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Managing fading in free space optics according to the service class

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***Abstract*—The impact of fading is analyzed in free space optics communications. A traffic-driven solution is proposed to mitigate transmission performance degradation, accounting for high- and low-priority traffic. The proposed solution experiences high robustness for high-priority traffic.**

***Index Terms*—Non-terrestrial networks, NTN, free-space optics, FSO, satellite communications.**

I. Introduction

Non-terrestrial networks (NTNs) have emerged as a solution for several applications, such as a backup of terrestrial networks in case of natural disaster or intentional attacks and also to reduce the *digital divide* by giving coverage to remote areas [1].

In such a context, *free space optics (FSO)* is gaining relevance, providing enhanced throughput with respect to radio techniques. Nowadays, FSO technology is already used in satellite communications. According to Starlink, there are thousands of FSO inter-satellite links [2], and FSO is being successfully tested between geostationary earth orbith (GEO) satellites and ground station, and, recently, even between low earth orbit (LEO) satellites and ground station [3]. FSO leverages consolidated devices and technology for fiber optics: e.g., transceivers, multiplexers and demultiplexers. A first demonstration of FSO was done in [4] relying on several 40 Gb/s channels. Differently from fiber optics, where channels are almost static (apart time-variant impairments such as polarization mode dispersion, which nowadays is compensated by means of digital signal processing in coherent receivers), FSO channels are highly time variant due to fading and atmospheric conditions. The work in [5] has shown that considering commercial Optical Transport Network (OTN) transponders, 100 Gb/s dual polarization quadrature phase shift keying (DP-QPSK) coherent transponders may be less robust than 10 Gb/s on-off keying (OOK) transponders against fading. In general, the reaction against outages due to fading in FSO is under investigation and can be mitigated through interleavers [6], adaptive optics [7], re-transmission [8], etc. . . Note that, although a system can be optimized reducing the fading probability, this probability unlikely goes to zero, thus fading events can still occur and may produce system outages.

In this paper, we present a method against fading based on classes of service. Such a method is not necessarily an alternative to other methods such as interleavers, but it can be complementary to. The ratio behind the proposed scheme has origin in the observation of the robustness of different OTN transponders. In particular, we propose to allocate *high-priority / gold* traffic to 10G OOK transponders (more robust), while allocate *low-priority / best effort* traffic to 100G DP-QPSK transponders (less robust). Once fading is experienced, best-effort traffic is excluded in order to feed the 10G high-priority traffic with more power, thus even increasing its robustness. Experiments show increased performance (e.g., by 80% in some conditions) for high-priority traffic.

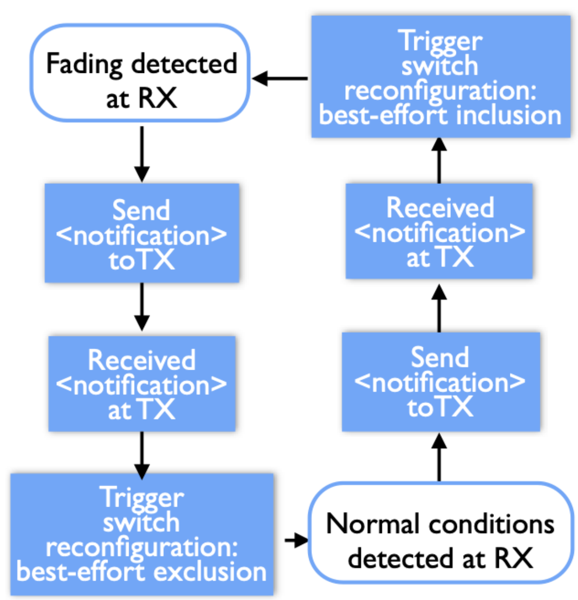

Fig. 1: Flow chart of the proposed method against fading.

