Adaptive Transceivers for Mobile Free-Space Optical Communications

Jeffrey R. Minch, David R. Gervais, and Daniel J. Townsend
The MITRE Corporation,
202 Burlington Road, Bedford, MA 01730.
Email: jminch@mitre.org; dgervais@mitre.org; dtownsend@mitre.org

Abstract— **Free-space optical (FSO) communication links are susceptible to a tremendous amount of variability and offer a real challenge for efficient, robust system design. Whether changes in link margin are predictable (i.e. weather conditions or mission profiles) or truly random (i.e. atmospheric turbulence induced scintillation or boundary layer induced tracking errors), FSO communication systems will experience a large dynamic range of performance through most mission scenarios. Recent system designs within commercial, academic, and military organizations have focused on leveraging COTS technology from the fiber optic telecommunications industry. These systems are typically based on fixed designs that use set data rates and modulation formats. Utilizing such modalities in a mobile free-space environment can lead to systems that are either overly conservative or have a high rate of failure. To maximize overall system efficiency, we propose a transceiver architecture with rate and modulation agility. The presented transceiver is built with COTS components, supports data rate adjustability, and can switch modulation formats between Differential Phase-Shift Keying (DPSK), Binary Pulse-Position Modulation (BPPM), and On-off-Keying (OOK). A prototype system illustrating adaptive operation is presented and experimental results are shown.**

I. Introduction

The military's use of bandwidth intensive applications and the ever-increasing demands on global connectivity has fueled the need for free-space optical communications (FSOC), also known as laser communications. While interest in using FSOC for such purposes existed since the mid 1960s [1], [2], the efficient application of the technology in a cost effective manner was largely driven by the advances made at the component-level in the telecommunications boom of the late 1990s. The advent of technologies such as the erbium-doped fiber amplifier (EDFA) which made the implementation of near-quantum limited receiver performance achievable [3] and the development of high-speed modulators and detectors provided the foundational components necessary to realize affordable and robust FSOC for military needs [4]. Further investments in optical beam steering technology [5], [6], [7], [8] extended the capabilities and possibilities of integrating FSOC on mobile platforms such as ground vehicles, airplanes, and satellites.

The current challenge in FSOC terminal design, and the focus of the presented research, is to find ways to exploit available channel resources when operating in a mobile, wireless environment. In contrast to fiber-based optical communication where link loss is fairly static, the mobile FSOC channel is very dynamic and the loss can fluctuate on a variety of different time-scales.

The simplest and most evident issue with mobile communications is diffraction loss. As nodes move, the link loss is related to the inverse square of the separation distance and represents a slowly varying loss component.

The atmosphere that exists between the communicating nodes can absorb and scatter the beam causing additional loss. The relative strength of absorption and scattering are location, altitude, and time specific, but tend to change on similar time-scales as diffraction loss.

The atmosphere also causes an effect known as scintillation (a similar effect known as boundary layer turbulence can occur around the skin of airborne platforms). Scintillation is caused by very slight temperature and pressure fluctuations along the propagating path of an optical beam. These fluctuations produce a change in the medium's refractive index. The spatial changes in refractive index cause parts of the beam to speed up or slow down relative to each other which results in phase aberrations. As the phase aberrations propagate, they redistribute the energy in the diffracting beam and cause rapid fluctuations in received power at the receive telescope [9], [10]. Platform vibrations and misalignment of the transmitter and receiver telescopes can cause similar time-varying fades of received power. These fluctuations can be mitigated using long interleaver spans combined with forward-error-correction (FEC) [11], [12] to translate the fast time-varying fade problem into a slowly-varying average power problem, more akin to the diffraction, absorption, and scattering loss terms described above. Other optical correction techniques such as adaptive optics or spatial diversity can be employed to achieve a similar compensating effect [9].

