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Experimental evaluation of adaptive distributed frame repetition at 10 Gbps for the satellite-to-ground optical link

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ABSTRACT

Performance instabilities due to the fading are vital subjects for long distance free space optical communication systems in which the signal lights travel through the atmosphere. The straightforward approach is to introduce the combinations of optical transmitters and receivers that can operate in various modulation speeds, and the operator selects the speed from the candidates in order to manipulate photons per bit according to the link conditions. However, the realization of such functions with single hardware may result in the halfway capabilities. For these problems, our group has been proposing the use of the technologies that we call Adaptive Distributed Frame Repetition (ADFR), in which a high-speed link is divided in time, and sending node replicates frames and transmits over a single link with the proper time intervals without concerning whether each frame arrives at the destination or not. Since the line rate is always constant, and functions equipped in the receiving node are simple, settings at the transmitting node relating to retransmission can be switched seamlessly without any negotiations with the opposite. In this time, the main functions of ADFR are implemented on the computers to be experimentally evaluated at 10 Gbps. In addition to the basic results about static and dynamic performances of ADFR, the combined performance with TCP assumed to be introduced in the GEO-Ground system will be discussed in the paper.

Keywords: Satellite, Atmospheric turbulence, Fade, Free space optics, Communication system, TCP, Throughput

1. INTRODUCTION

Due to the rapid growth of the advanced utilizations of the space, the fundamental improvements in the communication systems connecting artificial satellites and earth are strongly desired. Free space optical (FSO) communication is regarded as a promising candidate for this issue because of its drastically higher efficiency in spatial utilizations compared to the conventional microwave systems [1]. The prior issues with this technology are different whether the transmission link lies in the vacuum or in the air, and the practical use began in the inter-satellite communication systems whose transmission link is ideal for the laser propagation [2]. Japan follows similar scenarios, and will launch data relay GEO satellite having FSO system only for inter-satellite use in 2019 [3], and another GEO satellite in 2021 with which the technologies for optical feeder link systems will be tested [4].

Attenuation due to the clouds and refraction due to the non-uniform atmospheric conditions are two major problems for the FSO systems connecting between satellites and ground. For the first problem, site-diversity technique is a unique practical approach at this moment, in which the ground station with better condition would be selected for use from the separately-placed plural candidates on a moment-to-moment basis [5]. The second problem should be handled with the various kinds of technologies such as mechanics [6], optics [7], digital signal processing [8], communication protocols [9], and so on. Our group has proposed the use of Adaptive Distributed Frame Repetition (ADFR) to suppress the influence of fast fluctuating received optical power. Recently, we have numerically evaluated and reported the gains when this technology is applied to the 10Gbps LEO to Ground downlink systems. In that study, all the steps from the laser propagation to the throughput calculation were modeled in the computers [10].

In this time, we have developed an ADFR test equipment operating at the speed of 10 Gbps, which enables us to do more complex performance tests. Using this test equipment, we have evaluated the ADFR assisted TCP (Transmission Control Protocol) performance with the severely-faded and long-RTT (Round Trip Time) transmission links, assuming the future tests [4]. In this paper, the experimental results of this investigation in addition to some basic performance tests of this equipment are described.

2. ADAPTIVE DISTRIBUTED FRAME REPETITION

2.1 Backgrounds of ADFR

Figure 1 (a) shows an example of the protocol stack of the FSO communication system. This figure is just for the explanation, and each technologies here are not necessary common to the present systems. Users are connected with the lowest layer of FSO, which mainly consists of antennas and laser beams. The source of the laser beams are generated in the transponders, whose technologies are assumed, in this study, to be based on the terrestrial optical fiber communication systems using 1.55μm wavelength band.

