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Record Photon Information Efficiency with Optical Clock Transmission and Recovery of 12.5 bits/photon After 77 dB of Optical Path Loss

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Abstract*—We experimentally demonstrate optical detection at 12.5 bits per incident photon, 9.4 dB higher than the theoretical limit of conventional coherent detection. The signal undergoes 77 dB of optical attenuation before quantum detection followed by optical clock and data recovery.

Keywords*— Optical communication, Quantum detection, Clock recovery, Modulation formats, Satellite communication.

I. INTRODUCTION

The Photon Information Efficiency (PIE) [1] measures the information per unit of optical signal power entering a receiver and is generally expressed in Bits per Incident Photon (BIP). An important application of high-PIE optical communication is space exploration [2, 3] which suffers less from path diffraction loss than microwave frequencies currently used [4]. To our knowledge, the highest PIEs demonstrated to date using an optical phase-sensitive and phase-insensitive pre-amplifier are 0.48 BIP [5] and 1.25 BIP [6], respectively. Without optical pre-amplifiers, a PIE of 0.67 BIP with a coherent receiver has been achieved [7]. Experimental demonstrations using Superconducting Nanowire Single-Photon Detectors (SNSPDs) achieved 12.9 BIP at a rate of 6.4 kbits/s [8] but required the transmitter and receiver to be in close proximity as they shared a common electrical clock.

In this paper, we demonstrate detection with independent free-running clocks at a PIE of 12.5 BIP after large optical attenuation. To the best of our knowledge, this is the highest PIE achieved in an optical system without electrical clock sharing.

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup and modulation format used. The PPM frames are created by generating a single optical pulse in the position m out of the 2^M PPM timeslots corresponding to the decimal representation of a M -bit segment from a pseudo-random binary sequence (PRBS). The PPM guard time is set to 100 ns, i.e., 250 empty 400-ps timeslots, inserted to prevent detection blocking between PPM frames due to the 60-ns dead time of the SNSPDs [9]. After N guarded PPM frames, a 100 ns clock frame is inserted consisting of a single optical pulse in the first 400- ps timeslot followed by 249 empty timeslots. The data-clock ratio N is the ratio of the number of guarded PPM frames to clock frames. The number of PPM frames recorded are 760k, 380k, and 190k, with 1600, 800, and 400 being distinct due to the memory limit of the arbitrary waveform generator (AWG), for PPM frame lengths of 2^{17}, 2^{18} and 2^{19}, respectively.

The Electrical Pulse Generator (EPG) modulates a 1550-nm Directly Modulated Laser (DML), producing strong pulse confinement. The measured extinction ratio is 83.2 dB obtained by comparing the energies measured in the non-pulsed to the pulsed timeslots. The signal goes through Variable Optical Attenuators (VOAs) followed by a Polarization Controller (PC) before entering the SNSPD operating at 2.7K with a system detection efficiency of 85% and 20 dark counts per second. The photon-counting events are assigned timestamps before the clock and data recoveries are performed offline. The PPM Frame Erasure Ratio (FER), PPM frame errors, and Bit Error Ratio (BER) are extracted, and the achievable PIE is calculated. Frames without a photon and with two photons or more are considered erasure frames for the purpose of PIE calculation.

III. CLOCK RECOVERY AND SYNCHRONIZATION

Currently implemented algorithms for clock recoveries using quantum detectors rely on statistical accumulation and averaging, with the maximum PPM length demonstrated being M = 7 [10, 11]. In this paper, clock timing is recovered by first performing clock pulse extraction, followed by clock tick outliers removal and clock timing interpolation that closely tracks the clock random walk. No time averaging is required leading to a shorter clock sampling period and relaxed laser stability requirement. Clock sampling periods ranged from 50 ms to 2 seconds and oscillators with large phase noise of -47 dBc/Hz at 1 Hz were used. Clock recovery was performed with 45ps timing jitter accuracy at full width at half maximum from end-to-end, with as low as 20 photons per second.

[§] The contributions of S.K. Dacha, A. Blanco-Redondo, M. Weiner, and N. Menkart were performed while working at Nokia Bell Labs.