In general, one can now consider the free-space communication channel entirely as a slowly-varying link loss with a very large dynamic range. The current design methodologies applied in fiber-optic based telecommunication links no longer apply because of the nature of the wireless, time-varying channel. It is no longer sufficient to operate with a fixed communication rate and utilize a single amount of margin to guarantee a specific amount of availability, especially in power-limited applications. Factoring the large variations into the margin term results in an overly conservative design which fails to reach optimal performance a majority of the time. Therefore, an optimal system must be capable of reacting to changing link conditions to maximize overall throughput or

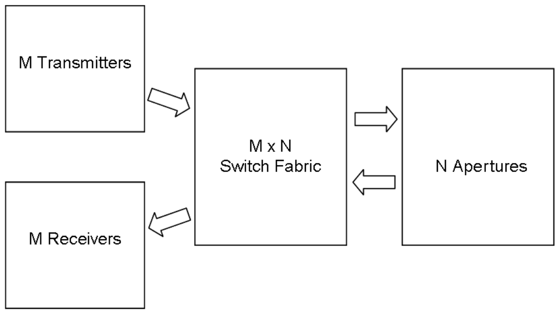

Fig. 1. General Architecture

availability.

The approach presented uses rate and modulation agility to provide multiple optimization points for various link topologies. The system is also capable of interchanging available link margin into useable capacity or improved availability. By exposing these options to the end-user, a more efficient use of the communication medium is possible. It also provides the user with more flexibility by allowing multiple modes of operation that can be used in ways yet envisioned.

II. Architecture

A general architecture for an adaptive terminal that suits the dynamic environment of the free-space optical channel is presented in Fig. 1. The architecture utilizes M transmitters and receivers connected to N apertures through a switch fabric. Each transmitter and receiver pair is capable of wavelength tunability, data-rate adjustability, and can transmit/receive multiple modulation formats. Each aperture has a separate pointing and tracking subsystem that is capable of adaptive beam forming and can optimize overall system performance by trading relative beam quality, tracking stability, and communication throughput. The switch fabric is used to connect the apertures to the appropriate transmitter/receiver. The connection can be made in a point-to-point, point-to-multipoint, or multipoint-to-multipoint configuration. By using a flexible interconnect, one can provide link handoff capability, utilize multiple apertures for transmitter/receiver gains, combine signals to produce advanced modulation formats, or provide spatial diversity to mitigate the atmosphere.

The adaptive transceiver presented here provides the ability to switch between Return-to-Zero Differential Phase-Shift-Keying (RZ-DPSK), Binary Pulse-Position Modulation (BPPM), and Return-to-Zero On-Off-Keying (RZ-OOK). Such functionality could be useful, for example, on an airborne platform where the same terminal must support the conflicting requirements of an air-to-space, air-to-air, or air-to-ground link. The air-to-space channel is dominated by diffraction loss and an energy per bit efficient modulation format, such as RZ-DPSK, is more appropriate. On the other hand, an air-to-air or air-to-ground communication link will not incur a significant diffraction loss, but will be subjected to potentially strong turbulence. Therefore, an intensity modulated waveform, such as BPPM, is more appropriate for this environment. By utilizing an intensity modulated waveform, multiple apertures may be combined to reduce atmospheric effects. BPPM also provides a greater dynamic range of data rates to combat the adverse channel effects.

For each modulation format, the transceiver design can support rate adjustability with a fixed, optimal receiver for all data-rates. Fig. 2 gives example waveforms for each of these modulation formats at a few key data rates.