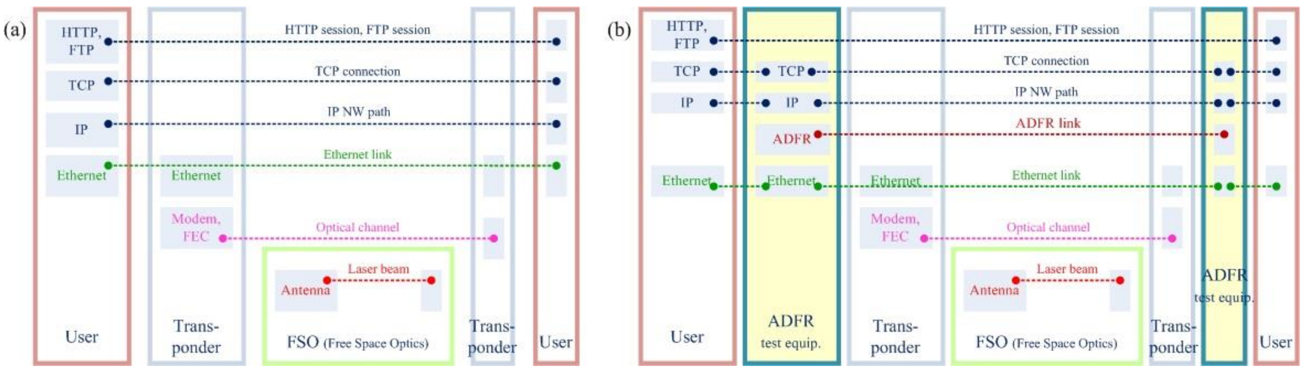

Figure 1. (a) Protocol stacks of the normal FSO communication systems, (b) Protocol stacks of the FSO systems with ADFR (test equipment) explained in 2.3. ADFR test equipment is designed to be inserted between User and Transponder as a simple add-on, and not to influence any versatilities of them.

One of the features of the FSO communication systems with the beam transverse in the air around the earth surface is that this FSO layer is unstable in two meanings: the existence of the power fluctuation to the receiver due to the atmospheric turbulence and the quick and wide change of its statistical property even within one system. On the other hand, technologies developed and used in the high-speed optical fiber communication systems are not designed with these kinds of instabilities, and generally, the flexibilities of the operational points in each devices or components become smaller as the expectations on the FSO communication systems are placed on the superior performances in signal speed and receiver sensitivity. The aim of the introduction of the ADFR is that, by introducing flexibleness in the upper layers to cope with link instabilities, it just makes transponders concentrate on showing their intrinsic capabilities by fixing their operational points.

2.2 Adaptive Distributed Frame Repetition

In the ADFR at the transmitter side, the signal to be transmitted is once split into small units, replicas are generated for each units, and they are transmitted to the free space with the appropriate time intervals. At the receiver side, unwanted replicas that are not needed to be forwarded are simply discarded. The statistical properties of the fluctuation of the received powers have two major parameters of fading ratio (FR) and average of fading duration (AoFD). The number and interval of retransmission in the ADFR are determined mainly corresponding to the FR and AoFD, respectively. The proper ADFR settings would decrease the probabilities of the failure due to fading. On the other side, since the transponders operate at the fixed speed, ADFR does not improve the receiver sensitivity, and the bandwidth will be reduced inversely proportional to the numbers of the retransmission.

2.3 ADFR test equipment

The roles and features of the ADFR test equipment developed in this time are explained with fig.1 (b). It is simply inserted between User and Transponder, and was designed for them not to lose their versatility and interoperability based on the present standardization. The unit of the retransmission is the frame of Ethernet carrying the IP packet. So, the FR is equal to the frame error ratio (FER). More essential performance indicators of packet error ratio (PER) under UDP (User Datagram Protocol) and throughput under TCP can be measured with the test tools implemented in this test equipment at any speed below 10 Gbps. Functions of ADFR are implemented on the commercially available Linux PCs with 10 Gbps Ethernet interfaces. Numbers and interval of retransmission can be varied from 0 to 9 and from 1ms to 100ms, respectively.

