Variable data rate for Optical Low-Earth-Orbit (LEO) Downlinks

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Abstract

With the advancement of earth-observation sensor resolution, demand for high data rate satellite downlinks is increasing. Laser communication is an attractive technology offering very high data rate, yet allowing small transmit terminals and secure communication while avoiding spectral regulation constraints. However, the communication quality strongly depends on the fast varying link distance that causes changes in mean power, and on the turbulent atmospheric transmission medium that causes fades of typically 2-20ms whose strength depends on the link elevation. Therefore, in order to cope with such atmospheric effects, systems are conventionally designed with high link margin to maintain acceptable performance for worst case conditions, thereby wasting the resources during good conditions. Variable data rate is a promising solution to such problems. We investigate different techniques to lower the data rate when the channel condition gets challenging, and to suggest a suitable combination strategy to optimize throughput for the optical LEO downlink scenario. The techniques include varying pulse-width of non-return to zero on-off keying (NRZ-OOK), modulation order of Pulse Position Modulation (PPM), and duty-cycle of Return-to-zero (RZ). This paper highlights simulation results for different types of receiver front-end (RFE) models for a static channel, and future ideas to mitigate fades.

1 Introduction & Motivation

Real-time and error-free data downlink from Low Earth Orbit (LEO) satellite to earth is one of the most popular scenarios in the free space optical communication research area because of growing throughput demand for earth observation applications. Free-space optical communication, in general, is considered as the best approach because of its high throughput possibility, less power and small terminal size requirement, high security, and no limitation in bandwidth. In addition to above-mentioned advantages, it also has challenges as the signal gets deteriorated by the atmosphere. Moreover, the pointing error and other factors like fog, rain, background light etc. also affect the signal stability [1]. Various mitigation techniques like aperture averaging, adaptive optics, spatial transmitter diversity, wavelength diversity, forward error correction with long interleavers, adaptive data rate etc. are used to cope against the atmospheric challenges [2]. Among those, adaptive data rate is one of the efficient techniques widely used in RF [2]. When non-adaptive systems are designed, the worst channel condition has to be considered to avoid drop-outs but when the channel condition is good, it is a waste of resources. Therefore, changing the data rate according to the channel condition is an efficient technique. Lowering the data rate decreases the throughput; however it avoids the complete loss of the data during worse channel condition and maintains the link.

Studies in [3] and [4] suggest that a system with the capability of adaptive data rate, code rate, modulation scheme and interleaver size would be the perfect approach to mitigate the atmospheric challenges. According to the study done in [5], in a typical LEO orbit situation, throughput improvement of more than 3 times for an adaptive scheme compared to optimum fixed data rate can be expected. However, the realistic factor would be slightly less as this calculation was done considering ideal assumptions like the satellite having a uniform position probability on its orbital sphere, no atmospheric turbulence, equivalent cloud probability, constant receiver sensitivity on photons per bit etc.

Adaptive transmission is a well-known technique used in RF communication and has also recently raised interest in the FSO world. Simple adaptive power transmission technique was explored in [6]. A parallel-channel encoder-rate adaptive coding scheme in a hybrid link is introduced in [7]. Furthermore, adaptive coding and Q-ary PAM modulation was studied in [8] for Gamma Gamma channels. Additionally, adaptive channel rate of the system based on an average power limited (APL) transmitter and a variable duty-cycle modulation format was demonstrated in [9] and a novel variable-rate pulse position modulation system with near quantum limited performance was demonstrated in [10]. However, no specific techniques or a combination of techniques have been investigated for data rate variation particularly in LEO scenario.

The main objective of this paper is to investigate different techniques for varying the data rate for optical LEO downlink scenario, analyze and compare them from different perspectives. The link geometry of typical LEO satellite downlink (about 500km from the earth surface) is given in **Figure 1**.

