Inter-Island Demonstration of an FSO High Speed Laser Ethernet Transceiver for Telerobotic Space-Surface Control

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Abstract *This paper presents the experimental results of 100Mbps Laser Ethernet Transceivers for high-speed communications in a 142Km free-space optical inter-island link. Round-trip times below 1.6ms and error free transmission at full throughput during several time intervals were demonstrated.*

Introduction

Free-space optical (FSO) communications are a promising solution for systems which are required to provide flexible and secure high bandwidth communication links. Point to point FSO systems guarantee tap-proof links, while state of the art optical transmitters, receivers and electromechanical devices a the integration of reliable mobile solutions.

FSO systems have to overcome the spurious effects introduced by the atmospheric turbulence onto the transmitted signal. These effects, which are exemplified in Fig. 1, are responsible for the loss of entire blocks of information

As seen, they are perceived as optical distortions in the received wave front which lead to power fluctuations –known as scintillation- on the received signal. The strength of the scintillation is influenced by the atmospheric refractive-index structure constant C_n^2, which is a function of the altitutde and the meteorological conditions. The path-weighted integral of C_n^2 along the link, together with the orthogonal wind speed, defines the strength and duration of signal fades and thus of data losses during fading.

In order to reduce the fading, researchers have focused their efforts in the fields of adaptive optics and error control techniques by means of Digital Signal Processing (DSP) systems, both of them being complementary and none capable of achieving by itself alone a cost effective and efficient solution.

In recent years, the optical communication group (OCG) of the Institute of Communication and Navigation of DLR has demonstrated novel FSO technologies for diverse application scenarios[1-4]. As part of these efforts, the DLR Transportable Optical Ground Station[5,6] (TOGS) was developed. Furthermore, a set of Laser Ethernet Transceivers (LETs) at 100Mbps[7] and 1Gbps[8] have been developed in full compliance with the Ethernet Standard 802.3. These devices act as media converters between an Ethernet network and an FSO link.

The objective of this paper is to present the performance of the LET1G, including FEC, operating at 100Mbps as part of the HICLASS-ROS (HIghly Compact Laser communications terminals for Robotics Operation Support) FSO inter-island link demonstration. The next sections describe the structure of the LET1G and discuss the experimental results obtained during the HICLASS-ROS experimental campaign.

LET1G

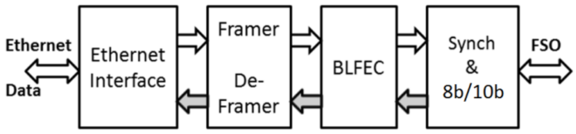

Fig. 2: LET1G block diagram and protection chain

The general block diagram of the LET1G is shown in Fig. 2. The data flow is as follows: at first the data is received from the Ethernet Interface in the form of Ethernet packets, these

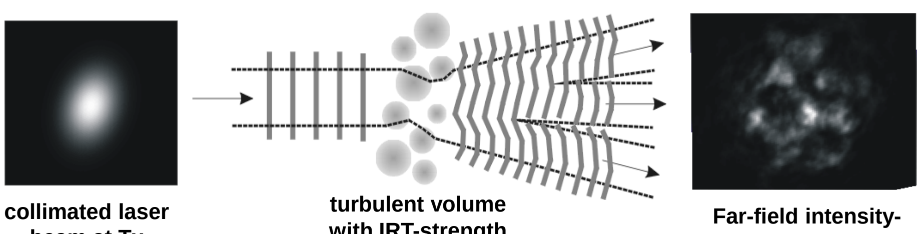

Fig. 1: Effects of the atmospheric turbulence onto an optical signal

are then processed and encapsulated into LET Frames by the Framer, whose structure is defined by the proprietary FSO protocol devised by DLR[8]. These LET Frames are encoded by the bit level forward error correction (BLFEC) block, which has been implemented as a Reed Solomon RS(204,188). Finally, the data is sent to the synch & 8b/10b block, where the line encoding is applied and the required synchronizing symbols are added. These last two steps guarantee the DC balance of the line as well as the synchronization of the data sequence at the receiver side. The receiver carries out the inverse operations.