There are three essential functions for ADFR to operate in the real systems: (1) generation of replica frames and alignment of them in order as specified, (2) determination of the appropriate next ADFR setting with some monitoring method, (3) seamless change of ADFR setting without system interruption. ADFR test equipment has functions of (1) and (3), and function of (2) is still under investigation.

3. PERFORMANCE EVALUATIONS WITH ADFR TEST EQUIPMENT

With the ADFR test equipment developed in this time, two kinds of performance tests were conducted. First one is the evaluations of pure PER improvement capabilities using UDP traffic, and the second one is the cooperation with TCP in the long RTT transmission link.

3.1 Experimental setup

Figure 2 shows the experimental setup used in the following studies. As the purpose of the experiments included performance tests of the developed equipment itself, the setup was very simplified so that the FSO layer as well as the transponders were removed from the configuration shown in fig. 1(b). Two of the ADFR test equipment were directly connected with optical fiber and 10GBASE-ER interface modules, and one of the two directions had an input port for the optical noise source. Frame errors (or Link loss) occurred during the optical switch placed between optical nose source and input port being on.

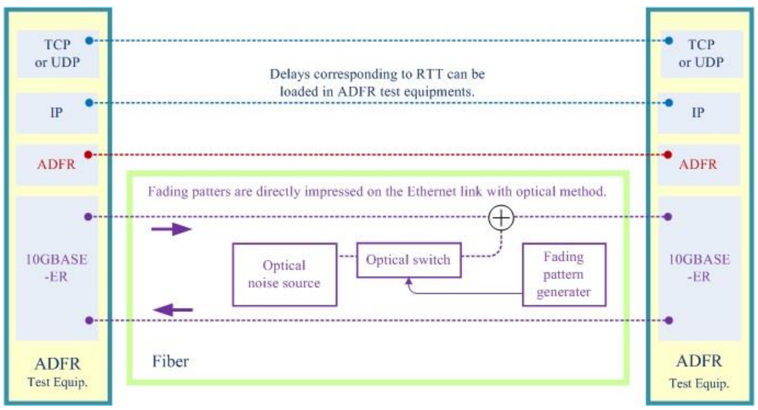

Figure 2. Experimental setup used in the evaluations of PER reduction with UDP traffics and throughputs of TCP traffics. Delay elements to emulate long RTTs are not described in this figure. Fade was generated by adding modulated optical noise on one direction of the signal light between 10GBASE-ER. This low-cost approach however enabled very precise transcription of the varieties of the fade patterns on the signal streams.

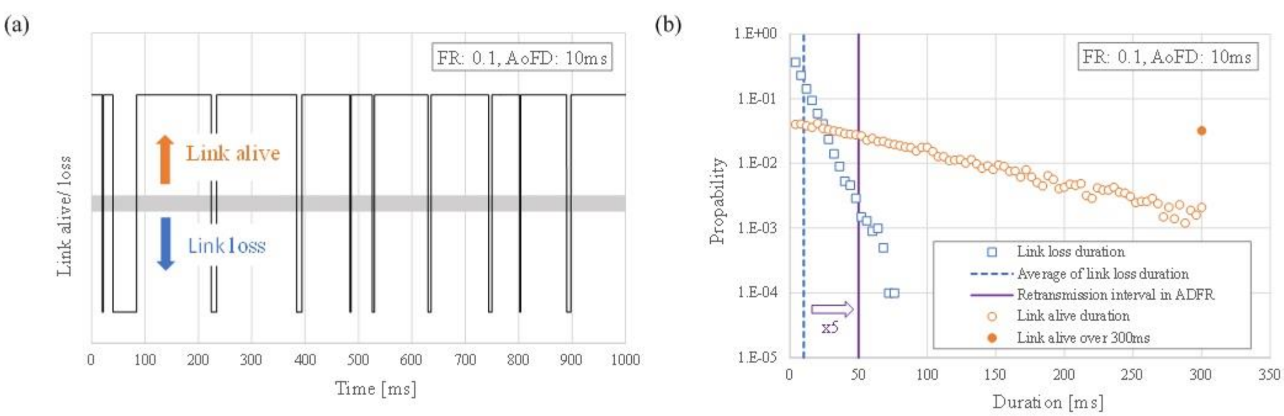

Figure 3. (a) Part of the fade pattern generated with random number generator. Fade ratio (FR) is 0.1 and average of fade duration (AoFD) is 10ms. (b) Statistical properties of the fade pattern in terms of durations of link alive/loss.

