Binary polarization-shift-keyed modulation for interplanetary CubeSat optical communications

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ABSTRACT

Recent developments for laser communication on CubeSats across interplanetary distances will be presented. A binary polarization-shift-keyed modulation scheme using dual gain-switched diode lasers is developed and demonstrated within an end-to-end link testbed to achieve signal acquisition under extremely poor signal-to-noise conditions (-43.5 dB average signal-to-noise power ratio at a 1-MHz symbol rate) to simulate direct-to-Earth links, while simultaneously targeting a limited SWaP footprint (1.5U envelope). Additional system design and constraints for the compact laser transmitter will be discussed.

Keywords: Laser transmitter, gain-switched, polarization shift keying, CubeSat

1. INTRODUCTION

Deep-space optical communication systems require photon-efficient modulation schemes such pulse-position modulation (PPM) [1,2,3] to establish high-rate links. In PPM, M bits are encoded by sending a single laser pulse during one of 2^M possible time slots. Optical transceivers for deep-space CubeSats are severely constrained in size, weight and power (SWaP), targeting an envelope of 1.5U (1U = 10 x 10 x 10cm). Under such severe constraints, PPM transmitters introduce too much complexity that is further exacerbated by the difficulty of temporal acquisition at the receiver end, especially when operating in extremely low signal-to-noise ratio (SNR) regimes, where channel capacity scales as $1/R^4$ instead of $1/R^2$, where R is the range [4]. In practice, the main limitations on the spacecraft is the laser transmitter power and aperture size, which determines the minimum beam divergence and collecting loss at the receiver. Both factors compound to severely limit the photon flux received back at a ground receiver in a direct-to-Earth link.

To enable direct-to-earth optical communication from CubeSats at interplanetary distances, we have developed an alternative modulation scheme that affords the link architecture considerable SWaP improvements on the spacecraft terminal as well as improve signal acquisition at the ground receiver. Binary polarization-shift-keyed modulation (BPolSK) discussed in this paper has been developed and verified in the laboratory. Additional background noise filtering can be performed in the time domain to increase the link SNR for signal acquisition by modulating in the polarization domain rather than the time domain. Moreover, the simplified nature of polarization modulation via direct modulation of two gain-switch diodes yields a smaller SWaP footprint for the laser transmitter.

2. PRINCIPLE OF OPERATION

2.1 Laser Transmitter

Our laser transmitter is based on binary polarization-shift-keyed (BPolSK) modulation, which encodes binary information in two orthogonal pulse polarization states; e.g. 1 and 0 binary bits may be represented as x- and y- linearly polarized pulses, respectively (see Figure 1). The transmitter begins with a driver circuit that converts the incoming bitstream into two complementary pulsed RF waveforms that directly modulate two laser diodes to generate optical pulse trains representing the 0 and 1 bitstreams. The modulated channels are then combined at orthogonal polarizations using a polarization beam combiner. A polarization-maintaining EDFA is necessary to amplify the signal power to support communication links over interplanetary distances. The EDFA output is free-space coupled to an optical transceiver assembly (OTA) and converted to circular polarization before being launched towards a ground receiver station on Earth.

To achieve high timing precision during signal acquisition (which will be discussed in the following section), it is advantageous to use optical pulses with the shortest temporal width possible. To generate such pulses within a limited-SWaP platform, the laser diodes are directly modulated via gain-switching. Gain-switching allows for the generation of very short optical pulses (<30 ps) from broader driving RF pulses (~300 ps). This eliminates the need for higher bandwidth driver electronics and saves on spacecraft resources. Gain-switching also offers many other benefits. First, direct modulation is more SWaP efficient than external modulation of a discrete electro-optic modulator. The RF drive voltage for gain-switching laser diodes (<2V) is less than that for external electro-optic modulators (>5V). The electro-optic modulator (12 x 3 x 3 cm, 0.1 kg), which occupies considerable real estate in a CubeSat, is completely eliminated. Second, direct modulation yields higher pulse extinction ratio, which improves the overall link budget. Third, the simplified transmitter enables a compact, all-fiber implementation within a 0.5U envelope (excluding the OTA).