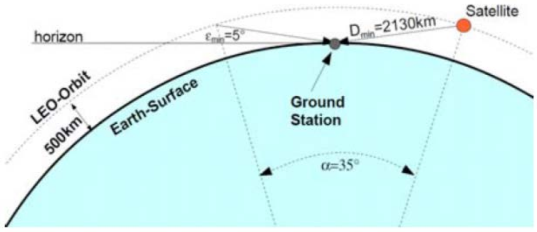

Figure 1. Link geometry of typical earth observation satellite downlink with minimum elevation angle of 5° and ground station at sea level (Source: [4]).

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2 Optical LEO Downlink Channel

During a LEO downlink pass, the satellite moves in an orbit, varying the distance between satellite and ground stations, therefore the link budget also varies. In addition, depending on elevation angle, atmospheric attenuation and scintillation also varies. This was verified during the experimental downlink from a Japanese satellite to DLR's optical ground station (KIODO downlinks) [3], [4]. Some of the results of experiments are shown in figures below. In **Figure 2** the link started shortly before 5° elevation and power increased with the elevation. After 25° the power starts to fall because of a cloud appearance. Regular drops of the mean power during the link as seen in the figure are tracking errors. In addition, **Figure 3** indicates higher power scintillation index at lower elevations in all the trials. Power scintillation index is the measure of normalized variance of the signal due to atmospheric effects. Moreover, the measurement of received power was further analyzed to calculate the duration of 3dB fades. **Figure 4**. shows fades up to 1.4ms at 8°-10° and around 0.2-0.8 ms at 20°. Atmospheric effects are greater at lower elevations; however, it cannot be neglected as it covers significant fraction of the link time. In [4] for the example scenario, it has been estimated that 20% of the time during one link, elevation angle of the satellite is between 5 to 10 degrees and another 25% of the time the elevation is between 10 to 20 degrees.

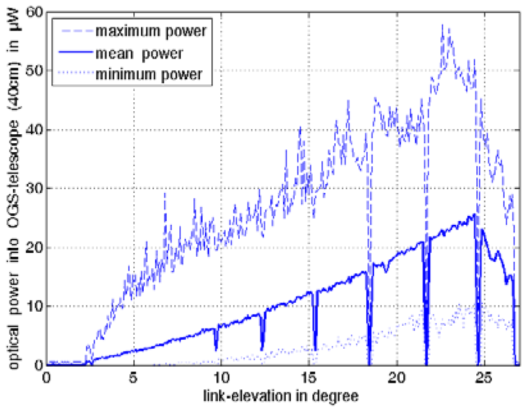

Figure 2. Measured received optical power during KIODO downlinks. (Source: [4])

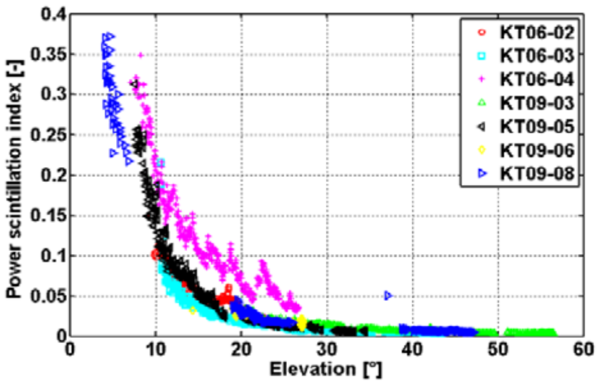

Figure 3. Measured power scintillation index with respect to the elevation measured during the KIODO downlinks. (Source: [3])

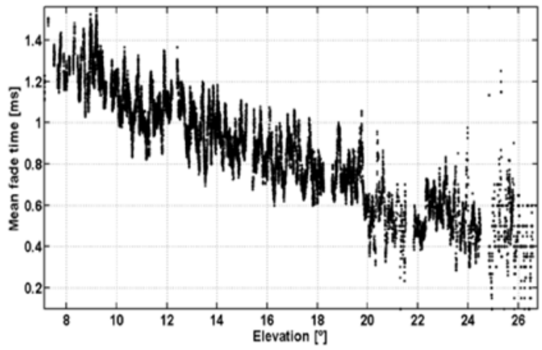

Figure 4. Mean fade duration according to the elevation measured during the KIODO downlinks in 2006. (Source: [4])

