COST CA 19111

European Network on Future Generation Optical Wireless Communication Technologies (NEWFOCUS)

Deliverable D4.2

Field Trial Evaluation

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1. Introduction

The working group4 (WG4) deals with Long-range links mainly focussing on airborne and satellite FSO links. Reporting on various field trials and experiments, various publications and internal documents summarizing collaborative work within the working group members have been presented fulfilling the Milestone 4.2.

The activities for WG4 has been presented in terms of various input documents during working group meeting and discussed. Some of the topics that were covered are:

1. Error control capability of NB-IoT MCS over satellite links with optical feeder links, Alexis Dowhuszko, Department of Communications and Networking, Aalto University, Finland
2. Airborne and space laser communication ground terminal, Andris Treijs, HEE Photonic Labs
3. Hristov Ivanov„Modeling near-Earth FSO channels and atmospheric seeing affected by turbulence and clouds“
4. M. Grillo, A. Dowhuszko, M.-A. Khalighi and J. Hämäläinen, "Resource allocation in a Quantum Key Distribution Network with LEO and GEO trusted-repeaters," in Proc. Int. Workshop Optical Wireless Comm., pp. 1-6, Sept. 2021 (T4.2 Phy and PAT Design ,T4.3 Mac and Upper layers)Joan Bas and Alexis Dowhuszko, "End-to-end error control coding capability of NB-IoT transmissions in a GEO satellite system with time-packed optical feeder link"
5. Hristo Ivanov, Erich Leitgeb, Frank Marzano, Pasha Bekhrad "Modeling near-Earth/deep-space FSO channels and atmospheric seeing affected by turbulence and clouds".
6. Dowhuszko Alexis , "Optical Wireless Channel Models for High Throughput Satellite Communication Systems"
7. Hristov Ivanov, "Testbed Emulator of Satellite-to-Ground FSO Downlink Affected by Atmospheric Seeing Including Scintillations and Clouds "
8. Marc Amay, Joan Bas (CTTC), " On Hybrid Optical-Radio Communication Systems for 6G NonTerrestrial Networks".
9. Ali Khalighi (ECM), "Influence of EDFA on the satellite QKD channel Research" – STSM
10. Gerhátné Udvary Eszter (TU Budapest), : "Background optical radiation measurement in Hungary"
11. Niek Doelman (TNO), "Adaptive approaches to reduce long-range FSO channel distortions"
12. Bui Thai -Chien (TNO), „"Atmospheric Turbulence Channel Modelling and Testbed for Uplink and Downlink"
13. "Outage performance of satellite-to-ground terminal system containing selection relaying", Goran T. Djordjevic, University of Nis, Faculty of Electronic Engineering, Nis, Serbia
14. "Development of High-Performance Adaptive Optics Control Algorithms for Free Space Optical", STSM report by Joana Sofia do Sul da Mota Torres, German Aerospace Center
15. "Atmospheric turbulence models for vertical optical communication", L. HUDCOVÁ (1), R. RÓKA (2), M. KYSELÁK (3), (1) Brno University of Technology, Czech Republic, (2) Slovak University of Technology, Slovakia, (3) University of Defence, Czech Republic
16. Mohammed Elamassie, and Murat Uysal, "FSO-based Multi-La yer Airborne Backhaul Networks"
17. Bui Thai-Chien (Airbus), Link budget and turbulence modelling for laser satellite communication system dimensioning "

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18. Carlos Guerra-Yánez, Innocenzo de Marco, Javier García Olmedo, Florian Moll, and Stanislav Zvánovec, " Outdoors Evaluation of the Crosstalk Between Classical and Quantum Signals in a Free Space Terrestrial Link”
19. Máté Galambos, Giulio Cossu, Ernesto Ciaramella, " Theoretical loss analysis for free space optical links”
20. András Mihály, “Extending fiber-based quantum networks with non-terrestrial nodes”
21. Javier Garcia Olmedo, Characterization of FSO cross-talk and impact on QBER
22. Mohammed Elamassie, Murat Uysal, “Multi-Layer Airborne FSO Systems: Performance Analysis and Optimization”
23. Niek Doelman, “Field test with Optical Feeder Link, ground terminal”
24. S. Basu, L. Oliviero, G. Cossu, C. Cantore, A. D’Orazio, E. Ciaramella, Prospects of Optical
25. Wireless Communications in Non-Terrestrial Networks

2. Task 4.2 Field Trial Evaluation

As a part of the task 4.2 field trial evaluation, various partners fo the NEWFOCUS cost action have done some experiments and evaluation of the result on various topics related to WG4 Long Range links. The contributions are summarized below:

