ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

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SYSTEM ASPECTS OF OPTICAL LEO-TO-GROUND LINKS

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ABSTRACT

Optical Direct-to-Ground data links for earth-observation satellites will offer channel rates of several Gbps, together with low transmit powers and small terminal mass and also rather small ground receiver antennas. The avoidance of any signal spectrum limitation issues might be the most important advantage versus classical RF-technology. The effects of optical atmospheric signal attenuation, and the fast signal fluctuations induced by atmospheric index-of-refraction turbulence and sporadic miss-pointing-fading, require the use of adaptive signal formats together with fading mitigation techniques. We describe the typical downlink scenario, introduce the four different modes of data rate variation, and evaluate different methods of rate-adaptive modulation formats and repetition coding techniques.

I. INTRODUCTION

The constantly increasing satellite sensor data volume in future requires new technologies for data repatriation. Also other space applications, like deep-space probes and scientific missions to moon and Lagrange-points, require a dramatic increase in data transmission capacity. The natural next step to leave the congested RF-spectral region will be directed free-space optical (FSO) data links. All major space agencies are pushing developments in this direction, with several space demonstrations and precursor missions running or planned [1], [2], [3], [4], [5]. The specific application of directed FSO in the LEO (Low Earth Orbit) direct-to-earth (DTE) scenario has been investigated in detail since 2006 with the Japanese Kirari satellite and according downlink experiments like KIODO [6], [7].

With channel rates of several Gigabit per second together, at low transmit powers, small optical satellite terminal mass and foremost the avoidance of any signal spectrum regulation issues, Optical LEO Down-Links (OLEODL) will replace conventional RF downlinks in specific applications. The anticipated downlink scenario comprises a small satellite transmitter terminal of some centimetre aperture diameter, together with a medium sized ground receiver terminal telescope of some decimetres diameter. Theoretical investigations with optimum system performance show the potential of this technology, with data rates of around hundred Gigabit per second at transmit powers below one watt [8].

Cloud blockage events must be mitigated by a network of optical ground stations (OGS) located in areas with low cloud occurrence. The specific downlink also faces challenges through the effects of atmospheric signal attenuation in addition to the free-space loss, which allows optimization with a completely variable data rate according to link elevation [9]. Furthermore, it must cope with the fast signal fluctuations induced by atmospheric index-of-refraction turbulence (IRT). Both effects become more severe with lower link elevation angles due to the increased air mass in the link path. IRT-effects on FSO data links, and solutions by coding and varying link parameters have been investigated in detail [10], [11], [12]. Accordingly, variable transmission formats are required to adapt to different spacecraft's needs (like pointing precision and transmit power), to different sized OGS aperture diameters, to different range of link elevations, and to varying atmospheric attenuation conditions. Link parameters to be varied include the channel rate, the modulation format, FEC-overhead, or repetition coding, and physical fading mitigation techniques like aperture averaging. Aspects of the protocol layer have been considered in [13]. Here we will only consider optical intensity modulation and direct detection (IM/DD) with bulk (multimode) photo detectors, as these do not require more complex techniques like adaptive optics, single-mode fiber coupling, or heterodyning receivers.

An optimum transmission format should maximize the overall data throughput - which puts emphasize to the high link elevations - and at the same time support link access also at low elevations for low delay in access.
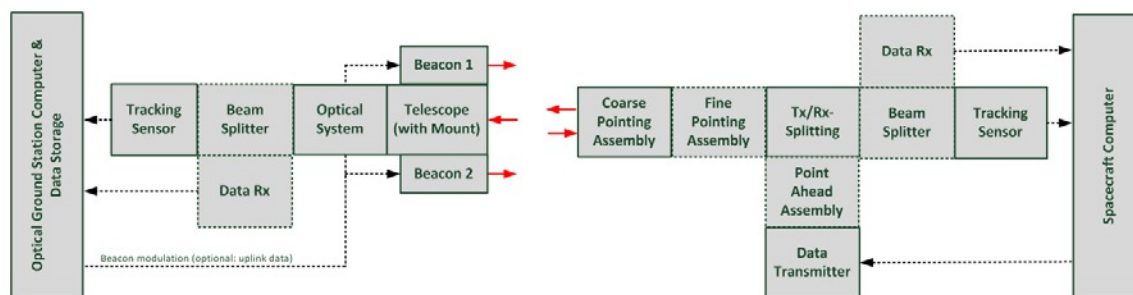

Figure 1: Block diagram of OLEODL-system components. Elements framed by dashed lines are optional.

