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Protection schemes for optical communication between optical ground station and a satellite

Sylvain Poulenard^{a1}, Benjamin Gadat^a, Lyonel Barthe^a, Ronald Garzón-Bohórquez^b

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ABSTRACT

Forward Error correcting Code design (FEC) and implementation for optical feeder link is reported. The designed LDPC codes present very good performances ($BER < 10^{-9}$) while requiring less than 20% hardware resources of FPGA compatible with space constraints. Protection scheme based on these LDPC codes combined with a physical layer bit interleaver is presented. Links sizing for GEO optical feeder link at 30° elevation angle under strong turbulence shows that uplink might require up to 100W per link.

Keywords: Optical Communications, Optical Satellite Feeder Link, Forward Error Codes

1. INTRODUCTION

Digital optical communication links are currently operational since 2016 for inter-satellite links in the European Data Relay System [1].

Since 2010, digital optical communication links at 1.55 μ m are foreseen to be a valuable alternative to the conventional radio-frequencies links between the spacecraft LEO/GEO and a fixed Earth ground station for missions such as Internet delivery, Earth observation data download, and Deep Space data download. Such links presents the technical challenge of crossing the atmosphere where clouds and turbulences impair the transmission. Regarding LEO Earth observation downlink and Deep Space data download, the Consultative Comity for Space Data System (CCSDS) set up few years ago working groups for standardization of such optical links [2], and demonstrations have been/ are running in many countries [3-6]. Regarding the mission of broadband access for Internet delivery, European space agencies and European Commission have financed system studies to evaluate technological feasibility of GEO optical feeder links since several years [7-8]. In 2016, the European Space Agency has launched the HydRON (High Throughput Optical Network) project targeting optical interconnections in the Tbps regime for inter-satellite links and feeder links [9].

For such GEO feeder links, the optical band presents the advantages of tremendous bandwidth capacity and no interference but also the drawbacks of being blocked by clouds and strongly distorted by the atmospheric turbulence when it crosses the atmosphere. Cloud blockages are commonly mitigated by site diversity between Optical Ground Station (OGS) geographically spread over the coverage area [8]. Atmospheric turbulence impacts are mitigated thanks to the implementation of adaptive optic system at each OGS reducing signal power fading [10-11] and thanks to the usage of a protection scheme to retrieve the information while the transmission has been corrupted by errors. Joint optimization between adaptive optic system and protection scheme is required to properly design and operate the link. Such optimization shall be compatible with space constraints in particular available power consumption/dissipation.

The paper is organized as follows: §2 presents the mission scenario, §3 describes the atmospheric transmission channel with adaptive optic system, §4 selects a protection schemes based on a physical layer interleaver and an error correcting codes, §5 provides the performances of error correcting codes designed to be compatible with space constraints of feeder links, §6 provides optical link sizing and space hardware resources required for encoding/ decoding, §7 is the conclusion.

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2. MISSION SCENARIO

Figure 1 depicts the mission scenario. A geostationary satellite provides broadband internet access to the end-users. The bidirectional link between the GEO and the fixed Earth station is the feeder link. The feeder link is a $1.55\mu\text{m}$ laser link between a 60cm Optical Ground Station (OGS) and 26cm On-Board Optical Terminal (OBT). Both terminals are monostatic. The OBT uses the same primary mirror for transmission (Tx) and reception (Rx). The OGS uses the full 60cm diameter primary mirror for reception and a part of it (20cm) for uplink transmission.

