity of 3.5 photons per bit at BER=10^{-3} is experimentally demonstrated at 2.5 Gb/s with digital coherent-detection, outperforming PDM-QPSK by >3 dB.

OCIS: (060.1660) Coherent communications; (060.5060) Phase modulation; (060.2605) Free-space optical commun.

TABLE OF CONTENTS

1. INTRODUCTION

There is a continued quest to improve the receiver sensitivity in optical communication systems, particularly for space communications [1]. Improving the receiver sensitivity or reducing the required signal photons per bit (PPB) directly leads to improved transmission link performance. For optically pre-amplified receivers, direct-detection binary differential phase-shift keying (DPSK) [2], coherent-detection binary phase-shift-keying BPSK [3], and polarization-division-multiplexed quadrature phase-shift keying (PDM-QPSK) [4-6] are known to offer high receiver sensitivity. In an attempt to find the most power-efficient modulation format in optical links, polarization-switched QPSK (PS-QPSK) was recently proposed [7], providing ~1 dB higher sensitivity than BPSK and PDM-QPSK at a bit error ratio (BER) of 10-3. Here, we propose a new power-efficient format based on PDM-QPSK and 16-ary pulse-position-modulation (PPM [1,8]), termed herein as PQ-16PPM, that offers ~3 dB theoretical sensitivity advantage over BPSK, PDM-QPSK, and 16-PPM at BER=10^{-3}. We further experimentally demonstrate the generation and detection of a 2.5-Gb/s PQ-16PPM signal, using a novel low-overhead pilot-assisted single-carrier frequency-division-equalization (PA-SC-FDE) scheme, and achieve a record receiver sensitivity that is >3 dB higher than all previous gigabit/sec-class records, as shown in Table 1.

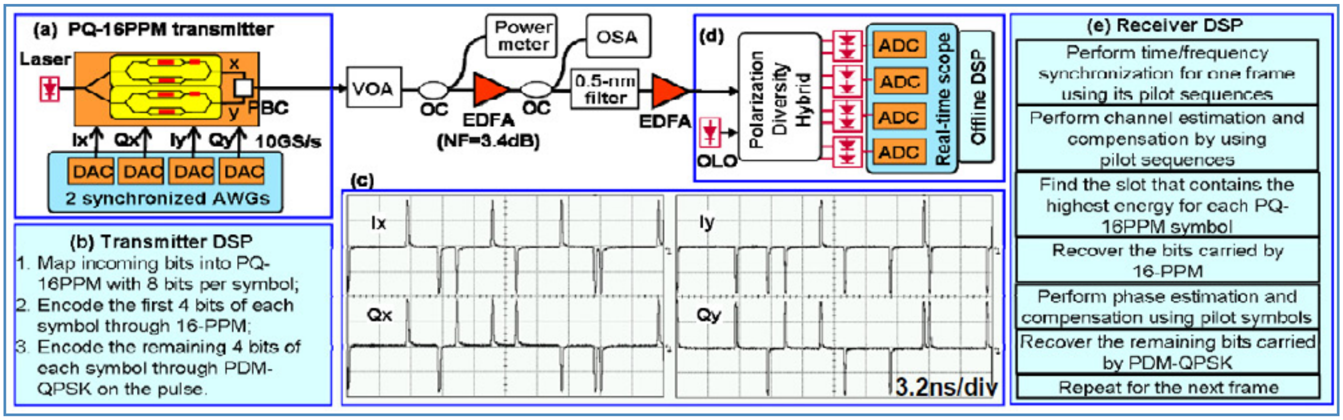
Table 1. Sensitivity (PPB in dB at BER=10^{-3}) comparison among various power-efficient formats in optically pre-amplified receivers.

Format	BPSK	PDM-QPSK	DPSK	16-PPM	PS-QPSK	**PQ-16PPM**
Theory	6.8 dB	6.8 dB	8 dB (with PF)	6.7 dB	5.8 dB [7]	**3.9 dB**
Experiment	~9 dB [3]	~10 dB [5]	8.6 dB [2]	~9 dB [8]	N/A	**5.4 dB**