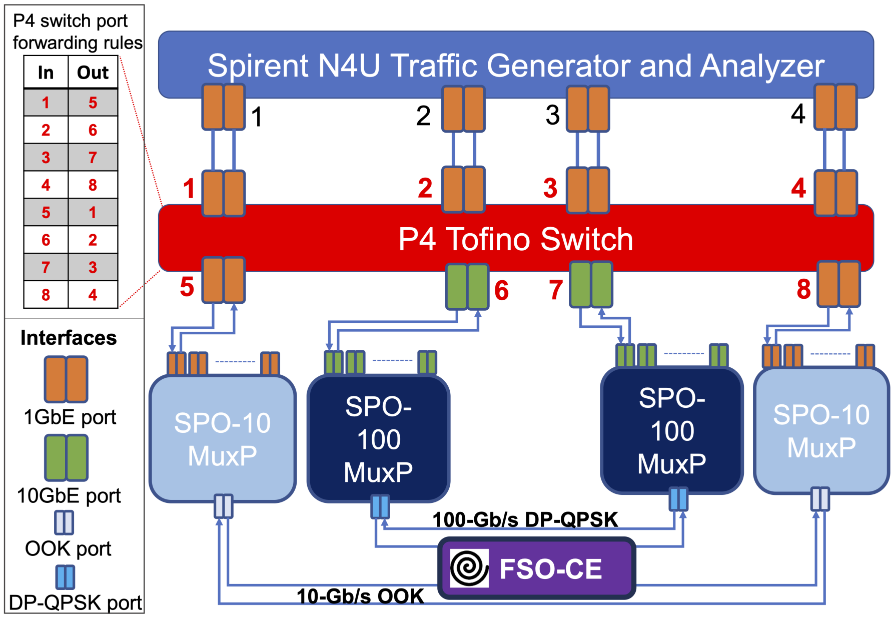

Fig. 2: Experimental testbed.

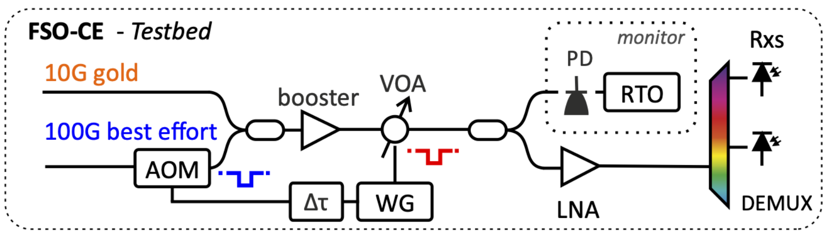

Fig. 3: Part of the testbed emulating FSO.

II. Method based on classes of service against fading

Figure 1 shows the flow chart of the proposed method. Once fading is detected at the receiver (RX), an *alarm* is sent to the transmitter (TX). Fading detection can be done by monitoring the instantaneous received power of channels, while the alarm can be implemented with a NETCONF <notification> message as done in [9]. When the TX receives the alarm, it triggers the exclusion of the 100G best-effort traffic. Such an exclusion can be done by reconfiguring an optical switch that, in normal conditions, collects both 100G and 10G traffic before a booster amplifier ahead the launch in the atmosphere. Once the 100G traffic is excluded from the input of the booster (which typically operates in power mode), the whole power is supplied to the remaining traffic, i.e. the 10G gold traffic. Such a power increase is expected also to increase the robustness of the gold traffic against fading. When normal conditions are detected at RX, another NETCONF <notification> message is sent to the TX and the 100G best effort is re-integrated in the transmission.

III. Experimental demonstration

Figure 2 shows the experimental setup. A Spirent N4U equipped with four 1 Gigabit Ethernet (1GbE) interfaces is used to generate and analyze the traffic. Four unidirectional packet streams (e.g., port1→port4, port4→port1, port2→port3, port3→port2) have been configured, with constant packet rate at 10^6 packet/second. We adopted the same interface type (i.e., 1GbE) and the same traffic stream configuration between the two transmission systems. We monitored the traffic of each stream while continuously generating packets at a constant rate. We used the number of dropped Ethernet packets as key performance parameter. The number of lost packets is due to two main contributions: the duration of the fading event and the recovery time needed by each transponder. A programmable P4-native switch based on the Tofino ASIC is utilized to keep the generator/analyzer interfaces always active and operative; otherwise, in case of outages due to fading, the interfaces would go down, altering the statistics. The P4 forwarding table flow rules enforced in the switch are shown in Fig. 2: these rules are designed to forward all the traffic received at a given port to a target output port, thus bypassing the standard layer-2 MAC-based forwarding.