Figure 1 shows typical components of the ground- (left) and the space-segment (right).

Within the space segment, the light from the OGS-beacon is received with a comparably small coarse pointing assembly (CPA) with wide angular range. Depending on the speed and accuracy of the CPA, a fine pointing assembly (FPA) might be required. An important part is the splitting between Tx- and Rx light. It must enable a sufficient separation between the two signals in order to make sure that the tracking sensor is not saturated by the outgoing light. On transmit side, a point ahead assembly might be required, depending on the orbit and beam divergence. A data receiver may be optionally integrated into the tracking receiver.

In the ground segment, the light from the communication partner is received with a telescope. After the light is forwarded through an optical system it is split to a tracking sensor (enabling closed-loop optical tracking) and a data receiver, before the data is being stored. Typically, two or more beacon lasers will be used as uplink beacons, since - besides achieving higher average power at the spacecraft - the transmitter diversity effect reduces fading at the satellite.

II. BOUNDARY CONDITIONS OF OPTICAL LEO TELEMETRY DOWNLINKS

Typical LEO orbit geometry and according geometrical visibility of exemplary orbits are depicted in Figure 2. Similar to RF-downlinks a minimum link elevation of 5° shall be achieved in OLEODLs. Distances at link start then are 1804 km for the ISS-orbit and 2992 km for the 900 km orbit.
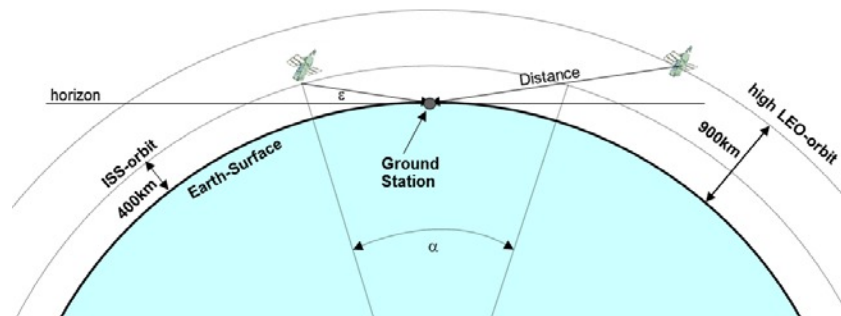

Figure 2: OLEODL link geometry for the 400 km ISS-orbit, and for a 900 km high LEO orbit. Typically, OLEODLs should work above a minimum elevation of ~5°.

Following this orbit geometry an OLEODL will see the three link phases as depicted in Figure 3:

1) *Link Acquisition*: The optical satellite terminal is illuminated by the OGS' laser beacon to enable precise reorientation and pointing of the space terminal towards the OGS.

2) *Tracking and Communication*: The space terminal sends data, OGS receives data and tracks the satellite using the downlink data signal as tracking beacon.

3) *Link Termination*: When the link reaches a minimum elevation angle, the space terminal stops sending data.
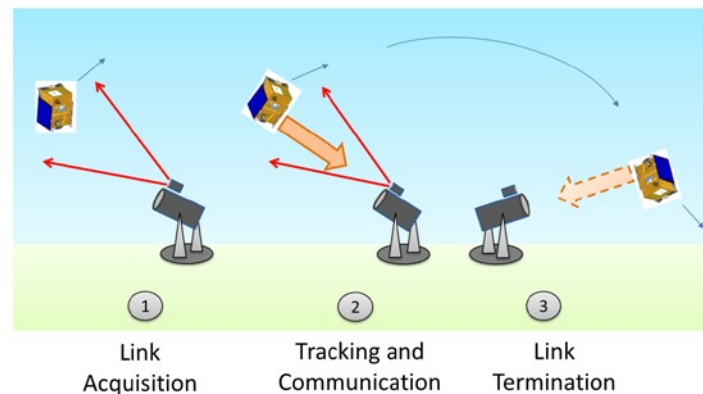

Figure 3: The phases of an OLEODL-Pass

Wavelength selection

Solutions for optical LEO downlinks differ in the system design with monostatic and bi-static designs. While bi-static designs use a separate optical path and aperture for receive and transmit beam, monostatic system designs share one optical system for both.