2. PRINCIPLE AND EXPERIMENTAL SETUP

Figure 1 shows the schematic of the experimental setup for the generation and detection of a 2.5-Gb/s PQ-16PPM signal. At the transmitter (a), each PQ-16PPM symbol contained 8 bits, of which the first 4 bits were encoded through 16-PPM and the remaining 4 bits were encoded through PDM-QPSK, as shown in the transmitter digital signal processor (DSP) diagram (b). The data bit sequence was PRBS of length 2^{15}-1. The four field components of the encoded PQ-16PPM signal, corresponding to the I and Q components of both x- and y-polarizations, were stored in two synchronized arbitrary waveform generators (AWGs), each equipped with two 10-GS/s digital-to-analog converters (DACs). Twofold oversampling was used, leading to a 16-PPM slot rate of 5 GHz (a symbol rate of 312.5 MHz), which resulted in a data rate of 2.5 Gb/s for PQ-16PPM. The DAC outputs were amplified to a peak-to-peak voltage swing of 3.5 V before driving a PDM-I/Q modulator. The optical carrier was from an external cavity later (ECL) at 1550 nm with a linewidth of ~100 kHz. Fig. 1(c) shows a sample portion of the four drive waveforms, I_x, Q_x, I_y, and Q_y, after exiting the four DACs.

Fig. 1 Schematic of the generation and detection of a 2.5-Gb/s PQ-16PPM signal. (a): transmitter setup; (b): transmitter DSP flow chart; (c): sample drive waveforms; (d): receiver setup; and (e): receiver DSP flow chart. PBC: polarization-beam combiner.



(b) Transmitter DSP

1. Map incoming bits into PQ-16PPM with 8 bits per symbol;
2. Encode the first 4 bits of each symbol through 16-PPM;
3. Encode the remaining 4 bits of each symbol through PDM-QPSK on the pulse.

(e) Receiver DSP

Perform time/frequency synchronization for one frame using its pilot sequences
Perform channel estimation and compensation by using pilot sequences
Find the slot that contains the highest energy for each PQ-16PPM symbol
Recover the bits carried by 16-PPM
Perform phase estimation and compensation using pilot symbols
Recover the remaining bits carried by PDM-QPSK
Repeat for the next frame

The generated 2.5-Gb/s PQ-16PPM signal was attenuated by a variable optical attenuator (VOA) before being split by a 90:10 optical coupler (OC) into two parts, one entering an Erbium-doped fiber amplifier (EDFA) with a noise figure (NF) of 3.4 dB, and the other entering a power meter for measuring the PPB. The optical signal-to-noise ratio (OSNR) of the amplified signal was measured by an optical spectrum analyzer (OSA). The optically pre-amplified signal was then filtered by a 0.5-nm optical filter before being received by a digital coherent receiver, shown as Fig. 1 (d). The digital coherent receiver frontend consisted of a 100-kHz-linewidth ECL serving as the optical local oscillator (OLO), a polarization-diversity optical hybrid, four balanced detectors, and four 50-GS/s analog-to-digital converters (ADCs) in a real-time sampling scope. The four sampled waveforms were stored and down-sampled to 10 GS/s before being processed offline. The flow diagram of the offline DSP is shown in Fig. 1(e). A key step is to find the time slot, out of the 16 slots of each PQ-16PPM symbol, that has the highest energy. The position of the highest-energy slot is used to recover the first 4 bits associated with 16-PPM, and the recovered optical field at this slot is used to recover the remaining 4 bits associated with PDM-QPSK. There is a certain probability that the pulse location of a PPM symbol is incorrectly identified, which may corrupt the convergence of constant modulus algorithm based channel compensation [6]. We thus resort to PA-SC-FDE [9,10], where channel estimation is based on known pilot symbols. Figure 2 shows the frame structure of the PA-SC-FDE scheme used for PQ-16PPM. We used similar pilot sequences (T1, T2, and T3) as those used in reduced-guard-interval coherent optical orthogonal frequency-division multiplexing systems [11] for frame synchronization and channel estimation (CE). One novel extension is that no guard interval (GI) is used for payload symbols in order to minimize overhead, although a GI is used for pilot sequences to ensure accurate CE. The overlap-and-add technique [10] was used during the channel compensation process. Pilot symbols, each occupying one slot, were inserted to assist phase estimation (PE). The use of these pilot symbols causes a negligible rate overhead of <1% (148/16000). The power penalty due to the pilots used for synchronization and CE is 0.2 dB, and that for PE is 0.4 dB. However, the use of these pilot symbols is essential to ensure reliable signal reception at extremely low PPB. Polarization filtering (PF) and matched optical filtering, often used to achieve high sensitivity [2], are not used here, thanks to the use of the PA-SC-FDE for polarization demultiplexing and equalization.