The traffic then enters commercial 10G OOK or 100G DP-

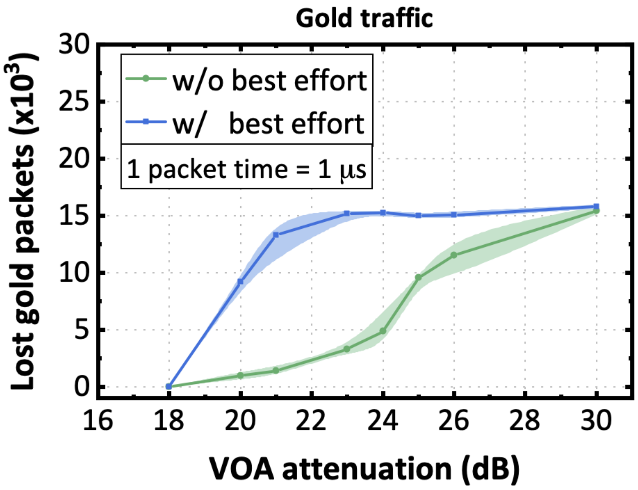

Fig. 4: Average number of lost packets of the gold traffic (fading length: 10 ms, 104 transmitted packets). Shaded areas indicate measurement uncertainty.

QPSK transponders (SPO-10 MuxP or SPO-100 MuxP, respectively) and flows through the emulator of the FSO channel (FSO-CE) – shown in Fig. 3 – where the fading is emulated. We used a coupler and an acousto-optic modulator (AOM), to emulate a spatial switch that can include/exclude best-effort traffic: the AOM is driven to either allow or block the 100G. A variable optical attenuator emulates fading through attenuation. In normal operating conditions, the 10G OOK enters the booster with an optical power of 3-dB lower than 100G DP-QPSK so that they have similar pre-FEC BER. If 100G DP-QPSK is excluded from transmission, the power of OOK at the booster output increases by 4.8 dB. In this work, we consider a total of 2 ms delay for the alarm to exclude DP-QPSK once fading is applied. The AOM was controlled with a delay relative to the fading event to shut down the line carrying the best-effort signal.

The proposed method is compared – in terms of number of lost packets (with a packet duration of 1 μs) – with a benchmark condition in which the best-effort traffic is not excluded from the transmission when fading is detected (i.e., AOM always lets pass the 100G DP-QPSK signal).

Fig. 4 shows the number of lost gold packets, i.e., only those carried by the 10G OOK, at different values of fading loss. We compare results achieved with the proposed method (*w/o best effort*) and with the benchmark (*w/ best effort*), i.e., keeping both channels active. Results show that, once fading is experienced, excluding the best-effort DP-QPSK traffic gives a consequent power increase to the gold OOK signal: this strongly reduces the number of lost gold packets, over a significant range of attenuation values. The two curves converge for very high loss values (30 dB), where the increase of power is not enough to counteract the fading. At 21 dB loss, the proposed method significantly reduces the number of gold packets lost, by around 80%.

IV. Conclusions

We proposed a method against fading for FSO-based satellite networks, exploiting OTN equipment. Based on the tolerance of different OTN transponders, we design such a method conditioned to the service classes: an high-priority and a best-effort class. 10G OOK transponder (more robust) is allocated to high-priority traffic, while 100G DP-QPSK transponder (less robust) to best-effort traffic. We experimentally emulated isolated fading events with controlled features (depth and duration) and then we measured the packet loss with OTN equipment. Since both signals share the same booster amplifier, shutting down the best-effort signal allows the booster to allocate significantly more power to the high-priority traffic, further enhancing its robustness. The positive outcome of this scheme was demonstrated by measuring the packet loss using GbE interfaces; this clearly shows that the proposed solution significantly reduces the number of lost high-priority packets, up to -80%.

Acknowledgements

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