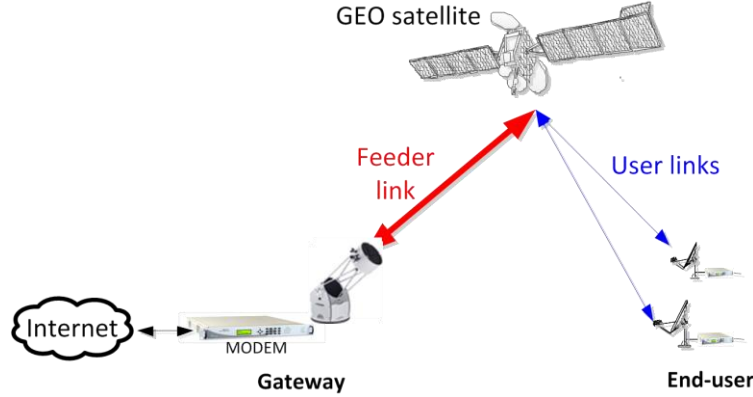


Figure 1: Mission scenario - the feeder link is the bidirectional link between the GEO satellite and the fixed Earth station gateway. The user links are classical radio-frequency links.

The specificity of the On-Board Terminal is due to space constraints to achieve 15 years lifetime on the GEO orbit. Such space constraints limit the hardware available. In particular, to the authors' knowledge, no space qualified Analog-to-Digital Converter (ADC) compatible with 10Gbauds signals are available on the market. As a consequence, hard inputs for the decoder are considered. For the OGS, we consider soft input quantified on 6 bits or more for the decoder.

Table 1: Optical terminal characteristics

	On-Board Terminal	Optical Ground Station terminal
Optical Head	26cm (Tx and Rx) with fine pointing mirror. Monostatic architecture.	60cm for Rx and 20cm for Tx with adaptive optic system. Monostatic architecture.
Decoder inputs	Hard inputs	Soft inputs on ≥ 6 bits
Communication chain	10Gbps NRZ OOK or DPSK [24]	10Gbps NRZ OOK or DPSK [24]

3. ATMOSPHERIC TRANSMISSION CHANNEL

3.1 Atmospheric turbulence strength

Atmospheric turbulence strength varies function of sites locations, season, hours, minutes... etc. Statistics relevant for GEO feeder link should cover Fried parameter, anisoplanetic angle, wind speed. Such data is only partially available for some sites, mainly astronomical sites. Different initiatives over Europe aim at fulfilling this lack of data. [19] derives C_n^2 profile from ECMWF data (European Center for Medium Range Weather Forecasts). Nevertheless there are still some uncertainties on the capability of such model to derive accurate statistics. ESA adopted a site survey approach consisting into deploying a network of instruments able to retrieve C_n^2 profile of day and night [21]. Before such data bank being available, Airbus DS and ONERA-DOTA have jointly worked to define a nominal case and a strong case of atmospheric turbulence strength. Such work was performed in 2019 on the C_n^2 profile data bank provided by J. Osborn from Durham University [22].

Table 2: Turbulence parameter function of strength, from nominal case to strong case

Turbulence strength	Nominal	Strong
Fried parameter at 1550nm on the line of sight	12cm	4cm
Anisoplanatism angle at 1550nm on the line of sight	26 μrad	11 μrad

3.2 Power attenuation time series due to turbulence

Power attenuations time were computed by ONERA-DOTA. Such time series take into account propagation through the turbulence atmosphere and adaptive optic system, the principle of numerical computation is explained in [23][25].