Regarding the BLFEC, this block is required to protect the data against the effects of noise in the channel and to provide the system with optical power margin to allow error free transmission in case of weak fades. Furthermore, the RS coding algorithm has been selected for implementing the BLFEC because of the supported bandwidth (up to 2.5Gbps) of its off-the-shelf component (COTS).

HICLASS-ROS Field Measurement Campaign

Scenario definition and set up description

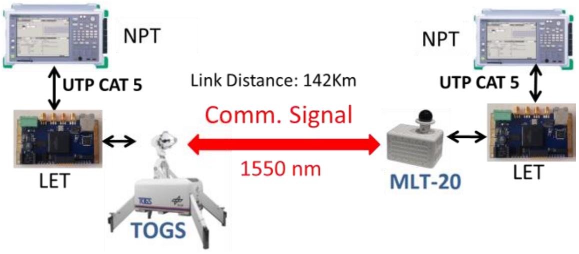

Fig. 3: ESA-HICLASS Experimental Set up

As mentioned, the inter-island experiment was performed in the framework of the HICLASS-ROS project. The goal of the project is to demonstrate that free space optical communication can meet the antithetic requirements for telerobotic space-surface control by providing short Round-Trip Times (RTT), low Symbol-Error Rates (SER) and Packet-Error Rates (PER).

For the link, the distance between the islands of Tenerife and La Palma on Canary Islands has been chosen. On La Palma, the Nordic Optical Telescope (NOT) within the Observatorio del Roque de los Muchachos was hosting DLR's TOGS[5,6]. On Tenerife, the counterpart was represented by the Micro Laser Communication Terminal (MLT) of ViaLight Communications GmbH[9] (VLC), installed on the Optical Ground Station (OGS) at the Observatorio del Teide. Fig. 3 shows the inter-island link setup used in HiCLASS-ROS, in which the Network Performance Testers (NPT) measured the Ethernet throughput and RTT and the LET1G measured the SER and PER.

Tab. 1. Technical specifications of the experimental set up

Parameters	TOGS	MLT
Tx power	5W	1W
Aperture Diameter	60cm	2cm
Distance	142Km	142Km
Tx divergence (FWHM)	0.1mrad	0.24mrad
Channel data rate	136Mbits/s	136Mbits/s
User data rate	100Mbits/s	100Mbits/s

In addition to the LET-measurements, received power scintillation vectors were recorded and analyzed to estimate the channel variations. Measurements were taken switching one or both of the Tx at TOGS on, varying the transmit power. The incoming signal at the counter terminal site was received by a 50mm aperture and focused onto an InGaAs detector, AD-converted and recorded. Power scintillation index of the measured vectors at different times are calculated, which measures fluctuation of the signal due to the atmosphere. The run of the power scintillation index with 1s-windows as measured on one morning for 50 seconds is shown in Fig 4. The channel condition was challenging with power scintillation index (PSI) of up to 1.5. Further experimental results presented in the paper were also recorded around same time period. It is important to notice that the PSI of the actual communication link should be slightly higher considering the smaller 20mm aperture of the receiver. However, the difference does not hinder the main purpose of this measurement, which is to provide an assessment of the channel condition.

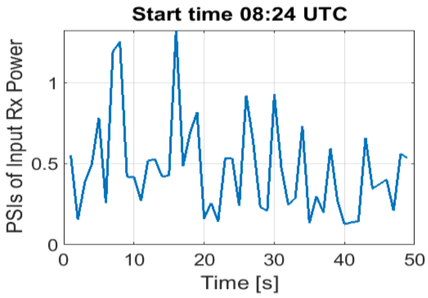

Fig. 4: PSI vs time (mean PSI over 1s window)

Experimental Results

Round Trip Time (RTT)

HICLASS-ROS required a RTT of max 3ms. Tab. 2 summarizes the results obtained for the minimum and maximum Ethernet packet length (EPL) according to the 802.3 Ethernet Standard. Jumbo Packets were not considered.