3 Variable Data rate

During one satellite downlink, link budget varies according to distance, satellite pass, and atmospheric condition. The statistics of the received power can be used as a guideline to design a system to mitigate this effect; an intelligent way would be to build an adaptive transmission using the channel state information (CSI). To implement a robust link and to maximize throughput under these variations, a variable line rate transmission is required in the transmission system. Varying the line rate can cope against following challenges in the link:

- Variation in link budget/received power due to varying distance
- Varying atmospheric attenuation (mean power reduction)
- Varying scintillation strength
- Different ground stations and space terminals supporting different data rates

CSI is very important for effective variable data rate system. It can be achieved using a feedback channel by allocating a small portion of bandwidth from a bi-directional FSO link. For a unidirectional link, the channel can be estimated by analyzing the quality of the beacon (signal sent by a ground station to illuminate the satellite terminal for acquisition and tracking) received. In addition, channel modelling based on previous experiments can also be used to roughly estimate the channel and design the system. Furthermore, in hybrid RF/FSO systems, RF links can be used for feedback purpose.

For satellite downlink scenario, variation of data rate according to the channel can be implemented in following modes:

Constant data rate for individual satellite pass: The particular data rate can be fixed for links depending on optical transmit power, beam divergence, satellite pass etc.

Pre-programmed variable data rate: Different sets of data rate for particular satellite pass can be pre-programmed according to the elevation or time.

Adaptive without feedback channel: The data rate can be adapted according to the channel condition that can be estimated by evaluating the received beacon signal at satellite tracking sensors. It would avoid the need for negotiation with the ground terminal. Furthermore, the ground

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terminal has to recognize the variation in the transmission rate or signal constellation or repetition scheme from the satellite terminal and react accordingly.

Adaptive with feedback channel: In this case, data rate variation can be done by direct communication between the ground and satellite terminals. Ground station includes various measurement equipment; therefore, it can better estimate the channel. Ground station can then command the satellite terminal via uplink channel to change the data rate accordingly.

Some of the possible data rate variation techniques are briefly explained below. The main idea is to design a system for one highest line rate which then can be lowered depending on the atmospheric condition. According to the estimation done for example scenario in [4], data rate variation of factor up to 25 is required without fading. When scintillation, fading and pointing error are also considered, it might go up to 100.

3.1 Variable pulse-width NRZ-OOK

On-off keying (OOK) is a popular modulation technique widely used in free-space optical communication because of its simplicity of direct detection technology. For NRZ, the optical pulse is transmitted for ‘1’ bit and no pulse is used for ‘0’ bit. In order to vary (lower) the data rate using this scheme, a width of the pulse (w) is changed as shown in **Figure 5** i.e. in order to decrease the data rate by half, pulse width is doubled. This technique is simple but requires a change in the receiver hardware as the bandwidth of the receiver frontend has to be tuned according to the data rate. Alternatively, a variable limiter circuit can be used at the RFE-output to provide the low-pass filtering.

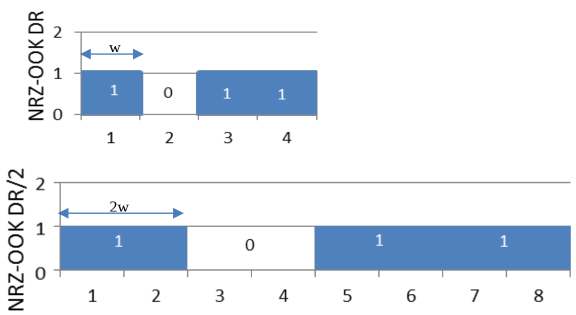

Figure 5. Data rate variation by varying the pulse-width (w) of NRZ-OOK system; top: high-data rate (DR), below: lower data rate (DR/2). Vertical axis shows the relative amplitude of the signal that stays constant and horizontal axis shows the relative time.