Rate agile RZ-DPSK is achieved using the method proposed by Minch, et. al. [13]. The lowest DPSK data rate is set by the fixed interferometer delay T in the receiver. At this fundamental data-rate, data is encoded in the difference in phase between adjacent bits as is done in conventional DPSK systems. At higher rates, which must be an integer multiple N of the fundamental, data is encoded in the phase difference between the current bit and the bit N bits prior. The optical intensity is carved into a pulse with fixed pulse-width w for all data-rates. Thus, the duty cycle changes with data-rate and the maximum rate is set by the pulse-width. It should be noted that the fixed pulse-width allows a single fixed receiver that is theoretically optimal for all data-rates. In the example of Fig. 2, the interferometer delay T is 8 times the pulse-width w. The fundamental rate $\left(\frac{1}{T}\right)$, an intermediary rate (4 times the fundamental), and the high rate ($\frac{1}{w}$ = 8 times the fundamental) are all shown. Data rates below the fundamental are not supported for RZ-DPSK. It supports, in principle, a 3 dB performance gain in receiver sensitivity when compared to either BPPM or RZ-OOK [16]. RZ-DPSK also has the added benefit of maintaining a constant decision threshold about zero that is independent of received power fluctuations.

Rate adjustable BPPM is implemented using the method outlined by Stevens et al [14]. Data is encoded in the position of an optical pulse of width w in the first or second time-slot of a bit. As shown in Fig. 2, the highest achievable rate is therefore one half the highest rate for RZ-DPSK or RZ-OOK $\left(\frac{1}{2w}\right)$. Lower data rates are obtained by changing the amount of dead time between the data time-slots. The lower limit on the achievable data rate is set by the low frequency cutoff of the transceiver electronics. Since a fixed pulse-width is used for each rate, the fixed receiver is optimal for any data-rate and very large increases in link margin can be realized by shifting to lower rates.

Rate adjustable RZ-OOK is achieved in a similar fashion as BPPM. Data is encoded on the intensity of the pulse. Fig. 2 shows the highest achievable rate of $\frac{1}{w}$. As in BPPM, lower data rates are generated by changing the amount of dead time between pulses. RZ-OOK supports the entire range of data rates provided by the system. It also has an identical theoretical receiver sensitivity to BPPM. However, BPPM is usually preferred for free-space optical communication links since the optimal detection threshold is independent of the received optical power and is therefore less susceptible to optical fading effects.