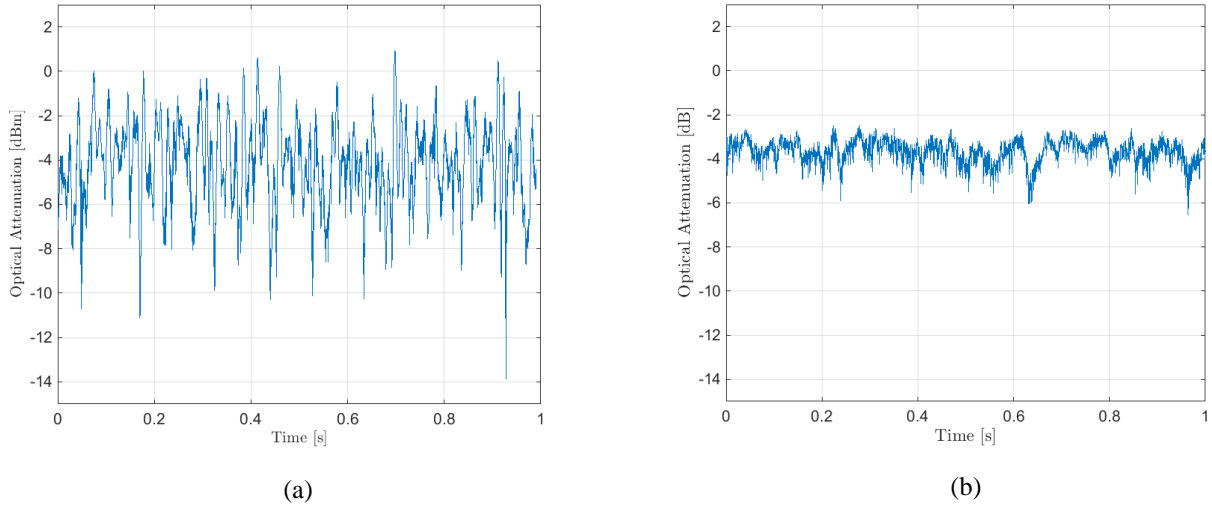


Figure 2: Power attenuation time series due to turbulence with adaptive optic system. A deformable mirror applies a pre-compensation to the uplink beam which is the conjugate of the distortion measured on the downlink beam. (a) uplink strong case / (b) downlink strong case

The impact of the turbulence is worst on the uplink than on the downlink due to the anisoplanatism effect [25].

4. PROTECTION SCHEMES CONCEPTS

The free space optical community has investigated many different protection schemes [12 – 16]: physical layer error correcting code combined with an interleaver, packet level erasure code, a combination of all of them. We investigate solutions based on physical layer error correcting code combined with an interleaver.

A good protection schemes in general shall have good performances, i.e.:

- To add a reasonable extra-latency and overhead: This implies limiting the number of decoding iterations, limiting the size of the interleaver, targeting high coding ratios.
- To provide great power saving on the link budget: This implies modern codes with great coding gain.
- To be able to adapt to atmospheric turbulence strength variation easily: This implies designing the code so that changing code rate is easy / real-time.

For resources starved applications such as space application, a good protection shall also require low on-board resources:

- This implies limiting resources for encoding algorithms for the downlink.
- This implies limiting resources for decoding algorithm for the uplink.

For the mission scenario targeted, the protection scheme shall be compatible with 10Gbps channel rate at least.

5. FORWARD ERROR CORRECTION CODES

Various FEC code families have already been investigated by the free space optical community [12 – 17]: graph based codes (polar code, or sparse code such as Low Density Generator Matrix, Raptor, LT, Low-Density Parity-Check, DVB-S2), algebraic (MDS like Reed Salomon, BCH, Turbo Product Codes with BCH component), and trellis based convolutional codes and their concatenations (serial turbo codes).

In [17], quasi cyclic regular LDPC codes were selected to achieve a BER after decoding below 10^{-9} with decoder throughput above 10Gbps on high end FPGAs [18].

5.1 Downlink

For the downlink we investigate IRA LDPC codes [27]. Figure 3 provides the FEC performances functions of the E_s/N_0 . The FEC performances of the DVB-S2 codes (LDPC + BCH) are provided as benchmark values. DVB codes present the drawback of requiring too many hardware resources for encoding and decoding. The decoding algorithm is Normalized Min-Sum (NMS) algorithm [26] with a normalization factor of 0.75 and a maximum of 25 decoding iterations