3.2 Variable Pulse Position Modulation (PPM-L) order with the same pulse-width

Pulse Position Modulation (PPM) scheme is well-known for its power efficiency and the information is encoded in the position of the pulse in a symbol duration. It can also be used to lower the data rate by increasing the modulation order (L) keeping constant pulse-width. An example of using PPM4 to lower the data rate by half is shown in **Figure 6**. One PPM4 symbol encodes two bits and requires 4 time slots with constant length ‘w’. This scheme is more suitable along with EDFA-based average-power-limited transmitters as peak power is increased (doubled in this case) for lower data rates.

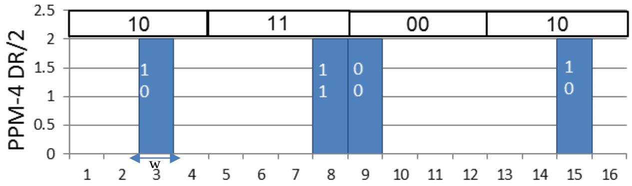

Figure 6. PPM-4 modulation for lowering the data rate by factor 2.

3.3 Variable pulse frequency with the same pulse width using Return-to-Zero (RZ-OOK) modulation

RZ-OOK is the modulation techniques in which the pulse of a ‘1’ bit occupies only a fraction of the bit interval and no pulse is transmitted for ‘0’ bit, depending on the chosen duty-cycle. For lowing the data rate and keeping the pulse-width constant, the duty-cycle of the RZ can be decreased thereby increasing the time required for transmitting a bit [11]. For example to lower the data rate by ‘n’ factor and keeping the constant pulse-width (w), RZ-n with the duty cycle = $\frac{1}{n}100\%$ can be used. An example of using RZ-2 (50% duty cycle) to reduce the data rate by half is shown in **Figure** 7. If APL source is used, RZ-OOK is advantageous compared to NRZ-OOK as it has higher peak power (similar to PPM) [12]. But unlike PPM, the pulse always appears at the same position and this property can be exploited for better detection at the receiver.

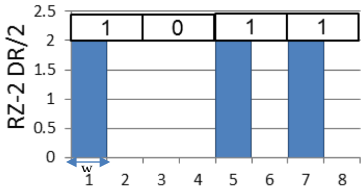

Figure 7. RZ-2 for lowering the high data rate (DR) by factor 2.

4 Results and Discussion

In addition to low complexity, receiver sensitivity is one of the important factors for selecting different techniques. The number of photons required to achieve certain BER defines the sensitivity of the receiver. The receiver sensitivity for each technique is evaluated for three different types of receiver models namely, shot-noise limited (SNL), realistic Avalanche Photodiode (APD) receiver front-end (RFE) and thermal noise limited (e.g. PIN diodes). In addition, the performance has been studied using an average-power limited (APL) source (e.g. EDFA, with energy-storage capacity) and a peak-power limited (PPL) source (e.g. simple current-modulated laser-diode with a maximum output power but no energy-storage capacity). A summary of different schemes, Tx and Rx types are listed in **Table 1**.

Tx type	Schemes	RFE types
• APL • PPL	• Variable pulse-width NRZ-OOK • Variable PPM modulation order with same pulse-width • Variable pulse rate with same pulse-width using RZ-OOK	• SNL • APD • PIN

Table 1. List of schemes, Tx types and Rx types used for the simulation.