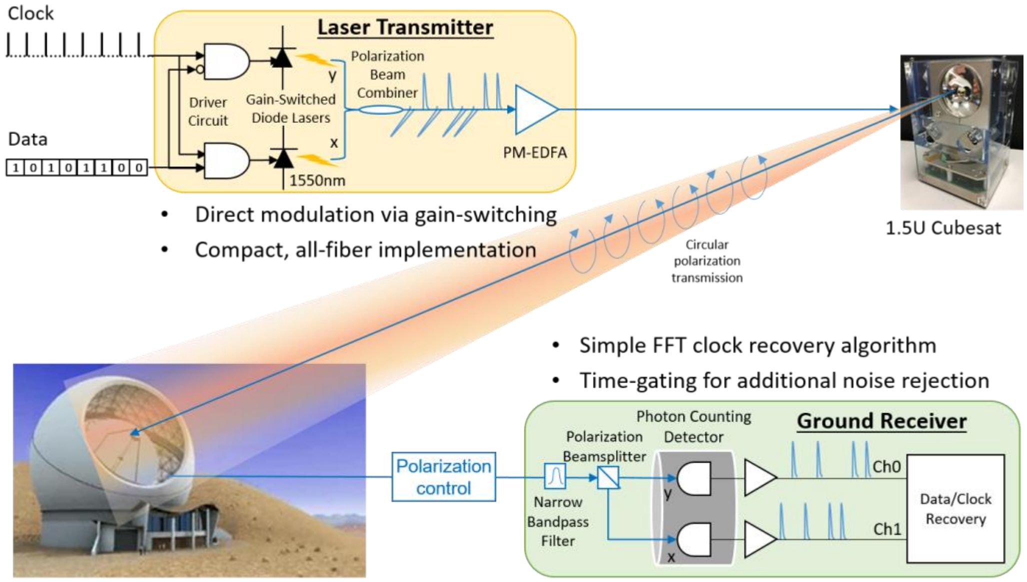

Figure 1. Overview of a binary polarization-shift-keyed (BPolSK) communication link architecture for low-SWaP laser transmitter over interplanetary distances using gain-switched laser diodes.

2.2 Ground Receiver

At the ground receiver, the incoming photon flux is collected with a large aperture (>5m) telescope and relayed through low-loss optics to maximize signal detection on a pair of photon-counting detectors. For BPolSK, additional polarization control is necessary to correctly demultiplex the incoming signal into the two original binary channels for detection. Timestamps for the detected photon arrival times are digitized and processed. It is also equally important to minimize the background noise to maximize the link SNR. To achieve high background noise rejection, a standard technique is to use a narrow bandpass filter assembly with high out-of-band rejection to spectrally filter at the transmitter wavelength [5]. This is common to both BPolSK and PPM.

The major advantages of BPolSK over PPM arise during the clock recovery phase of signal acquisition. To recover the clock with BPolSK, one only needs to compute a fast Fourier transform (FFT) of the pulse arrival times for the combined channels, since these timestamps represent a pulse train with a fixed repetition rate. This technique is data-independent. The speed and robustness of the FFT technique is evident in the presence of high pulse erasure rate (e.g. due to limited transmitter power, beam divergence, wander, and pointing errors) and error rates (e.g. due to sky radiance, background bodies, and detector dark counts). The FFT can quickly identify the clock signal frequency and phase even when the average SNR is largely negative (e.g. -43 dB). This is in contrast with the clock recovery algorithm for PPM where longer integration times are necessary to sufficiently populate the pulse arrival time histogram before identifying and synchronizing to the guard time window. Moreover, additional resources may be required onboard the spacecraft to implement a PN randomizer to generate a uniformly-distributed signal histogram to aid in guard time identification.

Another major advantage of BPolSK is that once the clock is recovered, additional background noise rejection can be achieved by time-gating the signal to reject noise counts outside of the expected signal arrival time window. The maximum additional background rejection achievable in BPolSK is proportional to ~t_p/t_{sym}, where t_p is the pulse width and t_{sym} is the symbol repetition period. For example, a pulse width of 100ps for a symbol rate of 1 MHz can yield 40 dB of additional background rejection when compared to PPM. This technique is not possible with PPM because the information is inherently encoded in time and cannot be time-gated for unknown signal data.

In summary, BPolSK is analogous to 2-ary PPM, but it benefits from major SWaP improvements for the transmitter (i.e. reduced drive power and bandwidth requirement for gain-switch modulation, and compact all-fiber-coupled implementation) and improved receiver performance (i.e. additional background noise rejection, and robust clock recovery via simple FFT).