Outdoors Evaluation of the Crosstalk Between Classical and Quantum Signals in a Free Space Terrestrial Link

Carlos Guerra-Yánez[1], Innocenzo de Marco[2], Javier García Olmedo[2], Florian Moll[2], and **Stanislav Zvánovec[1]**

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[2]Institute of Communications and Navigation, German Aerospace Center, 82234, Wessling, Germany.

a) State of the art of similar systems

In [1], the authors explore, experimentally, the behaviour of background light captured by the telescope on the roof of the KN-OSL building in DLR-Oberpfaffenhofen. The relation between QBER and background light for a decoy-state BB84 protocol with polarization-encoded qubits is used as a benchmark for the system behaviour. The work shows a high-degree of agreement between the experimental results and the simulations of the background light in different observation elevation angles. In [2], the results of an experiment implementing decoy-state BB84 achieving a kHz secret key generation rate at a distance of 1200 km between a LEO satellite and a ground station. In this work, an analysis of the background light is not performed, but the authors report that the impact of background light is important, and several measures are employed in the satellite and ground station design to reduce this impact (spectral and temporal filtering to distinguish between signal and noise detections). The work reported in [3] focuses on a technique to compensate for the distortion introduced by scattering media in a QKD link. The authors identify, however, the impact of background noise as time-varying, and introduce spatial filtering to reduce the impact of incoming background light. All these systems illustrate the different characteristics of background light in QKD links, and some of the techniques that can be employed to reduce its impact on the system performance.

b) Demonstrator setup description

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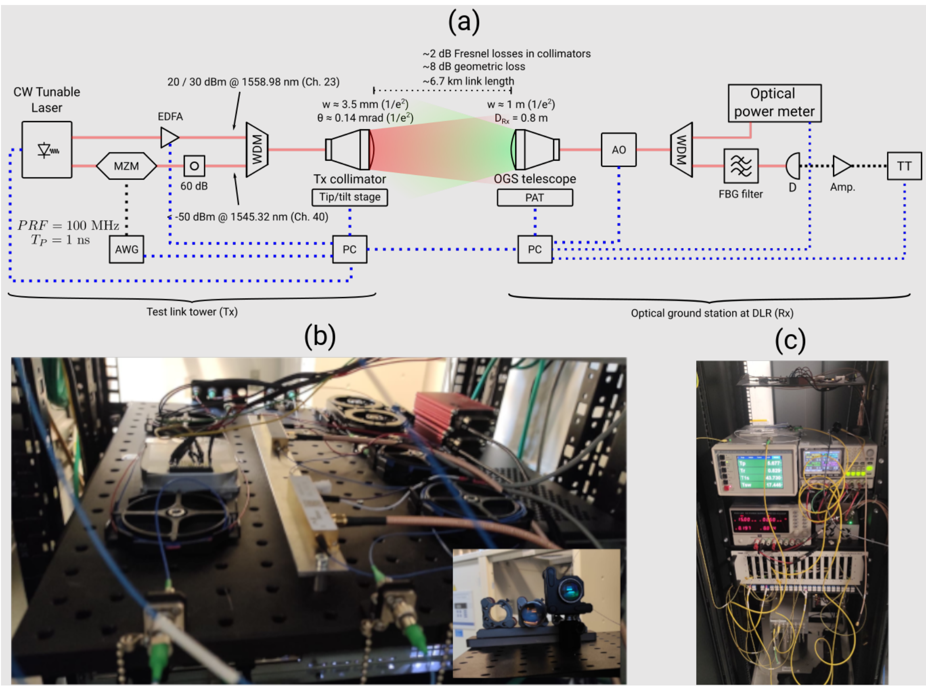
We used a CW laser source and a Mach-Zehnder Modulator (MZM) to generate 1 ns pulses with a peak intensity of approximately -75 dBm. The WCPs (ch. 40 in the ITU grid) were combined with an EDFA-amplified classical signal (ch. 23 in the ITU grid) and then demultiplexed to separate the quantum signals. The EDFA-amplified classical signal had a power of 30 decibels. Once the laboratory tests were completed, we prepared the transmitter board for deployment into the DLR rack inside the Funkturm Schöngeising (Schöngeising radio tower). The Funkturm Schöngeising is 6.7 kilometers north-west of the KN-OSL telescope in DLR-Oberpfaffenhofen, and the DLR rack is approximately 100 meters above ground level. The transmitter devices were successfully deployed into the tower, and the remote operation of the computer inside the rack was tested. For the FSO experiment, we used almost the same transmitter, with the exception of the synchronization signal, which was removed from the setup because we discovered it was unnecessary for this experiment, and the multiplexer output was launched into free space using a collimator. On the receiver side, we used the telescope on the roof of the KN-OSL building, as well as the adaptive optics (AO) system developed at DLR. To reduce noise and increase efficiency, the detection was performed with a superconductive nanowire single photon detector (SNSPD) rather than a SPAD. The outdoor experiment was conducted under three different environmental conditions (night, evening, and sunny morning). The raw data collected includes detection events with timestamps from the time tagger device, real-time power measurements, live meteorological data, and data from the AO system. Both the laboratory and outdoor experiments were completed successfully. The data captured during the laboratory experiment was used to establish and validate a bound on the required isolation for the different elements of the system. Note that if the demultiplexer and the filter have enough isolation, we can guarantee that the noise generated at the detector will be mainly due to the ASE noise copropagating with the WCPs in the same channel. The isolation (input at ch. 23, output at ch. 40) of the demultiplexer was measured to be ~70 db, while the filter's isolation was measured to be ~90 dB. On the other hand, the multiplexer's isolation (input at ch. 40 and output at ch. 23) was measured to be ~90 dB.