While evaluating different techniques, various factors have been considered, namely Tx type, Tx/Rx complexity, data rate factors, performance in terms of energy per bit required etc. For the simulation, the highest data rate is considered to be 10Gbps and parameters for commercially available 10G RFE (table 3 of [13]) is used. The performance of the RFE is closer to thermal-limited [13]. Some parameters and the values used for simulation are dark current = 0, noise density (in) = 15pA√Hz, responsivity (R) =0.85 and for APD, APD multiplication factor (M) = 20, noise figure (F_A) = 8. The simulation results for different techniques using APL source are presented in **Figures 8**, **9** and **10** respectively. The detailed comparison of different techniques in terms of energy required per bit to achieve BER of 1E-2 using APL or PPL Tx types, and SNL, APD or PIN Rx types is depicted in **Figure 11**. It is assumed that the system will have necessary coding to cope with BER of 1E-2.

Figure 8 shows performance of the technique to vary the data rate by changing the pulse-width of the NRZ-OOK modulation format using APL source. It can be seen that for SNL system the receiver sensitivity remains constant for all the data rates. However, for APD RFEs and thermal-limited case, up to 6dB more photons per bit are required to lower the data rate to 650Mbps (factor 16) at BER of 1E-2 (see **Figure 11**). It also shows that this technique is unaffected by the use of APL or PPL sources.

Similarly, **Figure 9** depicts the performance of changing the modulation order of a PPM system using APL source. The receiver sensitivity for this technique improves on lowering the data rates (except for PPM-2) when APL source is used. However, it behaves the contrary when PPL source is used (see **Figure 11**). Using any source types, the performance of the SNL receiver performs the best. Although the PPM has better receiver sensitivity, the complexity of transmitter and receiver limits the factor of data rates up to 8 (PPM256) due to synchronization and EDFA-storage capabilities requiring unrealistic high peak-power. In addition, PPM requires dead time between consecutive pulses.

Finally, the result of varying the data rate by varying the pulse frequency or duty cycle of the RZ modulation scheme using APL source is presented in **Figure 10**. It shows same receiver performance for all the data rates for all three receiver models when APL source is used. When PPL source is used (see **Figure 11**), the performance degrades but all the data rates require same energy per bit. This technique can provide more factors of data rates with similar level of complexity compared to PPM and the detection can be more robust as the position of the pulse is fixed and known to the receiver.

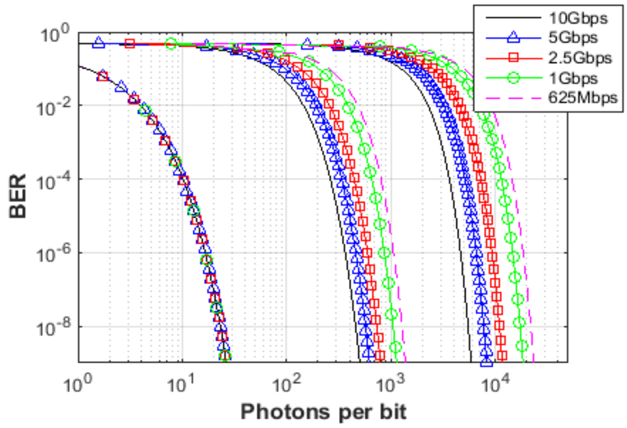

Figure 8. Receiver sensitivity for decreasing the data rate by increasing the pulse-width of NRZ-OOK and adaptive low-pass filter at the receiver and using APL source. Left: SNL, Mid: APD-RFE, Right: PIN

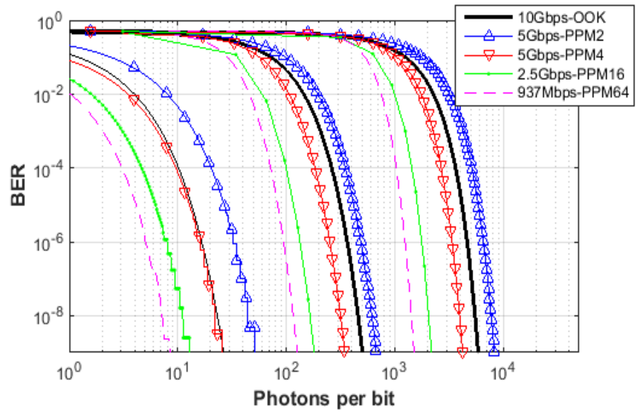

Figure 9. Receiver sensitivity for lowering the data rate by increasing the PPM modulation order using APL source. Left: SNL, Mid: APD-RFE, Right: PIN