The transmitter architecture for is illustrated in Fig. 3. The

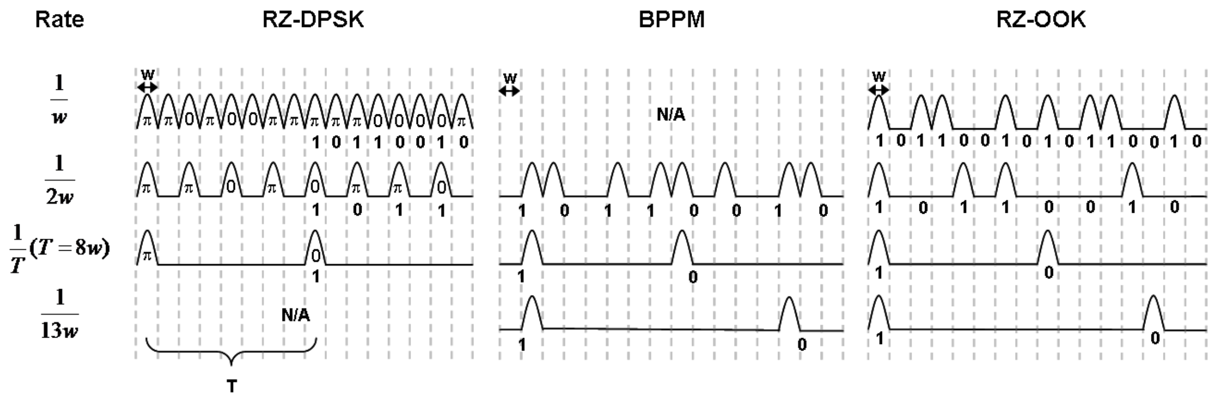

Fig. 2. RZ-OOK, BPPM, and RZ-DPSK Waveform Description

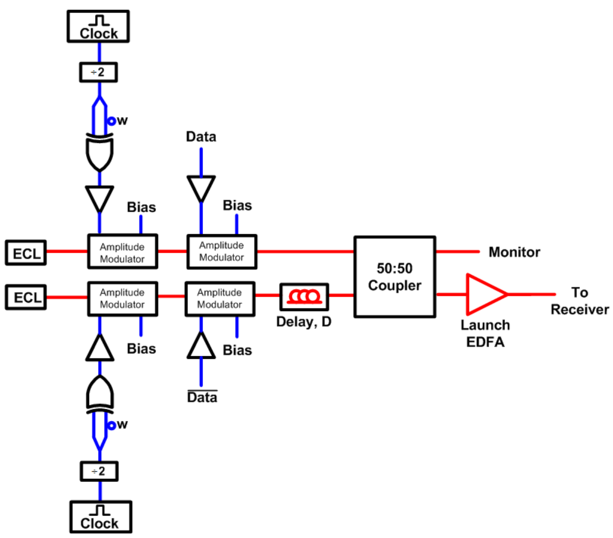

Fig. 3. Adaptive Transmitter Implementation

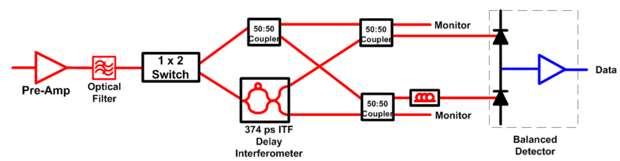

Fig. 4. Adaptive Receiver Implementation

output of two tunable external cavity lasers (ECL) are each modulated by a cascade of two $LiNb0_3$ modulators. The resulting signals are then combined and fed into a launch Erbium Doped Fiber Amplifier (EDFA). To support RZ-DPSK and RZ-OOK each light path operates independently and the transmitter can support two parallel channels if the tunable lasers are set at different wavelengths. For BPPM operation, the two lasers are set at the same wavelength and work together to generate a single waveform.

The first amplitude modulator of each path provides the variable rate optical pulse carving. The signal clock (rate R) is divided by two and the output is XOR-ed with a copy of itself delayed by the desired pulse-width w $\left(w \ll \frac{1}{R}\right)$. This operation results in a pulse of width w at each transition of the clock divided by 2 or for each cycle of the original clock signal. The pulse train is then amplified by a modulation driver to a peak signal of V_π and fed to the first amplitude modulator which is biased at the 50% point. The second modulator encodes data on the optical pulse train. For RZ-OOK, the modulator is biased at the 50% point and the driver is set to V_π in amplitude so that the data is encoded on the optical intensity. For RZ-DPSK, the modulator is biased at the null point and driven up to $2V_\pi$ to encode data symbols as a positive or negative phase with uniform intensity.

To create a BPPM signal, both transmitters are set to the same wavelength and identical pulse trains are created by the pulse carving modulators. While the data is modulated as in RZ-OOK on the first path, the second path is encoded with the inverted data pattern and delayed by the pulse-width w relative to the other path. When the two signals are combined, the BPPM waveform is created. The resulting signal is then fed into a launch EDFA. Since the EDFA is average power limited, as the data rate is reduced, the peak power of the optical signal will increase inversely with the duty cycle [15], enabling an increase in link margin as the data-rate is reduced.

The receive architecture for the adaptive transceiver is shown in Fig. 4. The incoming signal enters an EDFA preamplifier and is followed by a filter to eliminate out-of-band preamplifier noise as well as any other channels that are being sent in parallel on the link. It should be noted that if two parallel RZ-OOK or RZ-DPSK signals are being sent, a second receiver will be needed for the second channel. After the filter, an optical switch feeds the received signal to a delay interferometer for RZ-DPSK operation or to the second path for intensity modulated operation. The delay interferometer has a fixed delay T equal to the bit period of the lowest rate of RZ-DPSK. The delay interferometer used has a delay of 374 ps which yields a fundamental DPSK rate of