Fig. 2. Frame structure of the PA-SC-FDE scheme used for PQ-16PPM. CE: channel estimation; PE: phase estimation.

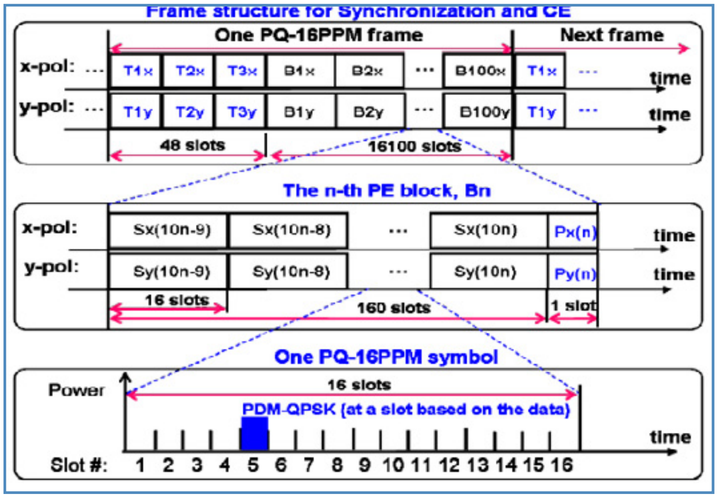
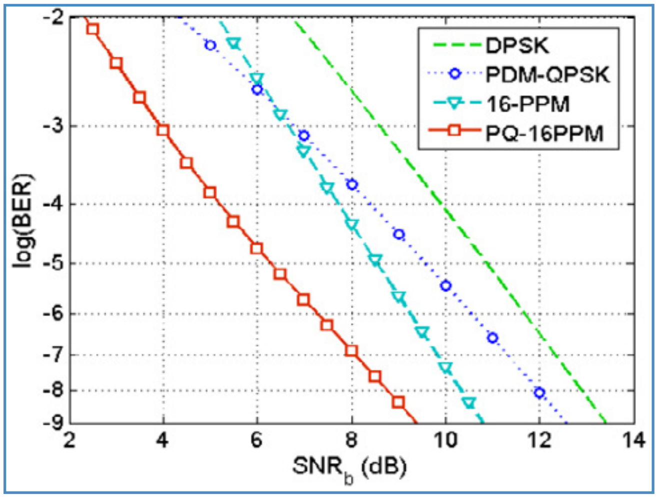


Fig. 3. Theoretical BER performance of PQ-16PPM as compared to DPSK, PDM-QPSK (or BPSK), and 16-PPM.



3. THEORETICAL RECEIVER SENSITIVITY

The BER of a PQ-mPPM signal can be expressed ascritical importance, such as in space communications and unrepeatered fiber transmission.

$$\mathrm{BER}_{\text{PQ-mPPM}} = \{\mathrm{SER}_{\text{m-PPM}}[2 + \tfrac{m}{2(m-1)}\log_2(m)] + 4(1-\mathrm{SER}_{\text{m-PPM}})\mathrm{BER}_{\text{PDM-QPSK}}\}/[4+\log_2(m)] \qquad (1)$$

where $\mathrm{SER}_{\mathrm{m\text{-}PPM}}$ and $\mathrm{BER}_{\mathrm{PDM\text{-}QPSK}}$ are respectively the symbol error ratio (SER) of m-PPM and BER of PDM-QPSK at a given signal-to-noise ratio per PQ-mPPM symbol ($\mathrm{SNR}_{\mathrm{sym}}$). We have [12]

$$\mathrm{BER}_{\mathrm{PDM-QPSK}} = 0.5\,erfc\left(\sqrt{\mathrm{SNR}_{\mathrm{sym}}/4}\right) \qquad (2)$$

and (after some derivations)

$$\mathrm{SER}_{\mathrm{m-PPM}} = \int_{v=0}^{\infty}\left[1-\left(1-p_0(\mathrm{SNR}_{\mathrm{sym}},v)\right)^{m-1}\right]f_1(\mathrm{SNR}_{\mathrm{sym}},v)\,dv \qquad (3)$$

