

Performance analysis of Variable Data Rate System for Free Space Optical Low Earth Orbit to Ground Scenario

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ABSTRACT

The Free Space Optical LEO downlink scenario will enable an enormous increase in data throughput from Earth observation and communication satellites, through its vastly higher data rates. Further advantages of directed optical links is secure key transfer for QKD satellite link, inter-satellite link for data relay, secure communication through minimized signal spread, and more. However, the LEO downlink channel is challenging due to elevation dependent free space loss and atmospheric effects such as absorption and scintillation. Various techniques like adaptive optics, aperture averaging, use of complex coding and very long interleaver techniques, are being used and studied to mitigate such effects. However, the implementation of such complex and expensive solutions for a constant-data-rate system (CDR) is often an additional overhead for the variable channel, as it has to be designed for the worst channel condition, which is around the lowest elevation angles. Therefore, we propose the variable-data-rate (VDR) system as a solution for such a varying channel, where the data rate can be adapted according to the channel conditions dependent on elevation. In this paper, a LEO-to-ground scenario is selected for detailed analysis and a VDR system is designed whose performance is compared with the CDR system for which the optimum data rate and start elevation angle are selected by maximizing the overall throughput. Some literature reports that the VDR system has a factor of 3 advantage over the optimal CDR system, and in this paper, we evaluate this situation in a more practical approach using the STK simulations and Matlab evaluations.

Keywords: Variable Data Rate (VDR), Constant Data Rate (CDR), Optical LEO Downlink (OLEODL), Free space Optical Communications (FSO), Optical Link Budget, low satellite elevation angle

1. INTRODUCTION

Free space optical communication provides several advantages like higher data throughput, secure data transfer and more. However, the channel is very challenging because of elevation dependent free space loss and turbulence. There are various mitigation techniques like use of very high rate coding and interleaving, adaptive optics, using very large telescopes etc. One of the smarter ways is to use variable data rate techniques for such a varying channel as it allows optimum use of the link time and complexity [1][2][3]. One of the simple way to apply variable data rate (VDR) system is to fix the data rate as per the elevation. This paper will report on the simulation of one of the LEO to ground scenario using VDR system and compare the throughput gain with constant data rate (CDR) system. The main objective here is to assess the advantage of Variable Data Rate (VDR) [1] for Optical LEO to Ground links compared to a Constant Data rate (CDR) system with the help of software simulation tools. The first part of the study shall be focused on modelling the statistics of two selected satellite orbits, key optical channel effects like atmospheric attenuation, turbulence effects etc., the link budget for different sectors of the LEO pass and finally collect the key performance indicators related to throughput and data return. The performance of the O3K waveform because of the non-ideal behavior of the receiver should also be considered. Performance of the VDR system should be compared for all scenarios against CDR system to understand that the implementation of VDR system is worth the additional complexity and digital signal processing power.

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For the simulation NRZ OOK modulation scheme is considered. For simplicity, the Reed-Solomon (255, 223) is considered as the coding scheme which is one of the standard codes in CCSDS O3K [4] and block- interleaving is considered for the simulation. Variable data rate (VDR) technique is used as mitigation technique to cope with elevation dependent atmospheric attenuation and free space loss in LEO to ground scenario. In this project, a VDR system is designed and performance is evaluated and compared with the constant data rate system. For particular example link scenario different elevation sectors and optimum data rate (data rates defined in CCSDS O3K standard) are identified as allowed by the link budget and maximizing the throughput. Simulations have been

performed to understand the performance of VDR for particular channel and finally a Constant Data Rate (CDR) system is designed and throughput is compared.

2. SCENARIO DEFINITION

For the study two satellite orbits namely, ISS and near polar orbit of Sentinel-1 was chosen. And three ground stations Svalbard, OGSOP, Tenerife were selected as shown in Table 1. However, in this paper only results for OGSOP to Polar orbit scenario are presented.

Table 1. Selected satellite orbits and ground stations for the study.