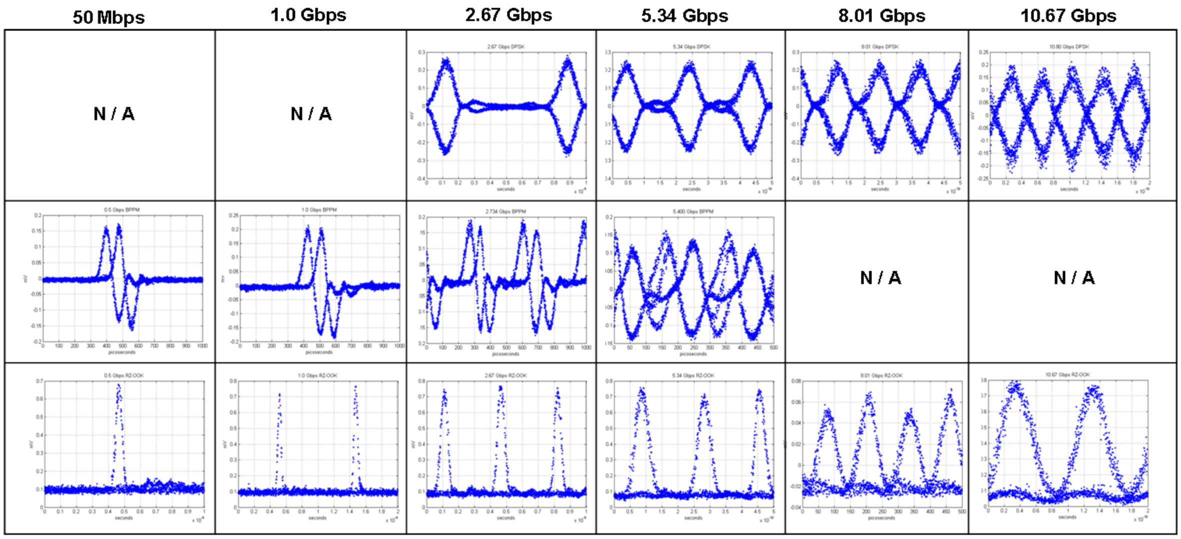

Fig. 5. Multiple rate eye diagrams for RZ-OOK, BPPM, and RZ-DPSK

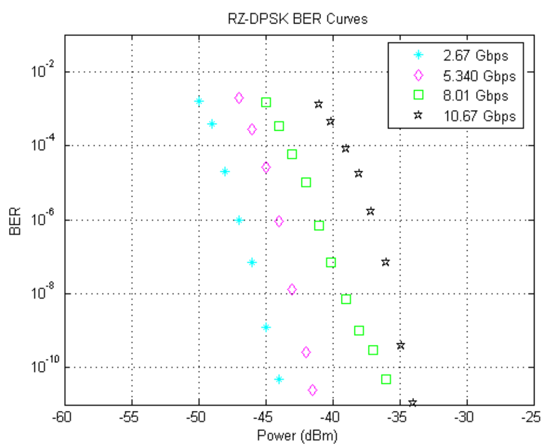

Fig. 6. RZ-DPSK Measured BER Curve

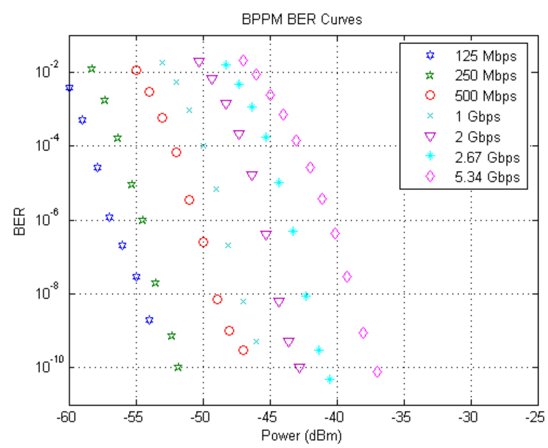

Fig. 7. BPPM Measured BER Curve

2.67 Gbps. The delay interferometer (when set to the proper phase bias) compares the phase of the encoded symbols and the constructive and destructive ports are fed to a balanced-pin/TIA detector where the resulting signal is ready for zero voltage threshold detection. For BPPM, the received signal is switched along the other path to a 3 dB coupler where the signal is split. One path is delayed by the pulse-width w and both are fed into the inputs of the same balanced-pin/TIA detector. The resulting photocurrents are subtracted in the balanced-pin and the resulting decoded waveform is again ready for zero threshold detection with the same optimal receiver as used for RZ-DPSK. For RZ-OOK operation, only the positive input terminal of the balanced detector is used.

III. Results

The eye diagrams measured from the adaptive transceiver are illustrated in Fig. 5. Open eyes were observed for all sam-

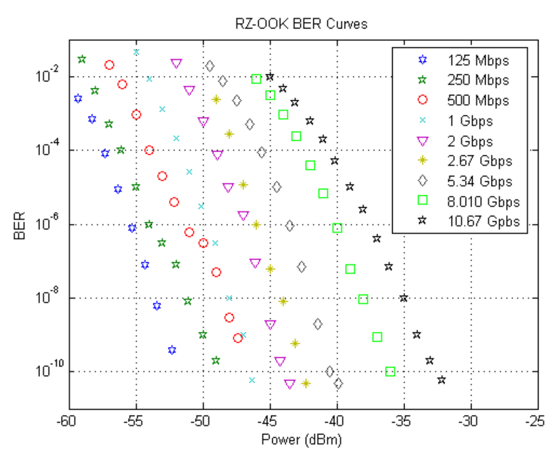

Fig. 8. RZ-OOK Measured BER Curve

pled data rates and modulation formats. The received signals were collected after the balanced receiver and are illustrated for several data rates. The eye diagrams for DPSK were measured at integer multiples of the fundamental frequency (2.67 Gbps) which is set by the optical delay interferometer. The electrical pulse carver's pulse-width was selected to operate with a maximum data rate of 10.67 Gbps. For BPPM, the setup is continuously adjustable from 50 Mbps to a maximum rate of 5.4 Gbps which is limited by the transmitted