Monostatic system designs provide advantages in the calibration of the system between receive and transmit path and allow for a more compact terminal especially when using a coarse pointing assembly. However, the wavelength selection for monostatic systems is more challenging compared to bi-static systems where due to separate optics no influence from the transmitter on the receiver and tracking sensor has to be expected. Therefore, bi-static systems allow transmit and receive wavelengths to be very close in the spectrum since no back reflections between the paths have to be considered.

In monostatic systems, depending on the system design and link budget, 30 dBm transmit power or more can be assumed while common tracking sensors have sensitivities of -70 dBm or more. Even with anti-reflection coated optical surfaces, the back reflections of the transmit signal from the optical surfaces can reach values up to 10 dBm which requires a filtering between transmit and receive path of up to 80 dB to achieve a complete separation. To allow filters with the required characteristics, a larger separation of transmit and receive wavelength compared to the bi-static design is required, resulting typically in 30nm band separation.
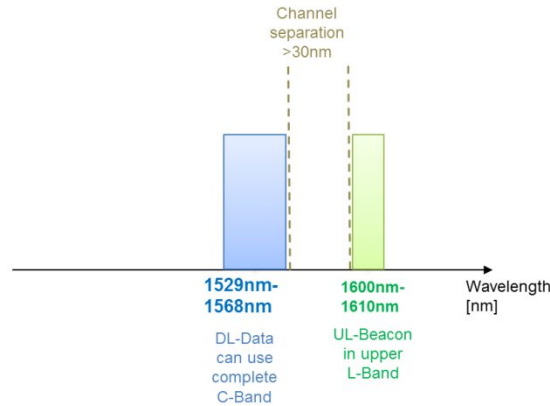

Figure 4: Typical Band-plan for uplink (UL) and downlink (DL)

Figure 4 shows a potential band plan for transmit and receive path (also called uplink (UL) and downlink (DL) seen from the optical ground station) in a LEO scenario. Here, the whole optical C-band (1529 – 1568 nm) can be used for the transmit path (downlink), while the optical L-band (1600 – 1600 nm) is used for the uplink beacon (receive path). This usage of the frequency spectrum in future will also allow techniques like Wavelength Division Multiplexing (WDM) in the C-Band with COTS components.

Cloud Blockage and OGS network

Link blockage by clouds is one of the major influences on optical communication systems which operate within the atmosphere. In order to achieve a good availability of the optical satellite-to-ground link, a network of Optical Ground Stations including sites with good weather conditions is required. Complete operational OGS networks are not available for optical downlinks yet. The optimization of optical ground station networks is also a current field of research. Investigations have been performed for the optimization of ground station networks for optical GEO feeder links [14] and European networks for OLEODL are presented in [15].

Atmospheric Attenuation

The optical attenuation due to absorption and scattering depends on the elevation angle between optical ground station and satellite, as the length of the atmospheric path is longer for low elevation angles. These effects also depend on the wavelength of the signal. Figure 5 shows the atmospheric transmission vs. elevation for a wavelength of 1550 nm. The values have been generated with a database available at the DLR Institute of Atmospheric Physics for a visibility of 23 km and 1550 nm wavelength.
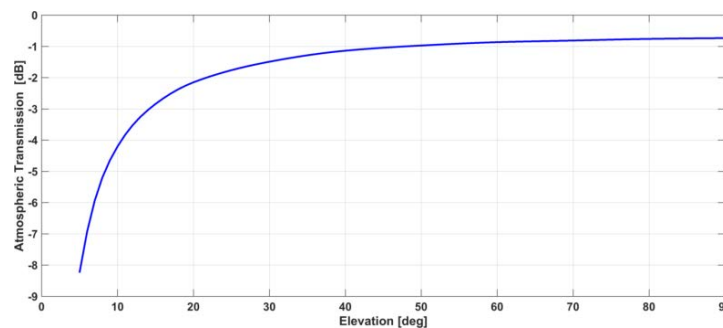

Figure 5: Atmospheric transmission vs. elevation angle.