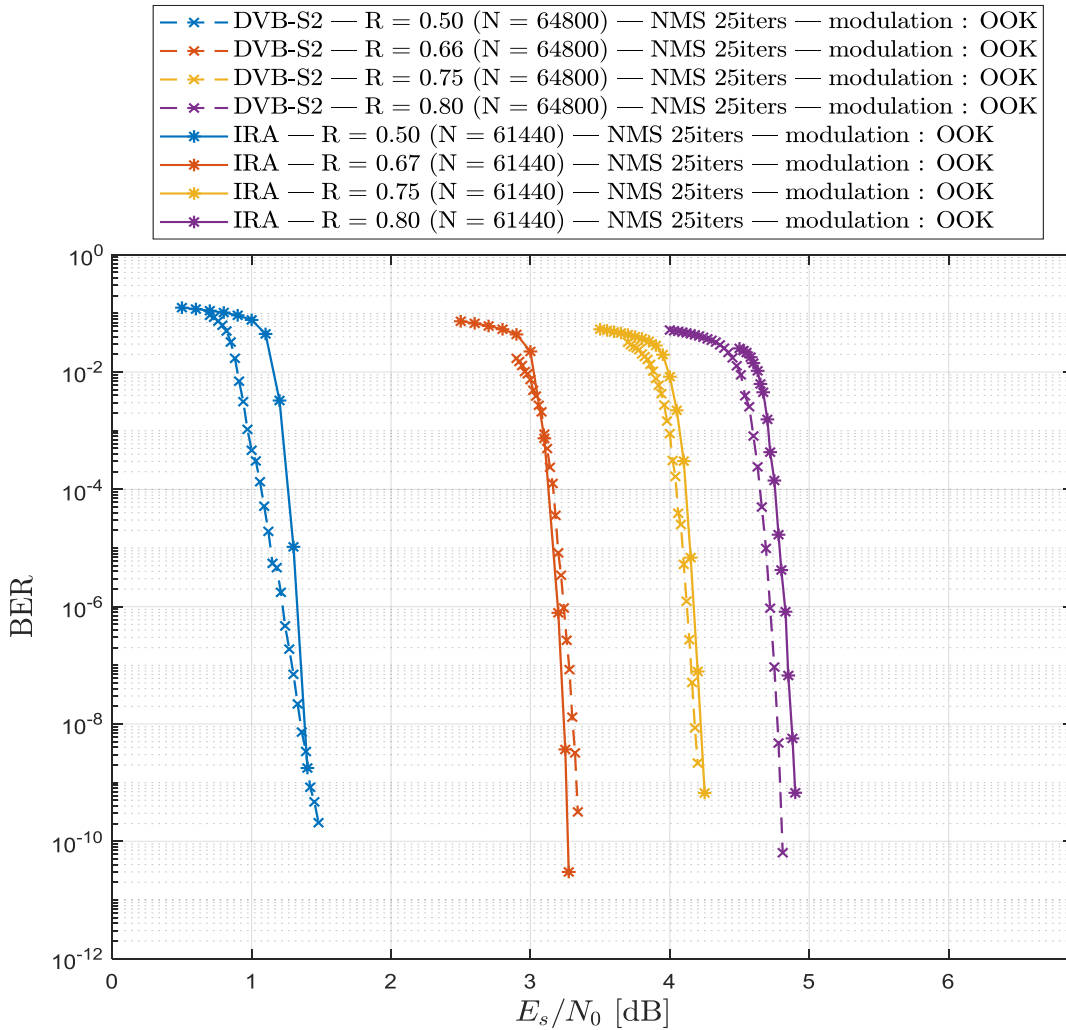


Figure 3: Bit Error Rate function of the E_s/N_0 for AWGN noise model considering soft inputs decoder

5.2 Uplink

For the uplink, we investigate LDPC codes based on Finite Geometry (FG)[17]. Figure 4 provides the FEC performances functions of the E_s/N_0 . The decoding algorithm is Gallager B extended algorithm [28] (namely the Gallager with Erasure) with a number of decoding iterations limited to 8 iterations.

The previous performances of the DVB-S2 codes (LDPC + BCH) with Normalized Min-Sum (NMS) algorithm [26] are superimposed in Figure 4 to provide the reader with order of magnitude of achievable gain in the case of no space constraints. The proposed FG LDPC codes operate between 0.8 to 1.3dB from the channel capacity for hard decoder.