pulse-width. The BPPM eye diagram in Fig. 5 uses differential decoding. This creates an eye opening, centered about zero, such that the optimal decision threshold remains fixed even in the presence of received power fluctuations. For RZ-OOK, the system is continuously tunable from 50 Mbps to a maximum of 10.67 Gbps. The RZ-OOK eyes were taken using only the positive side of the balanced-pin receiver.

Fig. 6, 7, and 8 show the measured bit error rate (BER) curves for RZ-DPSK, BPPM, and RZ-OOK modes of operation, respectively. For DPSK, the curves show no error floor and demonstrate improved receiver sensitivity at lower data rates. The improvement in sensitivity is due to the decrease in average power required to support the same energy per bit as the duty cycle is decreased. In order to translate this improved sensitivity into an increased link margin, an average power limited transmitter such as the launch EDFA must be used [15]. The improvement of almost 3 dB between 2.67 and 5.34 Gbps is what theory predicts, however, the larger difference of 5 dB between the performance at 5.34 Gbps and at 10.67 Gbps indicates an extra penalty at the higher rates. The BPPM curves have no observable error floor. At 2.67 Gbps, there is a 3 dB difference between the performance of BPPM and RZ-DPSK which is to be expected from theory [16]. The BPPM curves also illustrate an approximate 16 dB dynamic range from 125 Mbps to 5.34 Gbps and is inline with the 16.3 dB predicted by theory. Finally, results for RZ-OOK are similar to those for BPPM showing a 19 dB dynamic range between the measured rates of 125 Mbps and 10.67 Gbps which is also in accordance with theory. At the high rates, RZ-OOK shows a similar degradation in performance to what was observed in the results for RZ-DPSK.