where $p_0(\mathrm{SNR}_{\mathrm{sym}},\boldsymbol{v})$ is the probability that an empty ("0") slot has an energy higher than $\boldsymbol{v}$, and $f1(\mathrm{SNR}_{\mathrm{sym}},\boldsymbol{v})$ is the probability density function of a filled ("1") slot having an energy of $\boldsymbol{v}$. Both p_0 and f_1 can be analytically obtained [12]. For PQ-16PPM, SNR per bit, SNR_b, equals $\mathrm{SNR}_{\mathrm{sym}}/8$. Note that PPB equals SNR_b for an ideal optically pre-amplified receiver having a NF of 3 dB. Figure 3 shows the measured BER performance of PQ-16PPM as compared to PDM-QPSK. No PF was assumed for 16-PPM and DPSK. At $\mathrm{BER}=10^{-3}$, a typical threshold of enhanced forward-error correction, the required PPB for PQ-16PPM is 2.45 (or 3.9 dB), which is lower than those for PDM-QPSK (or BPSK), 16-PPM, and DPSK, by 2.9, 2.8, and 4.7 dB, respectively. Note that the spectral extent of PQ-16PPM is about half that of 16-PPM, and is similar to return-to-zero DPSK [2].

Fig. 4. Sample recovered signal power waveform (a) and constellation before (b) and after (c) PPM demodulation and phase compensation.

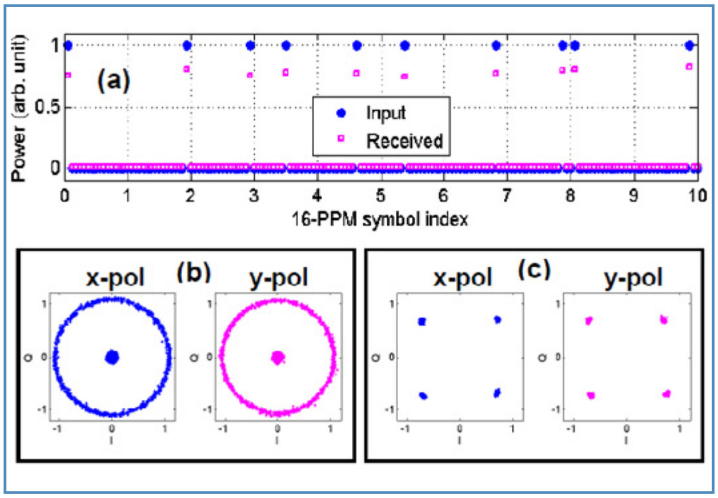
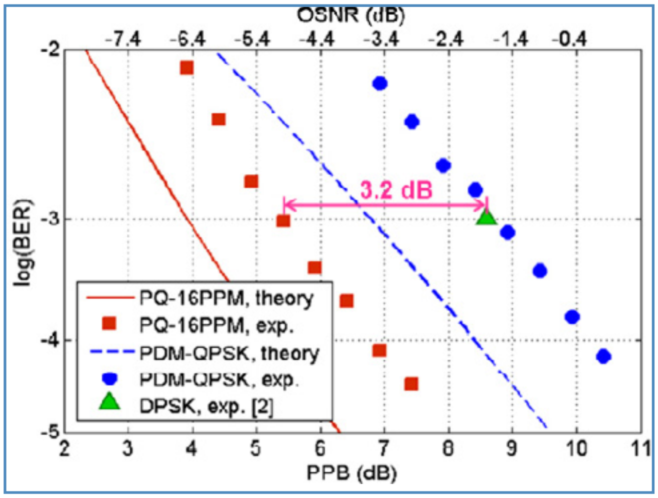


Fig. 5. Experimental BER performance of the 2.5-Gb/s PQ-16PPM signal as compared to PDM-QPSK.