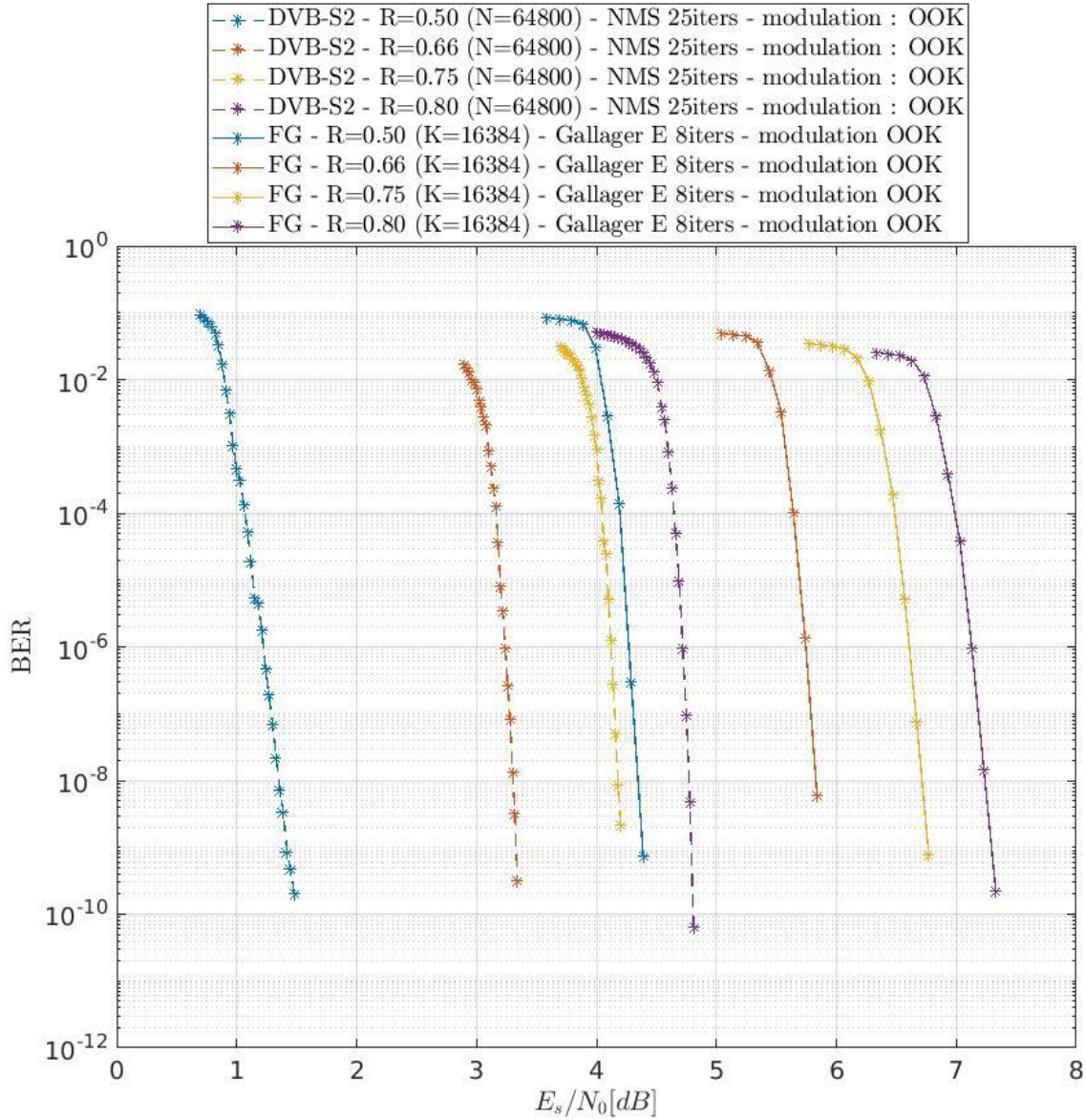


Figure 4: Bit Error Rate function of the E_s/N_0 for AWGN noise model considering hard inputs decoder

5.3 FPGA resources for 10Gbit/s channel rate

VIVADO tool (v2017.4) has been used to estimate hardware resources to encode and decode the 10Gbit/s channel rate data stream. Results are very promising with less than 20% occupancy on the space FPGA.