Selected Satellite Orbits	Selected Ground Stations
ISS Orbit: Inclination 51.6°, Height: 410 km	Svalbard: 78.2167° N, 15.3833° E, 458 m
Polar (Sentinel 1): Inclination 98°, Height 693km	OGSOP: 48.0847° N, 11.278° E, 650 m
	Tenerife: 28.301°N, 16.5118° W, 2395 m

Using the STK simulation tool, elevation distribution of each scenarios has been evaluated. The Figure 1(left) below shows the visibility of satellite in polar orbit from different ground stations normalized to the ground station Svalbard, as it has the highest geometrical contact time due to its geographical location. It can be seen that for roughly 50% of the time, the contact to the satellite remains below 10° for all the ground stations. This signifies the importance of lower elevation for optical LEO downlink scenario [6]. Similarly, the Figure 1(right) shows the probability distribution function of pure geometrical visibility for reference ISS Orbit and two ground stations (OGSOP and Tenerife). This shows the importance of the data downlink during the lower elevation areas which are normally neglected because of higher attenuation and higher turbulence for lower elevation region, highlighting the importance of variable data rate technique that allows the transmission at lower elevation range although at lower data rate.

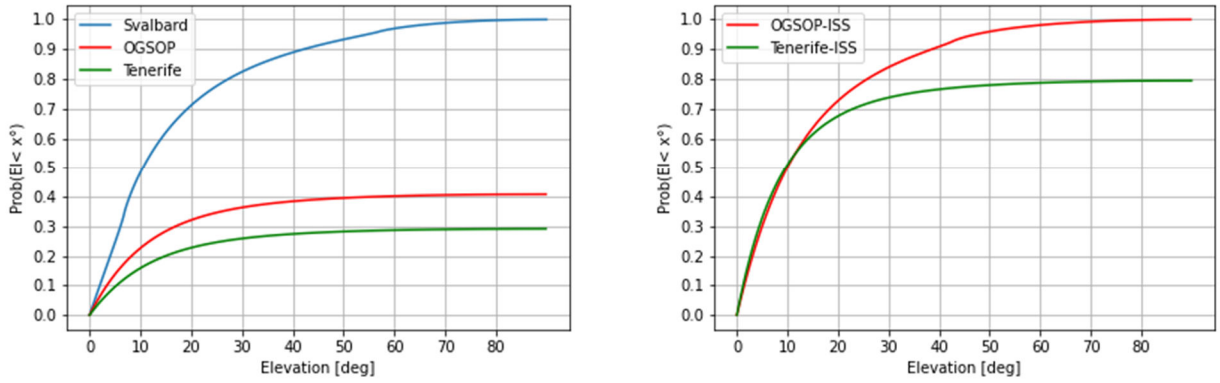


Figure 1. Left: Elevation occurrence of satellites in **polar orbit** from Svalbard, OGSOP (near Munich) and Tenerife, normalized to Svalbard. Right: Visibility of a satellite in **ISS orbit** from OGSOP and Tenerife (normalized to OGSOP) (Svalbard is not visible underneath the ISS orbit)

As mentioned earlier, one of the biggest challenges in OLEODL channel is elevation dependent atmospheric attenuation by aerosols like dust, ash, pollen, and haze. For the 1550nm spectral region (and when avoiding narrow but strongly absorbing molecular resonance lines), such transmission is typically close to 1 in zenith direction (in our example 0.94), but due to the increased air-mass in the link path at lowering elevations, it becomes significant below $\sim 10^\circ$, as seen in Figure 2 for OGSOP to Polar scenario.