Tab. 2: User RTT for min and max EPL

EPL (Bytes)	RTT(ms)		
	MIN	AVG	MAX
64	1.121220	1.131366	1.140932
1518	1.573416	1.596853	1.618552

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Codeword Error Rate (CER)

HICLASS-ROS required low PER. For this experiment the PER has been equated to the CER, which for LET1G constitutes the channel data packets. Fig. 5 presents the CER measured by LET1G at the MLT and TOGS. As shown, TOGS presented error free reception during several time intervals whereas MLT presented a consistent CER in the order of 10^{-2}. The different CER performance of TOGS and MLT is due to their different aperture sizes.

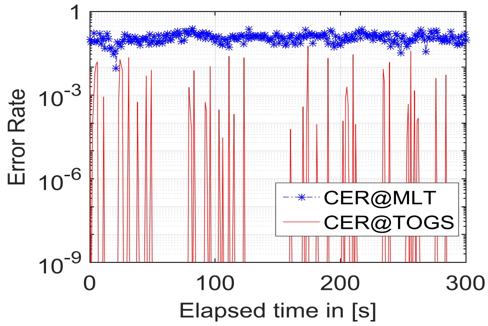

Fig. 5: TOGS CER over 6 minutes measurement

Ethernet Data Throughput

The NPTs were configured to transmit Ethernet data packets with randomly defined size between 64 and 1518 bytes. The effective transmitted data rate is 97.5Mbps, which corresponds to a 100% throughput according to the Ethernet Standard.

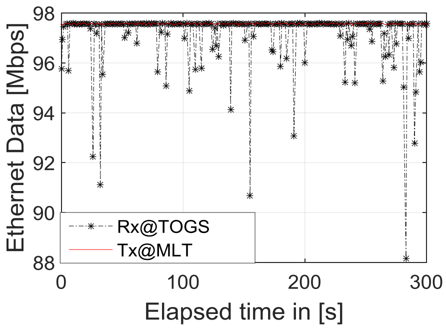

Fig. 6: TOGS User data Ethernet throughput at 100Mbit/s

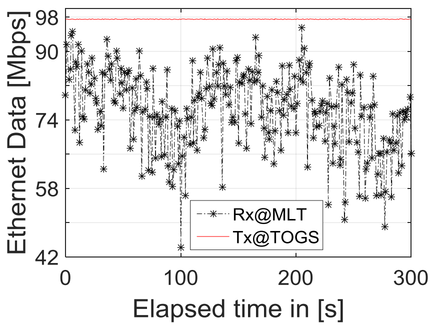

Fig. 7: MLT User data Ethernet throughput at 100Mbit/s

Fig. 6 and Fig. 7 present the results at TOGS and MLT, respectevely. As shown, minimum throughput values of 88% and 43% were measured at TOGS and MLT, respectively.

System Limits Measurement

In order to understand the effects of an eventual miniaturization of the system, a stress test was performed. Transmission power at MLT was reduced to 100mW and TOGS telescope was partially masked.

Tab. 3: Reduction of TOGS aperture diameter by applied mask (MLT Tx-Power: 100mW)

Mask	Effective diameter	CER
0%	60cm	Error-free
25%	50cm	Error-free
50%	40cm	1E-06

Conclusions

The feasibility of using high speed FSO link for telerobotic space-surface control application was verified by demonstrating 142Km inter-island link. An error–free transmission with RTT below 1.6ms was achieved. Furthermore, it was determined that the aperture size of the current system can be decreased by half without significant impact on the performance. In order to make the system more robust, design and implementation of packet level codes for LET1G are currently under investigation.

Acknowledgements

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