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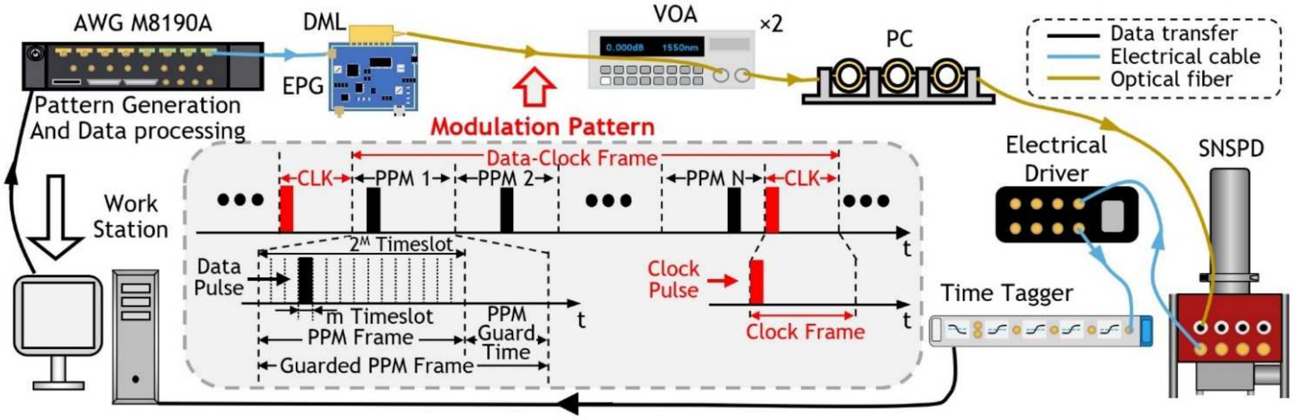

Fig. 1. Experimental setup. AWG: Arbitrary Waveform Generator; CLK: Clock; DML: Direct Modulation Laser; EPG: Electrical Pulse Generator; PC: Polarization Controller; PPM: Pulse Position Modulation; SNSPD: Superconducting Nanowire Single-Photon Detector; VOA: Variable Optical Attenuator

IV. MEASURED PHOTON INFORMATION EFFICIENCY

For a channel experiencing both errors (misidentified frame) and erasures (lost frame), a Reed- Solomon (RS) Forward-Error Correction (FEC) code is highly effective. Fig. 2 shows the PIEs calculated from the measured frame error rates and FERs using an RS FEC code similar to the code implemented in [8]. The number of photon per PPM frame is given by $(1 + 1/N)\,\lambda = 1.1\,\lambda$ for the data-clock ratio $N = 10$. A measured achievable PIE of 12.5 BIP is obtained for 2^{19}-PPM at a data rate of 13.94 kbits/s with photons per PPM frame of 0.235 (photons per pulse $\lambda = 0.213$) with 0.154 RS FEC code rate at 10^{-6} decoded block error rate, typical for deep-space communication. The PIE uncertainty is estimated to be ±0.42 BIP, based on signal power measurement uncertainty. This measured PIE is 9.4 dB lower power than the $1/\ln(2) = 1.44$ BIP theoretical PIE limit of conventional dual-quadrature coherent detection and 6.4 dB from the ultimate $2/\ln(2) = 2.88$ BIP single-quadrature coherent detection [12]. This experiment demonstrates the feasibility of communication with high PIE (> 10 BIP) at large PPM order (> 2^{16}-PPM) and low photon flux (< 0.1 photon per PPM frame) with independent free-running clocks.

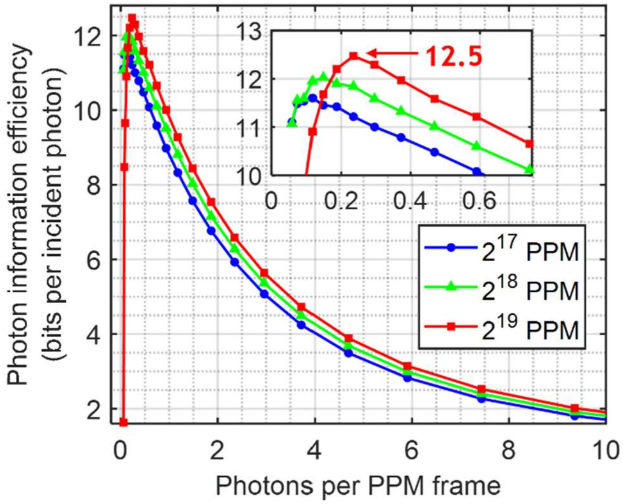

Fig. 2. Photon information efficiency vs photons per PPM frame for 2^{17},2^{18} and 2^{19}-PPM with data-clock-ratio $N = 10$

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