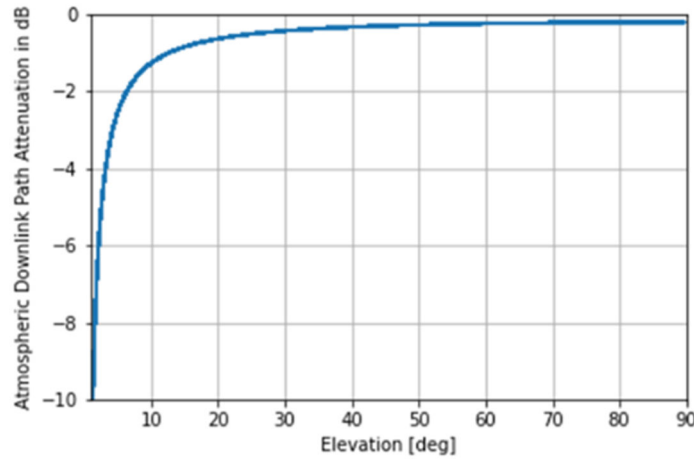


Figure 2. Atmospheric attenuation vs elevation for OGSOP to Polar scenario, with a zenith transmission of 0.94, compare calculation method from [8].

The specific simulation conditions for link budget calculation are summarized in Table 2. The details on the calculation of the link budget is summarized in the paper [6] [7]. Modulation speed depends on overall available power onto the data detector, defining the elevation windows for each data rate.

Table 2. Link Budget Parameters of a VDR-LEO-downlinks at 1550nm wavelength for Sentinel in 693km height.

<i>Parameter</i>	<i>unit</i>	<i>value</i>	<i>additional info</i>
<i>Tx-power</i>	<i>W</i>	0.5	+27 dBm
<i>data rates</i>	<i>Mbps</i>	312 / 625 / 1250 / 2500 / 5000	3 or 5 data rates, scenario dependent
<i>elev. steps for var. data rates</i>	<i>degree</i>	from 6° / 10° / 22° / 31° / 49° on	for data rates as in line above
<i>Tx-internal losses</i>	<i>dB</i>	-2	surfaces and obscuration
<i>Tx divergence</i>	<i>μrad</i>	200	FWHM
<i>mean pointing loss</i>	<i>dB</i>	-1.29	mean loss
<i>distance</i>	<i>km</i>	693 / 707 / 2545	zenith / 78° elev. / 5° elev.
<i>atmos. loss (Tz=0.94)</i>	<i>dB</i>	-0.27 ... -3	from zenith to 5° elev.
<i>scintillation loss</i>	<i>dB</i>	-0.5 ... -2.1	zenith ... 5° elev.
<i>OGS telescope diameter</i>	<i>cm</i>	60 / 20	outer, and inner obscuration
<i>Rx internal losses to RFE</i>	<i>dB</i>	-3	surfaces and for tracking
<i>req. Photons/bit</i>	<i>l</i>	500	for BER=1E-4
<i>link margin</i>	<i>dB</i>	-3	regarded as additional loss
<i>min. sensitivity of RFE at var. data rates</i>	<i>nW</i>	20 / 40 / 80 / 160 / 321	for the rates stated in third line above
<i>opt. signal power onto RFE</i>	<i>nW</i>	577	at zenith

This set of parameters defines the received power onto the data detector in the OGS vs elevation is shown in figure 3.