IV. Conclusion

The use of static terminals to support a wide range of mission needs and user requirements are not sufficient for most mobile, wireless channels. To satisfy the requirements of future combat systems, an adaptive terminal architecture must be capable of optimizing overall system performance for a large range of potential channel responses. A general architecture was presented that can provide flexibility and agile operation in environments that offer a large dynamic range.

The transceiver subsystem of the overall architecture was described in additional detail and a prototype system was constructed. The prototype system demonstrated the capability of trading margin for data rate / availability and utilized three specific modulation formats: RZ-DPSK, BPPM, and RZ-OOK. The device experimentally demonstrated an approximately 15 dB of dynamic range and could operate at rates from 50 Mbps to 10.67 Gbps. Eye diagrams and BER curves characterized the transceiver's operation at select data rates and modulation formats thereby proving the feasibility of an adaptive optical transceiver.

References

[1] Stephen G. Lambert and William L. Casey, *Laser Communications in Space*, Artech House, Inc., Norwood, MA, 1995.

[2] David L. Begley, *Select Papers on Free-Space Laser Communications*, SPIE Milestone Series Vol. MS 30, SPIE Optical Engineering Press, Bellingham, WA, 1991.

[3] J. Livas, *High sensitivity optically preamplified 10 Gb/s receivers*, OFC 1996, San Jose, CA, Feb. 1996, post deadline paper.

[4] V.W.S. Chan, *Optical Space Communications*, IEEE Journal on Selected Topics in Quantum Electronics, vol. 6, Dec. 2000, pp. 959-975.

[5] Paul F. Mcmanamon, et. al., *Optical Phased Array Technology*, Proceedings of the IEEE, vol. 84, Feb. 1996, pp. 268-298.

[6] Brian Matkin, *Steered Agile Beams support for Army requirements* Proceedings of SPIE, vol. 3952, 2000, pp. 4-14.

[7] Brian Stadler and George Duchak, *TeraHertz Operational Reachback (THOR) A Mobile Free Space Optical Network Technology Program*, IEEE Aerospace Conference Proceedings, 2004, pp. 1710-1721.

[8] Stephen Griggs, *Optical and RF Combined Link Experiment*, Proceedings of SPIE, vol. 5820, 2005, pp. 75-82.

[9] Larry C. Andrews and Ronald L. Phillips, *Laser Beam Propagation through Random Media*, SPIE Optical Engineering Press, Bellingham, WA, 1998.

[10] Larry C. Andrews, Ronald L. Phillips, and Cynthia Y. Hopen, *Laser Beam Scintillation with Applications*, SPIE Optical Engineering Press, Bellingham, WA, 2001.

[11] Hennes Henniger, et. al., *Evaluation of FEC for the Atmospheric Optical IM/DD Channel*, Proceeding of the SPIE, vol. 4975, 2003, pp. 1-11.

[12] J.G. Proakis, *Digital Communications*, 4th Ed., McGraw-Hill Companies Inc., New York, NY, 2001.

[13] Minch, J.R.; Townsend, D.J.; Gervais, D.R., *Rate adjustable NRZ-DPSK modulation scheme with fixed interferometer*, LEOS Summer Topical Meetings, pp. 43-44, 25-27 July 2005.

[14] M.L. Stevens, D.M. Boroson, and D.O. Caplan, *A Novel Variable-Rate Pulse-Position-Modulation System with Near Quantum Limited Performance*, LEOS '99, TuU5, 1999.

[15] D.O. Caplan, M.L. Stevens, D.M. Boroson, and J.E. Kaufmann, *High-sensitivity variable-rate transmit/receive architecture*, LEOS '99, TuU3, 1999.

[16] S.B. Alexander, *Optical Communication Receiver Design*, SPIE Optical Engineering Press, Bellingham, WA, 1997.