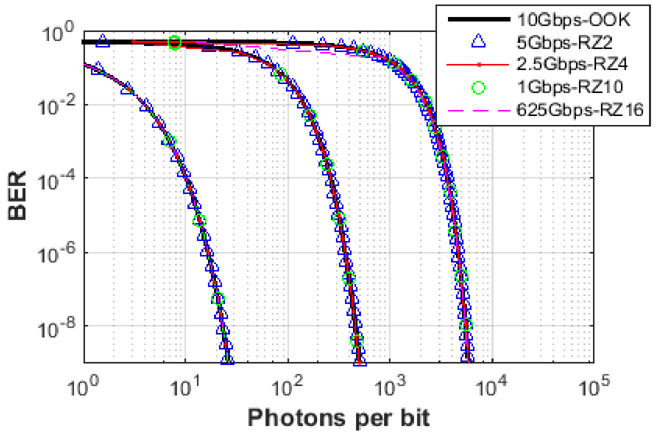

Figure 10. Receiver sensitivity for lowering the data rate by decreasing the pulse frequency of RZ using APL source. Left: SNL, Mid: APD-RFE, Right: PIN

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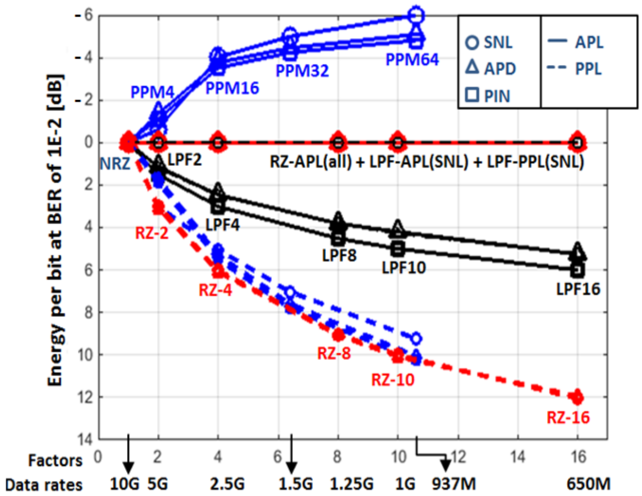

Figure 11. Receiver sensitivity comparisons for different variable data rate techniques for different factors of effective data rates w.r.t. the NRZ-OOK at 10Gbps, using APL (solid lines) and PPL sources (dashed lines)

5 Conclusion & Outlook

Variable data rate is essential for free-space optical LEO downlink scenario because of the dynamics of the channel according to the satellite position. Various techniques were identified and simulated and preliminary results showed that the variable pulse-width NRZ-OOK is simple and provides larger factors of data rate, but is rather inefficient from receiver sensitivity point of view. On the other hand, varying PPM modulation order is efficient but it is rather complicated and only few factors of the data rates are practically possible. Variable duty-cycle RZ modulation seems to fall somewhere in between as its photon efficiency remains same with the data rates but it also cannot provide the complete range of data rate factors alone. The limit to which data rate can be lowered using RZ is foreseen to be investigated in future. To reach the high rate-ratios required for LEO downlinks (more than factor 25), a system with a combination of first and the last option is suggested for lowering the data rate. Further techniques like delayed frame repetition can cope with longer fades together with various coding schemes. This will be investigated in future. In addition, the detailed design of data rate variation scheme for more realistic LEO downlink scenario need to be studied.

6 References

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