3. LABORATORY IMPLEMENTATION

3.1 End-to-end testbed

A preliminary end-to-end link testbed was constructed on a laboratory benchtop to evaluate the performance of the BPolSK laser transmitter and ground receiver (see Figure 2). The laser transmitter consists of two butterfly-packaged distributed feedback laser diodes (EM4) operating near 1560 nm with linearly polarized outputs. Their outputs are combined with a fiber-coupled polarization beam combiner (Thorlabs). Without any loss of generality, the EDFA, OTA, and circular polarization transmission are omitted for initial link demonstrations.

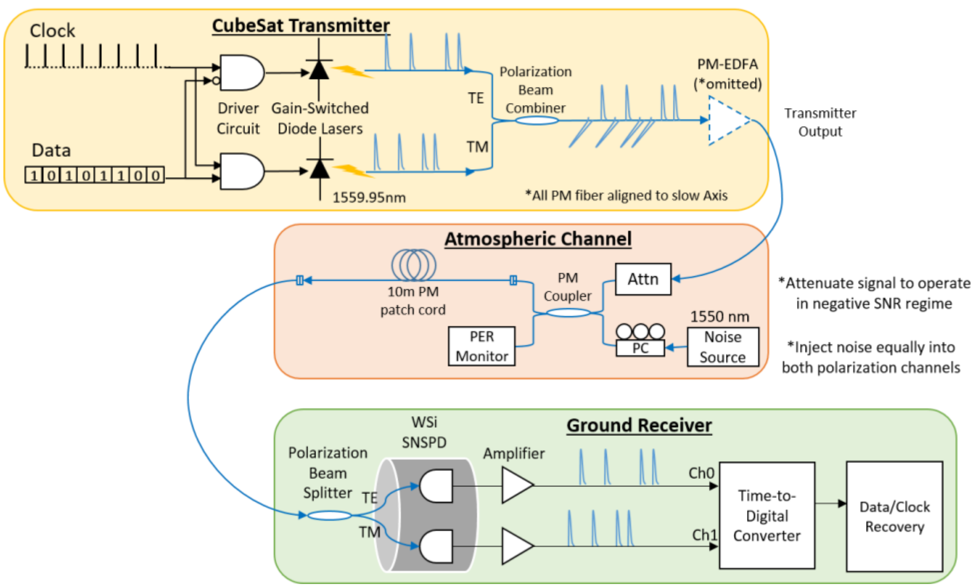

Figure 2. Schematic of the end-to-end link testbed used to demonstrate signal acquisition at extremely low average SNR levels (down to -43.5dB). The BPolSK laser transmitter signal is combined with background noise and detected on a pair of photon-counting detector in a representative ground receiver architecture.

The electronics driver for gain-switched laser diodes is a home-built, multi-stage PCB circuit. The first stage performs combinatorial logic to convert the incoming bitstream and clock signal (TTL voltage inputs) into two complementary RF modulation waveforms. The second stage is a high-bandwidth RF amplifier with variable gain to set the pulse amplitude. The third stage is a pulse shaper circuit, based on a nonlinear transmission line with a step recovery diode termination, to shorten the RF pulse from ~30ns to ~300ps. The output DC level is set to bias the laser diodes sub-threshold for gain-switching. Direct modulation of the laser diodes with these shortened RF pulses yields <30 ps gain-switched pulses.

Following the transmitter, the atmospheric channel was simulated within fiber. High attenuation via in-line attenuators simulated high erasure rates from direct-to-Earth links at interplanetary distances. Poisson-limited background noise was simulated by injecting a continuous wave laser with scrambled polarization. No polarization scrambling or tracking was implemented for the signal. The received optical signal is polarization-demultiplexed and detected on two independent single-pixel, WSi superconducting nanowire single-photon detectors (SNSPD) [6]. The detected counts from each channel are amplified and timestamped with a time-to-digital converter (PicoHarp 300). The timestamps are then post-processed to recover the clock and apply time-gating to improve the link SNR. The transmitted data was set to a bitstream of 1's to evaluate the uncoded modulation performance and channel isolation.