Scintillation Loss

The atmospheric index of refraction turbulence causes strong fluctuations of the received signal in OLEODLs. These can be more than +/- 6 dB, and have durations between one to several milliseconds – mainly depending on link elevation and Rx-aperture size. The strength of this effect is quantified by the receiver Power Scintillation Index (PSI) (the normalized power variance), as depicted in Figure 9. From the PSI values, together with the assumption of lognormal fading of the power at the OGS, according to [21], one can estimate the loss a_{sci} (Figure 6) that has to be accounted for in the link budget calculation.
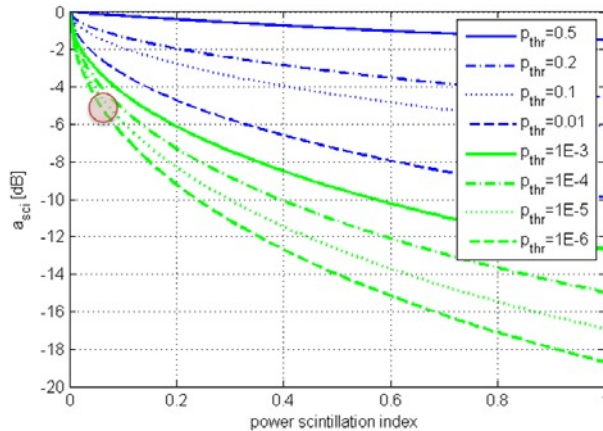

Figure 6. Based on PSI (Power Scintillation Index, including aperture averaging of OGS) and with an allowed loss fraction (here assuming 1E-6 for OLEODL), the according scintillation-loss can be estimated at maximum ~6 dB.

Link Budgets

Figure 7 then shows exemplary link budgets for satellites with orbit heights of 400 and 900 km and different elevation angles. An optical output power of 1 W and an aperture diameter of 40 mm at the spacecraft side are considered. A maximum channel rate of 10 Gbps is considered as can just be received with bulk (multimode) photo detectors. Scintillation loss has been modelled according to Figure 6. A receiver sensitivity of 800 Ph/bit [22] and a standard Reed-Solomon (255,223) code with a gain of about 4 dB at a BER of 1E-6 has been considered. This is a standard code and has a comparably low implementation effort, enabling its use also at higher data rates. The results show very well the need for variable data rates: While a data rate of 10 Gbps is achievable above 10° of elevation for a 400 km orbit, it does not become feasible before 15° of elevation with the 900 km orbit → if elevations below 10° are to be used for data transmission, lower data rates are required.

			400 km Orbit				900 km Orbit			
	Parameter	unit	5°	10°	15°	20°	5°	10°	15°	20°
Tx	mean modulated signal power	W	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	optical Tx loss	dB	-1.49	-1.49	-1.49	-1.49	-1.49	-1.49	-1.49	-1.49
	Tx-divergence FWHM	mrad	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
	Tx-telescope gain	dB	98.19	98.19	98.19	98.19	98.19	98.19	98.19	98.19
	Pointing Penalty	dB	-3.01	-3.01	-3.01	-3.01	-3.01	-3.01	-3.01	-3.01
Comm. System	data rate	Gbps	2.50	10.00	10.00	10.00	1.00	5.00	10.00	10.00
	Wavelength	nm	1550	1550	1550	1550	1550	1550	1550	1550
	Modulation Format	-	IM/DD	IM/DD	IM/DD	IM/DD	IM/DD	IM/DD	IM/DD	IM/DD
	Bit Error Rate	-	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06
	Receiver Sensitivity @ BER	Ph/Bit	800.00	800.00	800.00	800.00	800.00	800.00	800.00	800.00
Channel	link distance	km	1804	1439	1175	984	2992	2568	2224	1947
	Free-space-loss and Rx-telescope gain	dB	-54.14	-52.18	-50.41	-48.87	-58.53	-57.21	-55.96	-54.80
	Scintillation Loss	dB	-5.00	-3.50	-2.50	-1.70	-5.00	-3.50	-2.50	-1.70
	Atmospheric attenuation	dB	-8.00	-4.00	-3.00	-2.00	-8.00	-4.00	-3.00	-2.00
Rx	Aperture Diameter	cm	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00
	Optical Rx Losses	dB	-6.02	-6.02	-6.02	-6.02	-6.02	-6.02	-6.02	-6.02
	Rx-Power after Losses	dBm	-37.21	-29.75	-25.98	-22.64	-41.60	-34.78	-31.53	-28.57
Comms	Splitting Ratio to Comm Sensor	dB	-0.46	-0.46	-0.46	-0.46	-0.46	-0.46	-0.46	-0.46
	Tracking/Coupling Loss	dB	-0.97	-0.97	-0.97	-0.97	-0.97	-0.97	-0.97	-0.97
	Rx-power onto comm-detector	dBm	-34.66	-27.19	-23.43	-20.09	-39.05	-32.22	-28.97	-26.02
	Coding Gain	dB	4.0	4.0	4.0	4.0	3.98	3.98	3.98	3.98
	Required Power (Rx-sensitivity)	dBm	-35.91	-29.89	-29.89	-29.89	-39.89	-32.90	-29.89	-29.89
	Communication Margin	**dB**	1.3	2.7	6.5	9.8	0.8	0.7	0.9	3.9