4. EXPERIMENTAL RESULTS

Figure 4 shows a sample portion of the recovered signal power waveform and constellation after channel equalization at an OSNR of 30 dB (defined with 0.1-nm optical noise bandwidth). Fig. 4 (a) shows that the random input 16-PPM pulse locations were correctly identified at the receiver. Before PPM demodulation and phase compensation, the signal constellation of each polarization contains "0s" and a ring due to laser frequency-offset and phase wandering, as shown in Fig. 4(b). After PPM demodulation and phase compensation, clear QPSK constellations were recovered, as shown in Fig. 4(c). Figure 5 shows the BER performance as a function of PPB and OSNR. The required PPB at $\mathrm{BER}=10^{-3}$ is 3.5 (or 5.4 dB), or 1.5 dB away from theory, of which 0.4 dB is due to excess EDFA noise, 0.2 dB is due to the pilot sequences used for synchronization and CE, and 0.4 dB is due to the pilot symbols used for PE, leaving only ~0.5 dB to account for the overall hardware implementation penalty. The power penalty from the pilots used for PE is expected to decrease with the increase of modulation rate and/or decrease of laser linewidth. Inspection of the error statistics shows that symbol error events are uncorrelated and random, so FEC can be effectively applied. As a reference, PDM-QPSK performance was also measured (by turning off the PPM modulation). The overall implementation penalty for PDM-QPSK is ~2 dB, which is reasonably low [3-5]. At BER=10^{-3}, PQ-16PPM outperforms PDM-QPSK by 3.4 dB, and the previous DPSK record obtained with PF and matched optical filtering [2] by 3.2 dB, as shown in Fig. 5. Even compared to 256-PPM, which is to the best of our knowledge the highest-level PPM reported (at 73 Mb/s) [1], the PQ-16PPM offers higher sensitivity and an 8-fold optical bandwidth reduction.

5. CONCLUSION

We have proposed a new power-efficient modulation/detection scheme that combines PDM-QPSK and 16-PPM to achieve ~3 dB theoretical sensitivity advantage over PDM-QPSK (and BPSK) in an optically pre-amplified receiver. Both analytical and experimental studies have been conducted to quantify the sensitivity improvements of the PQ-16PPM format over PDM-QPSK, 16-PPM, and DPSK. Using a novel low-overhead PA-SC-FDE technique, we experimentally achieved a record sensitivity of 3.5 PPB at BER=10^{-3}, outperforming all previous gigabit/sec-class sensitivity records by over 3 dB. This power-efficient modulation format is expected to be attractive in applications where photon efficiency is of critical importance, such as in space communications.

The authors wish to thank A. R. Chraplyvy and P. J. Winzer for support, and A. H. Gnauck for fruitful discussion.

5. REFERENCES

[1] D. O. Caplan et al., “Free-space laser communications: global communications and beyond,” ECOC’09, Tutorial paper 9.6.1.
[2] D. O. Caplan et al., “Demonstration of optical DPSK communication with 25 photons/bit receiver sensitivity,” CLEO’06, paper CFH5.
[3] M. G. Taylor, “Coherent detection method using DSP for demodulation of signal and subsequent equalization of propagation impairments” IEEE Photon. Technol. Lett. 16, 674-676 (2004).
[4] C. Laperle et al., “Wavelength division multiplexing (WDM) and polarization mode dispersion (PMD) performance of a coherent 40 Gbit/s dual-polarization quadrature phase shift keying (DP-QPSK) transceiver,” OFC’07, Post-deadline paper PDP 16.
[5] C. R. S. Fludger et al., “Coherent equalization and POLMUX-RZ-DQPSK for robust 100-GE transmission,” JLT 26, 64 (2008).
[6] S. J. Savory, “Digital filters for coherent optical receivers,” Opt. Express 16, 804-817 (2008)
[7] M. Karlsson and E. Agrell, “Which is the most power-efficient modulation format in optical links?” Opt. Express 17, 10814 (2009).
[8] N.W. Spellmeyer et al., “Demonstration of multi-rate thresholded preamplified 16-ary pulse-position-modulation,” OFC’10, OThT5.
[9] W. Shieh et al., “Coherent optical OFDM: has its time come?” J. Opt. Netw. 7, 234-255 (2008).
[10] R. Kudo et al., “Coherent optical single carrier transmission using overlap frequency domain equalization for long-haul optical systems,” JLT 16, 3721-3728 (2009).
[11] X. Liu et al., “Transmission of a 448-Gb/s reduced-guard-interval CO-OFDM signal with a 60-GHz optical bandwidth over 2000 km of ULAF and five 80-GHz-Grid ROADMs,” OFC’10, Post-deadline paper PDPC2.
[12] X. Liu, S. Chandrasekhar, and A. Leven, “Self-Coherent Optical Transport Systems,” in Optical Fiber Telecommunications V B, Systems and Networks, I. P. Kaminow, T. Li, and A. E. Willner, eds., Chapter 4, Academic Press, Burlington, MA, 2008.