Fading patterns that drived the optical switch were made with the random number generator in order to precisely control their statistical properties. So, the generated fading patterns do not necessary reflect on the real atmospheric phenomenon nor the responses to them in the real transponders. Each fading patterns consists of 500k samples, and the sampling interval is designed so that it becomes 20% of the AoFD. So, if the AoFD is 10ms, a fading pattern with 500k samples consumes 1,000 seconds. Figure 3 (a) shows a part of a fading pattern with the conditions of FR: 0.1 and AoFD: 10ms, and (b) shows the probabilities of the durations of the link alive/down with these conditions. According to our basic evaluations with various combinations of FE and AoFD, optimum interval of retransmission in ADFR was about 5 times as long as AoFD, and this value was used in all the following experiments.

3.2 PER improvements to the random fade patterns

We prepared fade patterns with various FRs, and evaluated the capabilities of PER improvements against these fade patterns in terms of the numbers of retransmission. Details of the parameters in this evaluation are summarized in Table 1. Figure 4 shows measured results of the relationships between raw FRs and obtained PERs after ADFR processes. Owing to the proper choices of retransmission interval (5 x AoFD), the measured results were well suited for the design targets. According to the fig.4, if the requirement to the PER is to be less than 0.001, the four-time additional retransmission relaxes the required FER to be about 0.25.

Table 1. Parameters and results in the evaluations of PER reduction

Parameters					Results
Transmission link		ADFR		UDP traffic	Required FER for PER of $1\text{x}10^{-3}$
FR	AoFD [ms]	Interval [ms]	Number of retransmission	Bandwidth [Gbps]	
$10^{-0.25}$, $10^{-0.50}$, $10^{-0.75}$ $10^{-1.00}$, $10^{-1.25}$, $10^{-1.50}$ $10^{-1.75}$, $10^{-2.00}$, $10^{-2.25}$	10	(w/o ADFR)		10	$1.0\text{x}10^{-3}$
		50	1	5	~ $3.2\text{x}10^{-2}$
			4	2	~ $2.5\text{x}10^{-1}$
			9	1	~ $5.0\text{x}10^{-1}$

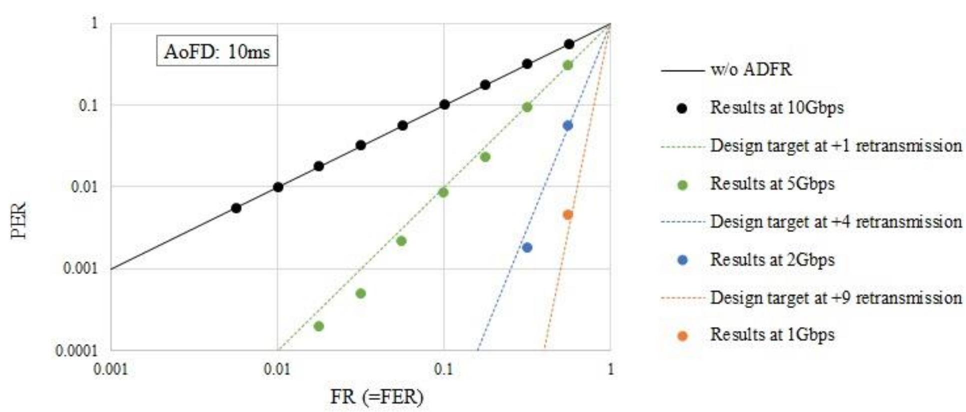

Figure 4. Measured results of the capabilities of PER improvements by ADFR. Due to the statistical characteristics of the fade patterns shown in fig.3 (b), one more additional retransmission makes PER to be reduced accordingly to the raw FER if the retransmission interval was properly selected.