Figure 7: Link Budgets for satellites with an orbit height of 400 km and 900 km

Summarizing the link budget values from 5° to zenith elevation during one pass (free-space loss, atmospheric loss, and scintillation loss), we find that *for the ISS-orbit variations become ~22 dB, and ~20 dB for the 900km*

orbit. Even higher variations are to be expected in a non-clear atmospheric situation or with smaller aperture diameters than 60cm. This clearly shows the need for rate variation techniques in OLEODL-systems.

III. RATE VARIATION MODES

The overall demand for an optical downlink system is to maximize data throughput while securing access to the satellite at a large range of distances or elevations, respectively. The different OLEODL system sophistication levels require different modes for rate variation in a given OGS-network. We hereby use the term data rate as the user bit rate, or effective sensor data downlink rate. This data rate is different from channel bit rate, and can vary effectively, e.g. through repetition coding, or variable FEC-overhead, while the channel symbol rate might stay constant or again vary in a different way, dependent on change of modulation format.

Altogether, we can discern four different modes why and how the effective data rate can change (Figure 8):

1. The simplest mode is defined by a satellite transmitter with a fixed data rate. This rate is fixed per mission, but can change in between missions. Since one OGS must be able to serve different satellites, the OGS must adopt its modulation format and channel rate, while a single mission will not. A minimum elevation that will ensure sufficient reception quality with a specific OGS-aperture size can be derived for each mission.

2. According to a specific pass-geometry, an optimum fixed data rate can be predetermined, that will maximize data throughput in the specific pass. This rate is mostly given by the maximum pass elevation. This mode precludes that the satellite terminal can change its transmit rate from pass to pass.

3. Taking into account the free-space loss, atmospheric attenuation, and IRT-scintillation strength as a function of link elevation, a maximum rate per elevation angle can be predetermined and programmed into the link-planning. A secured link can however not be assured, since contingent events like intermittent cloud blockage or links losses cannot be excluded, as also in modes 1 and 2. This fact will always require according error correction techniques.

4. With additional channel sounding – e.g. of the uplink beacon signal (influenced by atmos. attenuation, cloud blockage, strength of scintillation) – the quality of the downlink channel can be estimated by the satellite terminal, and thus the downlink data rate can be optimized accordingly for each part of the downlink pass. Intermittent link losses can be detected and the presumably lost data can e.g. be retransmitted or stored for the next downlink. This very flexible mode however requires a level of sophistication that might not be available in most near-future OLEODL systems.
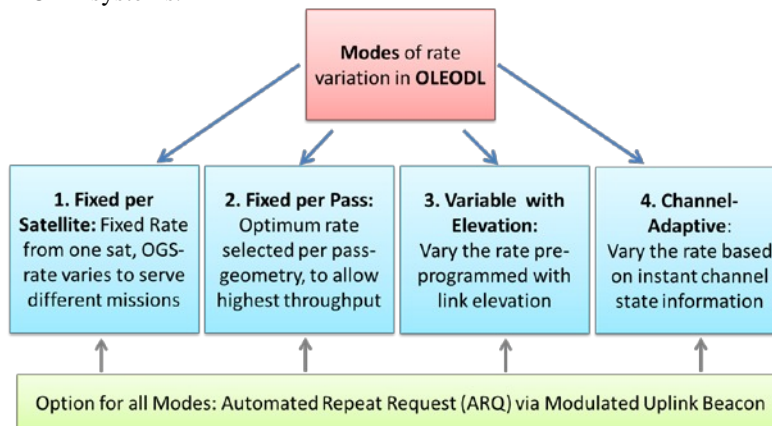