3.2 1.5U standalone prototype

A prototype of the 1.5U CubeSat transmitter was also constructed (see Figure 3) to demonstrate how the fiber laser transmitter would integrate with the OTA and meet desired optical performance specification for interplanetary distances. The all-fiber laser transmitter described in section 2.1 is confined to a 0.5U envelope and consists of two slices. The first slice houses the gain-switched diode driver circuit. The second slice houses the two DFB laser on its underside and the remaining fiber-coupled components and fiber spool on its topside. The EDFA was not incorporated into the current version of the prototype, but is expected to fit within the remaining space available in the 0.5U volume. The EDFA will require an additional butterfly-packaged pump diode, drive circuitry, and fiber-optic components such as a WDM coupler and Er-doped fiber. The remaining 1U is reserved for the OTA, which includes an acquisition camera channel for wavelengths below 1100 nm and a signal transmit channel near 1550 nm. The transmit channel consists of a fiber collimator, fold mirrors, and a custom-designed on-axis monolithically-integrated telephoto lens assembly (JPL) with a ~5 cm aperture diameter. All opto-mechanics of the lens assembly is designed to be mounted within a single 3D-printed enclosure. This prototype does not include an attitude control system because the CubeSat was envisioned to be part a larger 6U CubeSat that would contain a separate module for attitude control.

Figure 3. Prototype of the 1.5U CubeSat laser transmitter, consisting of a 1U free-space optical transceiver assembly and 0.5U fiber-coupled laser transmitter; (a) CAD model, (b) laboratory implementation.

4. RESULTS

The end-to-end link performance of a single channel was first characterized by using a start-stop correlator at the link output. The data clock from the laser transmitter was the start trigger for the correlator, while the output of the photon-counting detector was the stop trigger. In principle, this is analogous to using an error-free clock recovery algorithm at the receiver and would provide an estimate for the upper performance bound for uncoded BPolSK modulation. The measured pulse arrival time histograms are displayed for various average SNR levels in Figure 4(a). The signal flux was fixed, while the background signal flux was increased. High erasure rates (99.8%) was chosen to simulate extreme operating conditions at interplanetary distances.

In BPolSK, all signal pulses arrive at a fixed repetition period and can be clearly observed within a narrow signal acquisition window, T_{slot}. The average SNR is defined as the signal count within the acquisition window divided by the noise count per symbol period. Signal acquisition was successfully achieve with average SNR levels as low as -43.5 dB at 100 ms integration times At the lowest operating point of -43.5 dB SNR, the mean signal within the acquisition window exceeded the noise variance by 3.2 standard deviations. Once the signal peak is identified, time-gating can be applied to reject noise counts external to this acquisition window to further improve the SNR. With a signal acquisition window of 600 ps and a symbol rate of 1MHz, the additional background noise rejection due to time-gating is 32 dB, thus yielding an effective SNR of -11.5 dB. The main conclusion here is that although signal acquisition with a -43 dB average SNR would prove challenging for PPM, time-gating for BPolSK recovers an effective SNR of -11 dB for signal acquisition with relative ease. Figure 4(b) shows the estimated erasure, error, and correct rates for uncoded modulation for measurements shown in Figure 4(a). The rates are estimated because only data from a single channel is available.