3.3 Performance of TCP in the long-RTT transmission link

For the FSO communication systems to be versatile, it is preferable for them to be under the reliable data transfer protocols like TCP, however, a long round trip time (RTT) with the use of GEO satellite tends to result in the low TCP throughput which is not worth the physical bandwidth. Among the so-called TCP-boosters that provide superior performances in some specific conditions, TCP-FSO that was used in the following experiments were specially tuned to exhibit performances with the long-RTT transmission links by its unique recovery mechanism from fading [9]. Since ADFR is a different approach to this problem with its PER improvement capabilities, the combined performances are intriguingly to be investigated.

With the experimental setup shown in figure 2, the TCP throughputs on the long-RTT transmission link were measured for two cases (w/o and w/ ADFR). Table 2 summarizes the details of the parameters used in the experiments.

The plots with solid line in figure 5(a) shows the measured throughputs of the TCP. A slight FR of 0.01 could be an apparent degradation factor, and the throughputs rapidly degreased as the FR increased. The dashed curve lines were the expected performances when ADFR would be introduced with the numbers of additional retransmission being 1, 4 and 9. These expected performances were the simple calculation results using the original TCP performance (plots with solid line in figure 5(a)), PER improvement capabilities (shown in figure 4) and bandwidth reduction effects both by adoption of ADFR. Since the additional retransmission due to ADFR lost at least half of the original bandwidth, and then the throughput with ADFR became less than 5 Gbps, the area of interest was where the FR was over 0.011. According to the figure 5(a), we can find out some candidates of ADFR settings in this area which would achieve better throughputs compared to the case without ADFR.

Figure 5(b) shows the examples of the measured TCP throughputs in cases without and with ADFR. Details of the parameters are listed in table 2. The plots of “w/ ADFR (Measured results)” mostly followed the expected performances explained with figure 5(a) and outperformed the case without ADFR. This indicates that, if the monitor of the link conditions could continuously and properly determine the ADFR settings, the two technologies of ADFR for PER improvement and TCP for reliable data transport can cooperate to increase the overall performances of the high-speed FSO communication systems on the long-RTT and unstable transmission link.

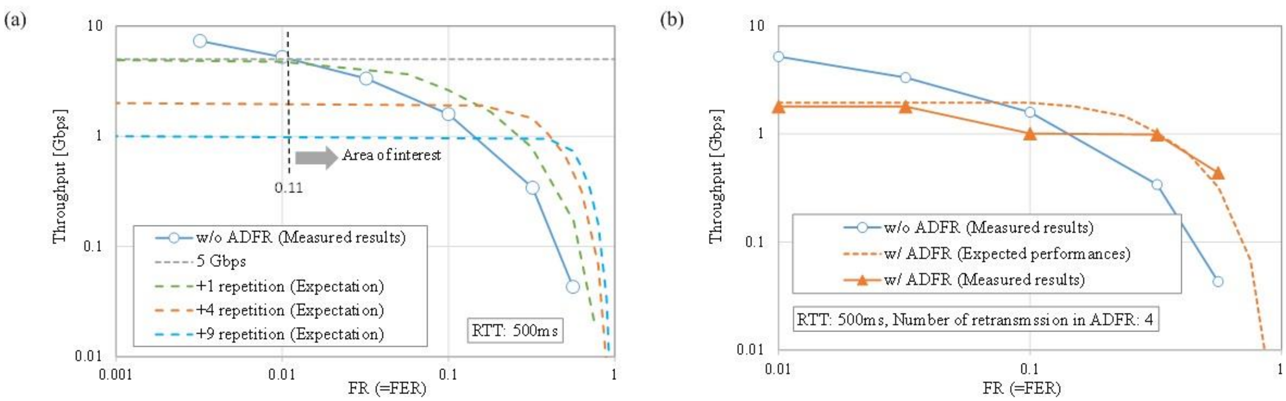

Figure 5. (a) Measured results of the throughput with TCP only, and expected performances with ADFR. (b) Examples of measured results of TCP throughput with ADFR (number of retransmission: 4).