Figure 8. The four modes for varying the data rate in an OLEODL system

IV. ADAPTIVE SYSTEM COMPONENTS

Receiver Aperture Averaging for Fading Mitigation

The choice of the suitable receiver aperture size for the ground segment is crucial for the overall system performance and cost. Currently deployed telescope sizes of ground segments from DLR, Tesat, NICT, and NASA-JPL range from 27 cm to 1.5 m [16], [17], [18], [19]. Rx signal fluctuations can be reduced by aperture averaging, with receiver apertures larger than the intensity correlation width. Aside the antenna gain, the specified tolerable fading loss determines the maximum allowed signal fluctuation and therefore minimum aperture size for a given location and atmospheric condition. For an exemplary ground station near Munich, the expected power scintillation index ranges from ~0.004 at 55° elevation to ~0.3° at 5° elevation at a

measurement wavelength of 847 nm and 40cm aperture. In terms of fading loss, this translates to between 1 dB and 11 dB at a threshold of 1E-6 (compare Fig. 6). These values are derived from an average of several individual measurements during nighttime satellite overflights [20]. Figure 9 shows the measurements with the 40 cm aperture (orange line and marker) and with an additional 5 cm aperture (blue line and marker). The solid lines denote model calculations for comparison with the measurements and to show the expected power scintillation index for apertures varying from 5 cm to 60 cm. The graph also shows the decrease of the PSI by use of 1550 nm transmission wavelength. It must be mentioned that the model evaluations are only valid above 20° elevation due to the limitation of weak fluctuation theory here. This explains the strong deviation of the 40 cm measurement below 20°. A scaled Hufnagel-Valley-5/7 model is used as C_n^2-profile. The scaling factor is directly multiplied with the standard $HV_{5/7}$ and selected to obtain minimum residual error with the power scintillation measurements above 20°.
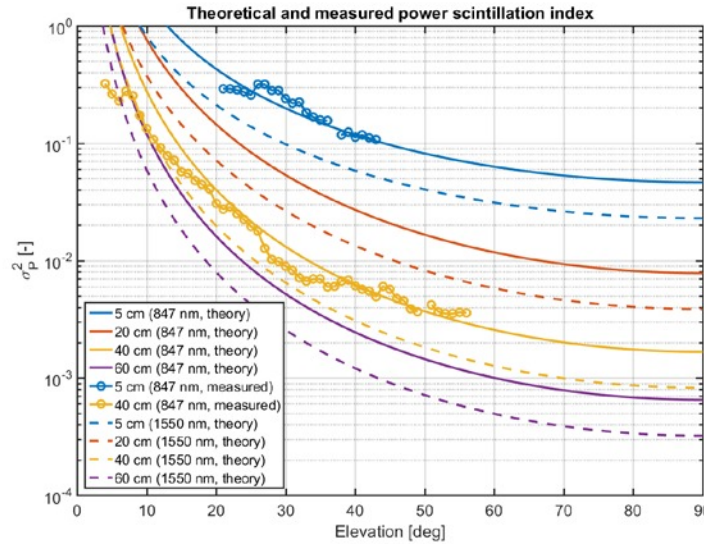

Figure 9. Power scintillation index versus link elevation with different receiver aperture diameters, wavelengths of 847 nm and 1550 nm, for an exemplary downlink scenario.

Variable Channel Rate Techniques

One of the most effective ways to cope with variable link budget conditions in space communications is to lower the data rate [23]. This technique maintains the link even under difficult conditions - although at lower data rates - instead of completely loosing communication. Various techniques to vary (lower) the data rate have been investigated and some of the simple techniques are discussed below with the help of Figure 10. Each technique is evaluated in terms of receiver sensitivity calculated as number of photons required per bit for certain BER performance and the result is summarized in Table 1. The sensitivity depends upon whether peak-power limited (PPL) or average-power limited (APL) transmitters and different receiver models namely, shot-noise limited (SNL), avalanche photodiode (APD) and thermal limited (PIN).

Longer bit-lengths:

For non-return to zero on-off keying (NRZ-OOK) modulation, data rate can be lowered simply by transmitting pulse for longer duration, when the channel gets challenging. For e.g. transmitting pulse of duration "*2w*" instead of "*w*" will reduce the data rate by half. This technique is simple and provides flexibility to lower the data rate by larger factors. However, also receiver bandwidth needs to be adapted accordingly to ensure optimum receiver sensitivity with non-SNL receivers.