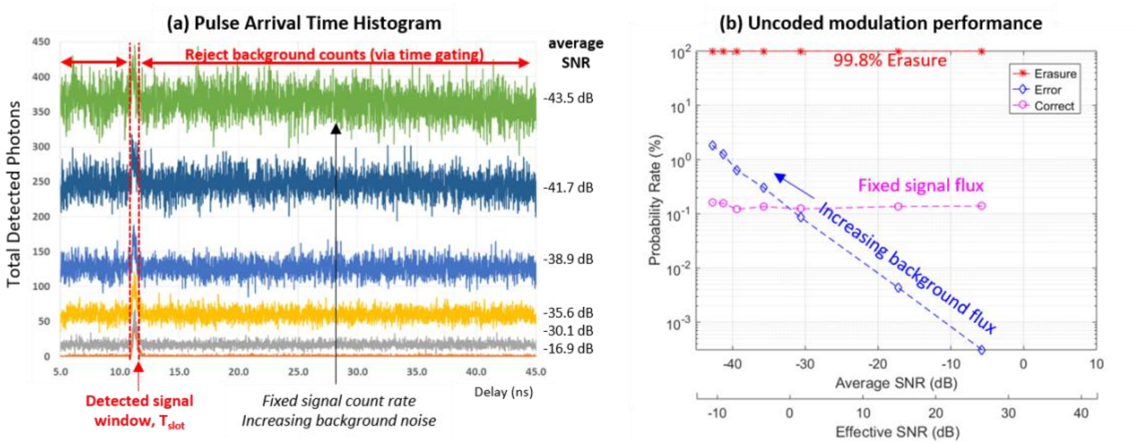

Figure 4. Link demonstration results using ideal clock recovery to estimate the upper bound link performance; (a) pulse arrival time histogram measured by the start-stop correlator; (b) corresponding estimated rates for uncoded modulation.

With the upper performance bound estimated, another end-to-end link demonstration using two channels was performed to evaluate the FFT clock recovery algorithm. The start-stop correlator is replaced with a free-running time-to-digital converter to timestamp the detected pulses from two channels for clock recovery processing. This configuration is representative of a typical ground station receiver where the receiver clock is not synchronized with the spacecraft clock and is subject to clock drift errors. In this demonstration, the background flux was fixed while the signal flux was decreased. Clock recovery was successful down to -26 dB average SNR, or +6 dB effective SNR after time-gating. The limit was set by the relative drift between the transmitter and receiver clocks. The recovery algorithm is expected to perform down to lower SNR levels (as shown in the first link demonstration) if a more stable clock reference is used on the spacecraft. Crosstalk between the two channels was also confirmed to be 30 dB, which corresponds to the finite polarization extinction ratio of the polarization beam splitter in the laser transmitter. Figure 5(b) shows the measured erasure, error, and correct rates for uncoded modulation for measurements shown in Figure 5(a).

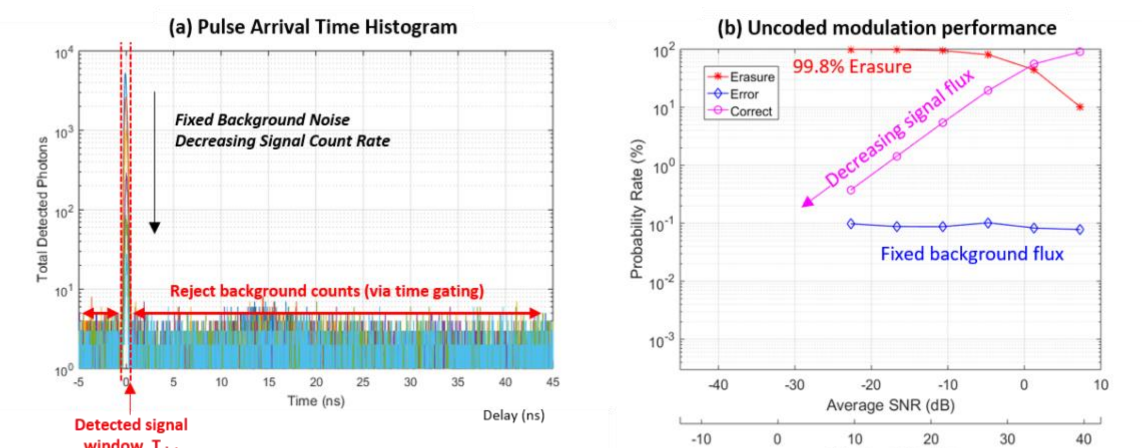

Figure 5. Link demonstration results using the FFT clock recovery algorithm; (a) Pulse arrival time histogram after signal acquisition; (b) corresponding measured rates for uncoded modulation.

5. CONCLUSIONS

BPolSK is similar to 2-ary PPM; however, it offers significant benefits in terms of SWaP improvements for the laser transmitter (i.e. reduced drive power and bandwidth requirement from gain-switch modulation and compact all-fiber-coupled implementation) as well as improved receiver performance (i.e. additional background noise rejection and robust clock recovery via FFT). Initial end-to-end link demonstrations confirm that 32 dB of additional background rejection from time-gating enables BPolSK to achieve signal acquisition at -43 dB of average SNR, which is a considerable advantage over conventional PPM. Future work is necessary to test the link performance under representative conditions for specific interplanetary ranges and to transmit real-time data across a free-space channel with simulated atmospheric effects.

ACKNOLEDGEMENT

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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