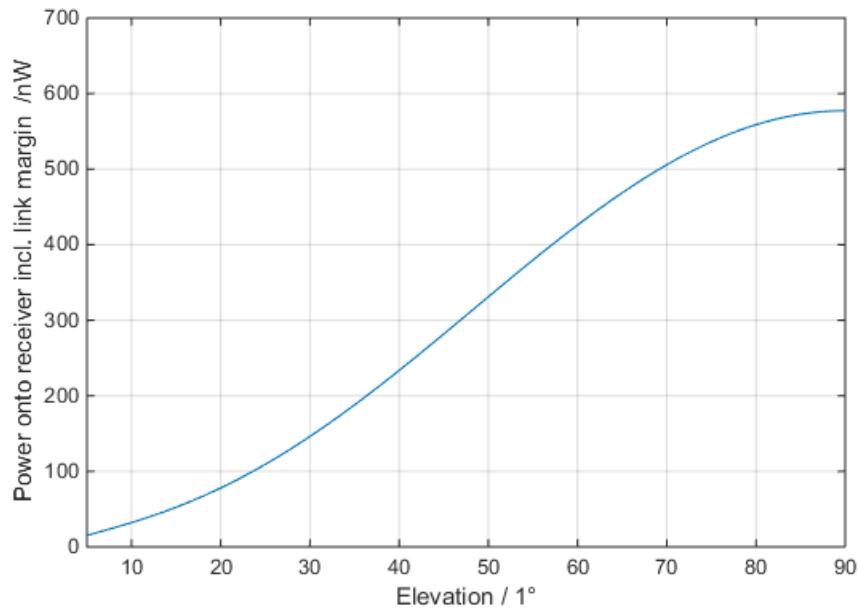


Figure 3. Optical power received by the data detector, according to Link Budget calculation.

3. GENERATING POWER VECTORS FROM CHANNEL MODEL AND ORBIT

For the simulation of the variable data rate technique, time series of the received optical power were generated for the full path of selected scenarios, assuming two different passes: one with high maximum elevation of 78° , and another pass with lower elevation of 32° . The details on the generation of power vector are described in [5]. Some examples of such power vectors for particular scenarios are shown below.

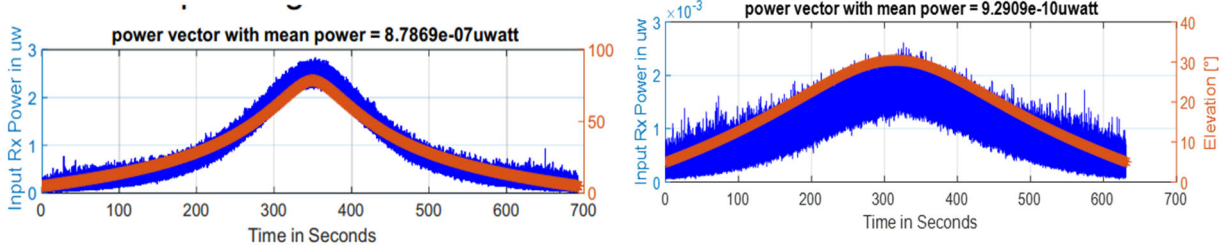


Figure 4. OGSOP to Polar scenario - pass with maximum elevation of 78° (left- pass 1), pass with maximum elevation of 32° (right- pass 2).

These time series include all link budget losses and gains – static, elevation-dependent, as well as dynamic – as they are described in Table 2.

4. ELEVATION SECTORS AND OPTIMUM DATA RATE FOR VDR SYSTEM

For defining the VDR system initial elevation sectors were estimated by analytically calculating the transmissible data-rate vs elevation for each scenario. See an example for OGSOP to Polar scenario in Figure 5.

Assuming 5Gbps of data transmission at highest elevation range, different sectors have been identified where the data rates are given by $r = 5\text{Gbps}/2^k$ with $0 \leq k \leq 4$ as per the CCSDS standard [4]. The optimum data rate for the sectors are calculated on the basis of link budget and maximum throughput for the sectors. The simulation for the whole pass considering different data rates and defined sectors were done using the power vectors for the particular scenario.

NOTE: same transmit power of 27dBm is used for each scenario, and 5Gbps can be transmitted in highest elevation window.