Variable Modulation Formats:

Channel data rate can also be varied by changing the modulation formats. For e.g. using Return to zero (RZ-n) on-off keying (OOK) instead of NRZ-OOK with same pulse duration reduces the channel data rate by factor "*n*". This is because when using RZ-n, if the pulse duration is kept constant as that for higher data rate, the symbol duration increases by factor "*n*". Similarly, with added complexity and limited data rate reduction factors, PPM-L (Pulse-Position-Modulation) can be used instead of RZ to reduce the data rate by factor=$\frac{L}{log2L}$. .
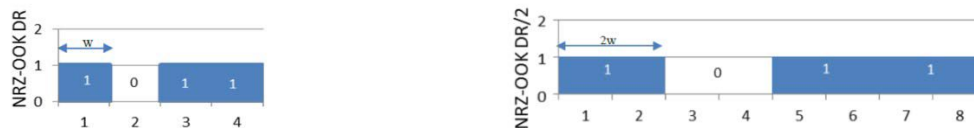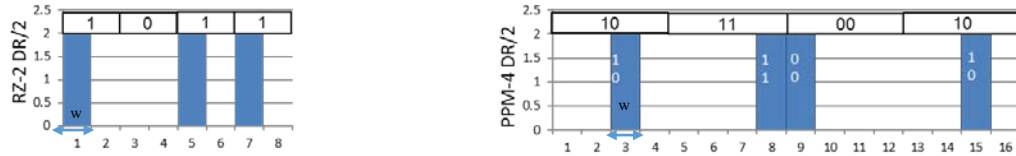
Figure 10. Channel data rate variation by using different methods. DR = maximum data rate, w = pulse duration. Vertical axis shows the relative amplitude of the signal and horizontal axis shows the relative time.

Table 1. Summary of various options to vary the data rate and its performance [24]. For complexity, 3 is most complex

Options	Factors (~up to)	Rx sensitivity	Tx type	Complexity
NRZ-OOK	any	Constant for SNL, bad for APD, worse for PIN	APL/PPL	1
RZ-OOK	8-16	Remains constant for all Rx types	APL	2
		Decreases for all Rx types	PPL	
PPM-L	4-8	Increases for all Rx types	APL	3
		Decreases for all Rx types	PPL	

Variable FEC-Protection and Interleaving

According to [25] a variety of channel codes can be used for standard RF satellite downlink. In a first approach one would apply these also to OLEODL and chose different coding strengths to enable various levels of coding gains. However, as the characteristics of the transmission channel for optical links deviate strongly from the RF domain, existing RF transmission formats might be non-optimal and their use must be carefully considered.

Such bit-level coding may be used for an overall improvement of the link budget w.r.t. uncoded transmission. However, to compensate link outages due to fading – with fade durations of several ms – FEC must be combined with a long interleaver length, i.e. large memories with fast access times are required, increasing the complexity of the system.

Variable Repetition Coding Techniques

Channel rate (and thus the receiver frontend) can stay constant by simply sending the packets two or more times. This reduces the data rate by factor equal to the number of retransmissions. In the atmospheric fading channel, the repetitions must be separated by a delay larger than the typical fade length, a technique called *delayed-frame repetition*. Additionally, FEC and soft decoding techniques can be combined to further improve the system sensitivity. The received frames can be treated in different ways, while the format stays unchanged:

- Repetition coding with hard-decision and different selection algorithms: Receiver selects the packet-instance whose SNR is highest or which has no remaining bit-errors after decoding. By comparing the bits of two packet instances, erasures can be marked, further improving error decoding. If an uneven number of packets are sent, majority-decision of the bits can be applied.
- Repetition coding with soft combining: samples of the received data stream are buffered and combined with additional instances by equal-gain-combining or maximum-ratio combining, thereby increasing the signal to noise ratio before decoding.

V. SUMMARY AND OUTLOOK

We have described technologies to be applied in future optical LEO-satellite telemetry downlink systems. The scope is on low complexity and low cost of implementation, and thus we leave out several techniques that but can be considered in mid-future. These are namely the application of *adaptive optics* in the OGS to enable coupling of the received field into single mode fibers, which again allows more sensitive OOK receivers (using optical preamplifier) and higher order coherent modulation formats with heterodyning. Also to be considered is *Automated Repeat Request* (ARQ) in a two-way communication system, and *Wavelength-Division Multiplexing* (WDM) for further data throughput expansion. *Packet-level-coding* is an efficient higher-layer method to bridge long erasures through fades, without using bit-level interleaving.

With the massive effort currently going into the development of optical space communications we will see operational implementations of OLEODL-systems soon. The international coordination of data formats and modulation techniques is therefore crucial to enable global cross-support and efficient use of international

ground station networks. The Consultative Committee for Space Data Systems (CCSDS) therefore has established a working group to standardize optical space links.

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