Table 3: FGPA resources for 10Gbit/s channel rate

	On board	On-ground
Decoder inputs	Hard inputs	Soft inputs on ≥ 6 bits
FPGA	Kintex 060 Xilinx	High end FPGAs
f_{max}	200MHz	Compatible
Required resources for encoding	< 20%	
Required resources for decoding	< 20%	

6. OPTICAL LINK SIZING

As it can be seen from the Figure 5, even with modern FEC described in §5.2, the uplink requires very high power optical amplifier. Greater on board terminal and optical ground station could be used to reduce the required optical power.

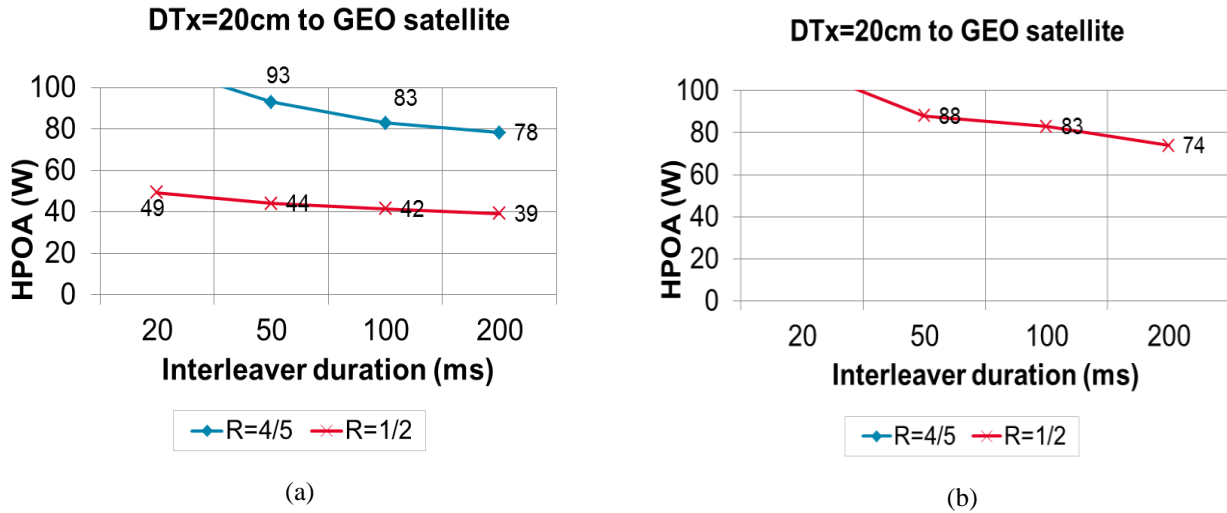


Figure 5: Optical booster power (HPOA) required to achieve an error free uplink at 30° elevation function of the interleaver duration and the FEC coding ratio. (a) nominal turbulence strength, (b) strong turbulence strength

In contrast, optical downlink is easier to design. With the FEC described in §5.1, 10Gbits encoded DPSK downlink at 30° elevation is error free under « strong » turbulence with a 4/5 FEC rate, an interleaver of few milliseconds, and a < 5W optical amplifier.

7. CONCLUSIONS

In this paper, LDPC codes are designed to achieve good performances while requiring small hardware resources to be compatible with space implementation constraints. LDPC codes are designed differently on the uplink and on the downlink for the considered GEO feeder link user case. The required resources for encoding and for decoding the 10Gbit/s channel data rate stream is less than 20% of a FPGA to be space qualified. Despite very good FEC performances and long interleaver, the optical uplink under strong turbulence require very high optical power booster on ground.

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