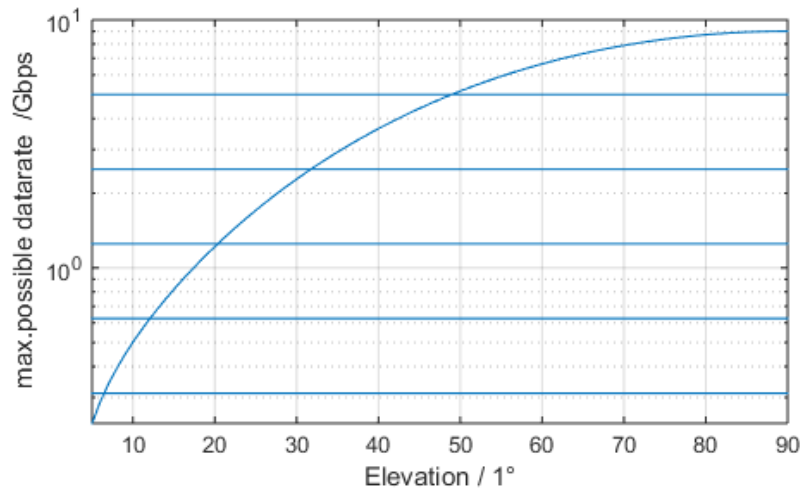


Figure 5. Normalized bit rate vs elevation for OGSOP to Polar scenario assuming general path with maximum elevation of zenith.

Finally, using the estimated elevation sectors simulations were done and sectors were slightly changed to optimize the BER performance of the overall system. The final result is shown in Figure 7. The detailed calculation is out of scope of this paper however was done for the study and final optimum elevations are stated in Table 3.

Table 3. Elevation sectors and optimum data rates for Pass 1 and 2 of OGSOP to Polar scenario.

Pass 1: OGSOP to 693km orbit (polar) with higher max. elevation and without pointing error						
Elevation sectors	deg	6-10	10-22	22-31	31-49	49-78
Data rate (DR)	Mbps	312.5	625	1250	2500	5000
Pass 2: OGSOP to 693 km (polar) with lower max. elevation and without pointing error						
Elevation sectors	deg	4-11	11-26	26-30		
Data rate (DR)	Mbps	312.5	625	1250		

5. SIMULATION RESULTS

Effect of Interleaver for the channel

One of the obvious solutions for mitigating the challenging channel condition is adding high order coding and interleaving schemes. However, this adds complication for the higher elevation sectors, where it is not required.

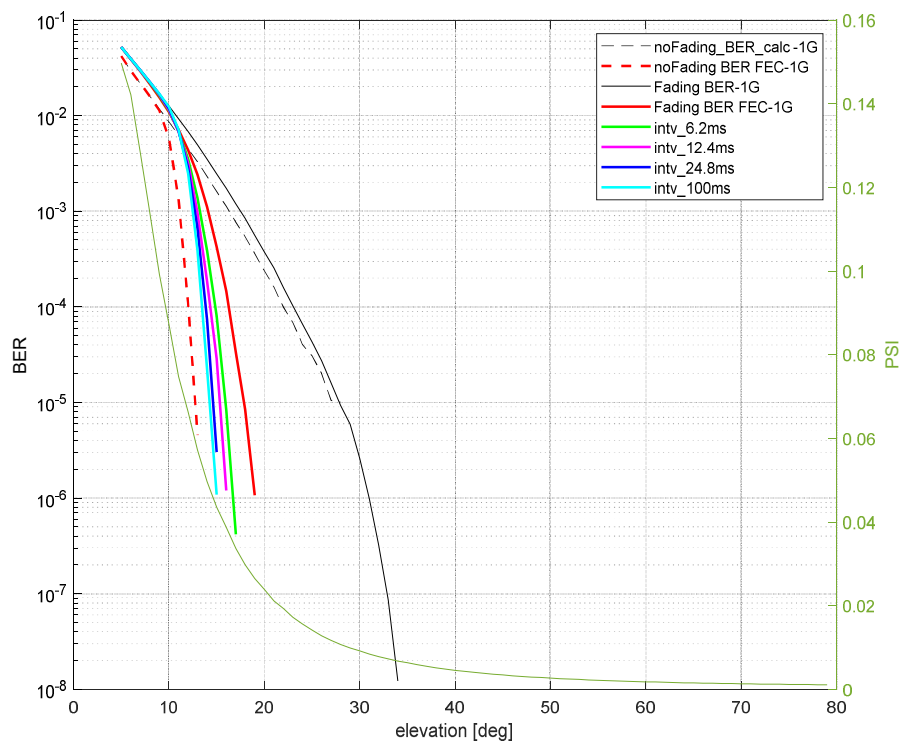


Figure 6. Performance of the system using interleavers of different lengths for selected scenario.