Table 2. Parameters in the evaluations of TCP throughputs in the long-RTT transmission link

Transmission link				ADFR		Signal
FR	AoFD [ms]	RTT [ms]	Application	Interval [ms]	Number of retranmission	TCP traffic [Gbps]
$10^{-0.25}$, $10^{-0.50}$, $10^{-1.00}$ $10^{-1.50}$, $10^{-2.00}$	1	500	Ground – GEO Sat.– Ground	(w/o ADFR)		~ 10
				5	4	~ 2

4. SUMMARY

Our group has proposed to use Adaptive Distributed Frame Repetition (ADFR) for the high-speed FSO communication systems to operate flexibly against the time-changing fade characteristics. In this time, an ADFR test equipment with 10GbE interfaces was developed to experimentally evaluate the functions and effectiveness of ADFR. Capabilities to accept wide range of ADFR settings (mainly number and interval of retransmission) enabled to effectively reduce the packet error rate (PER) against the variety of artificially-generated fade patterns, though the proper settings should be provided from the outside at present. Suppression of excess degradation of TCP throughput with the severely faded, and long RTT transmission link has also been demonstrated with this test equipment.

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REFERENCES

[1] V. W. S. Chan, “Free-space optical communications,” J. Light. Technol. 24(12), 4750–4762 (2006).
[2] Harald Hauschildt, Joerg Herrmann, Hermann Ludwig Moeller and Michael Witting, “European Data Relay System Goes Global,” IEEE International Conference on Space Optical Systems and Applications (ICSOS) 2017, Paper S1.3.
[3] Yohei Satoh, Yuko Miyamoto, Yutaka Takano, Shiro Yamakawa and Hiroki Kohata, “Current status of Japanese optical data relay system (JDRS),” IEEE International Conference on Space Optical Systems and Applications (ICSOS) 2017, Paper S8.1.
[4] Morio Toyoshima, Tetsuharu Fuse, Alberto Carrasco-Casado, Dimitar R. Kolev, Hideki Takenaka, Yasushi Munemasa, Kenji Suzuki, Yoshisada Koyama, Toshihiro Kubo-oka and Hiroo Kunimori, “Research and Development on a Hybrid High Throughput Satellite with an Optical Feeder Link - Study of a Link Budget Analysis -,” IEEE International Conference on Space Optical Systems and Applications (ICSOS) 2017, Paper S9.3.
[5] Optical Link Study Group Addendum to Final Report. IOAG.T.OLSG.2012.V1A. Washington, D.C.: IOAG, November 2012.
[6] Ruochi Zhang, Jianmin Wang, Guang Zhao, and Junyi Lv, "Fiber-based free-space optical coherent receiver with vibration compensation mechanism," Opt. Express 21(15), 18434 (2013).
[7] Carlos E. Carrizo, Ramon Mata Calvo, and Aniceto Belmonte, "Intensity-based adaptive optics with sequential optimization for laser communications," Opt. Express 26(13), 16044 (2018).
[8] David J. Geisler, Curt M. Schieler, Timothy M. Yarnall, Mark L. Stevens, Bryan S. Robinson and Scott A. Hamilton, "Demonstration of a variable data-rate free-space optical communication architecture using efficient coherent techniques," Opt. Eng. 55(11), 111605 (2016).
[9] Yohei Hasegawa, “A Transmission Control Protocol for Free-Space Optical Communications," in Proc. of IEEE GLOBECOM 2017, DEC 2017.
[10] Yoshimasa Ono, Yasunori Futatsugi, Yohei Hasegawa, Manabu Arikawa and Toshiharu Ito, "Performance improvement in LEO-to-ground free space optical communication systems with adaptive distributed frame repetition," Proc. SPIE 10524, Free-Space Laser Communication and Atmospheric Propagation XXX, 105240I, (2018)