It can be seen that for the channel, the performance improves with the interleaver size. However, the gain because of interleaver saturates and not much gain is seen for the interleaver size of 100ms compared to that of 24.8ms. The data rate used is constant data rate of 1Gbps for all the elevation angles. It can be seen that to achieve the $BER < 1E-6$ the system without interleaver requires the elevation angle to be $\sim 19^\circ$. However, the system with interleaver of 100ms is error-free ($BER < 1E-6$) already at elevation angle of $\sim 14^\circ$. This means that even for the system using 100ms of interleaver the error-free transmission can only happen after 14° .

Constant Data Rate vs Variable Data Rate system

The paper [9] accesses the long-term throughput of optical links between a circular-LEO satellite and a ground station for CDR and VDR systems. This paper has been used an initial basis to understand and access the performance. For the CDR system a minimum elevation angle is calculated to maximize the throughput and ideal adaptive data rate system is considered to evaluate the VDR system. The evaluations are done analytically with some assumptions and the paper claims the VDR system provides 3 times higher throughput compared to the constant data rate system. The details on the calculation is explained in the paper [9]. In order to compare the result of the paper to our simulation and for our scenario, the throughput for the CDR and VDR system designed as per our simulation in earlier sections is used. It should be noted that the calculation is done only for particular scenario i.e. OGSOP-to-Polar high elevation pass (max of 78°) without pointing error. The result is summarized in Table 4. The BER performance of the VDR vs 1G system is presented in Figure 7. Finally, the throughput for the designed CDR and VDR system for both passes (one with high elevation and the one with lower elevation) is calculated and summarized in Table 4 and Table 5.

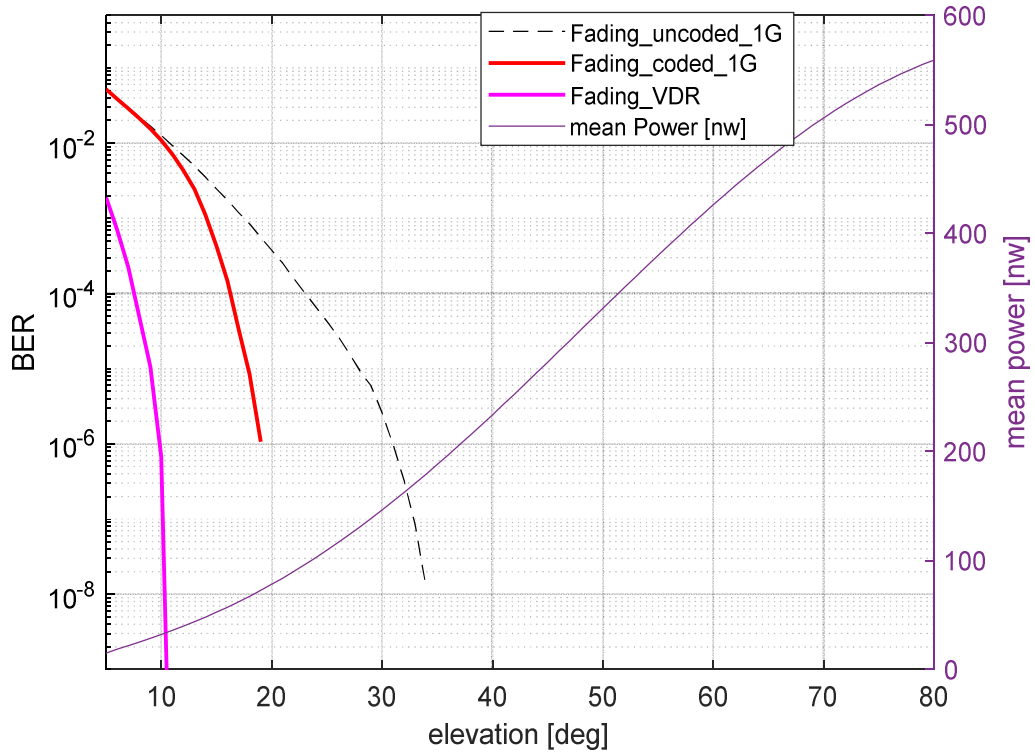


Figure 7. The performance of VDR vs CDR 1G system for the selected channel.

Table 4. Throughput of CDR system with different start elevation, and VDR system, for *OGSOP-to-Polar high elevation pass*.

CDR/VDR	elevation	Data rate [Mbps]	Duration [s]	Data volume [Gbps]	Throughput [Mbps]
CDR1	6°-78°	312.5	673.58	210.5	312.5
CDR2	10°-78°	625	582	363.75	540.9
CDR3	22°-78°	1250	376	470	697.8
CDR4	31°-78°	2500	279	697.5	1035.5
CDR5	49°-78°	5000	144	720	1068.9
VDR	4°-78°	312.5-5000	673.57	1299	1928.4

Table 5. Throughput of CDR system with different start elevation, and VDR system, for *OGSOP-to-Polar low elevation pass*.

CDR/VDR	elevation	Data rate [Mbps]	Duration [s]	Data volume [Gbps]	Throughput [Mbps]
CDR1	4°-30°	312.5	606.14	189.418	312.5
CDR2	11°-30°	625	484	302.5	499.1
CDR3	26°-30°	1250	172	215	354.7
VDR	4°-30°	312.5-1250	606.14	405.04	668,2

For CDR system, different start elevation angles are considered. For simplicity, first elevation angle of each sectors is only used as options for start elevation angle for CDR system. For VDR system the defined sectors and data rates are stated in Table 3. The data rates used are one of the options from the CCSDS O3K physical layer standard.

For high pass link, it can be seen from the table that among all options of CDRs, CDR5 has maximum throughput although the starting elevation is 49° because of higher data rate. Comparing the most optimum CDR (i.e. CDR5) with VDR system, for this particular case, VDR seems to have 1.8 factor better throughput. It is comparable to the study presented in [1].

For low pass link, among all options of CDRs, CDR2 has maximum throughput and comparing it with VDR system for this particular case, VDR seem to have 1.3 factor better throughput. The advantage is observed lesser compared to the high elevation pass because the elevation ranges are lower and also the number of sectors is less.

However, these performance factor cannot be generalized for all cases and is only valid for this particular pass where the maximum elevation angle is 78° for the first case and 30° for the second case, which is not always the case. As an outlook, we should also consider the probability distribution of elevation for better general comparison.

6. CONCLUSION & OUTLOOK

Variable data rate is one of the optimum solutions to cope with the varying link budget as per elevations in optical LEO-to-ground links. This not only improves the performance of the system but also increases the overall throughput by maximizing the link time. In this paper, the performance of the variable data rate (VDR) system including FEC was simulated for different optical LEO to ground scenarios and results are compared against constant data rate (CDR) system. It has been seen that VDR system has 1.8 factor higher throughput compared to the CDR system for high elevation pass and 1.3 factor for lower elevation pass. However, these results are for only two specific scenarios, and for general throughput assessment, more passes and scenarios must be considered. Furthermore, the local cloud coverage can be considered in an advanced type of assessment. In [10] two years of cloud images with temporal resolution of 30s are employed to assess the availability of specific satellite orbits over Alemeria OGS-location, but without considering FEC and for daytime-data only. An operational situation would require the combination with an all-sky imager for clouds at night as well as the satellite signal. In current assessment of VDR vs CDR system the cloud coverage was not included because it affects both systems in a similar way.

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