c) Evaluation results

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The jitter between the clocks of the AWG and the time tagger was evaluated to be ~11 ps, thus, a post-processing algorithm can be used to recover the WCPs without having to transmit a synchronization signal. The current state of the analysis shows that the predominance of background or crosstalk is not a trivial matter. Depending on the channel state (alignment, atmospheric perturbations, AO-tuning) and the amount of background light, each of the effects will have a predominant effect.

[1] Stefanie Häusler, Davide Orsucci, Leonard Vollmann, Eltimir Peev, Florian Moll, "Measurement-based characterization of atmospheric background light in satellite-to-ground quantum key distribution scenarios," Opt. Eng. 63(4) 041211 (2024) doi: https://doi.org/10.1117/1.OE.63.4.041211

[2] Liao, SK., Cai, WQ., Liu, WY. et al. Satellite-to-ground quantum key distribution. Nature 549, 43–47 (2017).doi: https://doi.org/10.1038/nature23655

[3] Q.-H. Lu et al., "Quantum Key Distribution Over a Channel with Scattering," Phys. Rev. Appl., vol. 17, no. 3, p. 034045, Mar. 2022, doi: https://10.1103/PhysRevApplied.17.034045

3. Field test with Optical Feeder Link, ground terminal

a) State of the art of similar systems

Enabling the next generation of very high-throughput satellites and constellations requires high-bandwidth feeder links. To overcome the limited availability of bandwidth in the RF domain, optical feeder links (OFLs) can be employed to benefit from the vast amount of bandwidth available in the THz-regime of the electromagnetic spectrum and to operate license-free. An overview of optical feeder link technology, challenges and progress can be found in [Arapoglou]. Reference [Martinez] provides a review of Adaptive Optics technology for optical feeder links.

Several OFL communication tests have taken place, which assess modulation and coding technology and also diversity techniques for feeder links. Some of those have achieved record data- rates of more than 13 Tbps [Fuchs] and 1 Tbps per wavelength division multiplexing (WDM) channel [Horst]. It should be realized however that these experiments are based on the non real-time processing of the received data, in which error correction is performed in an offline fashion, after the retrieval and storage of data.

Field tests with Adaptive Optics pre-compensation have been performed at Tenerife [Bonnefois], on a 13 km slant link. In [Walsh] a demonstration of a 100 Gbps coherent FSO communication over a folded link of 1.4 km is described. Early in-orbit demonstrator tests with optical feeder link technology have been recently reported in [Kudielka] and [Hristovski].

b) Demonstrator setup description

Here, we describe the field tests performed with optical feeder link technology in the context of the TOmCAT project.

- The TNO TOmCAT OFL system –

The TOmCAT project was implemented under the ESA's ARTES program ScyLight and is co-funded by ESA with the support of the Netherlands Space Office. In TOmCAT an optical ground terminal (OGT) has been developed for a Terabit/s optical feeder link from ground to GEO-satellite. Within TOmCAT, a demonstrator of the OGT has been tested in a campaign performed in 2022. This OGT demonstrator test aims to verify the following combined technologies: (1) Adaptive Optics (AO) pre-correction, (2) RF end-to-end communication link and (3) high power optical channel multiplexing.

Field test configuration [Broekens]

The field tests have been performed during spring and summer of 2022 at a location southwest of Utrecht, Netherlands. As depicted in Figure 1, the slant link spans approximately 10 km from the OGT demonstrator located in Cabauw to the Space Terminal Breadboard (STB), which is placed at a height of 226 meters inside the Gerbrandy tower in IJsselstein. The inclination of the link is approximately 1.3°. The area below the link is flat and mostly covered with grassland.

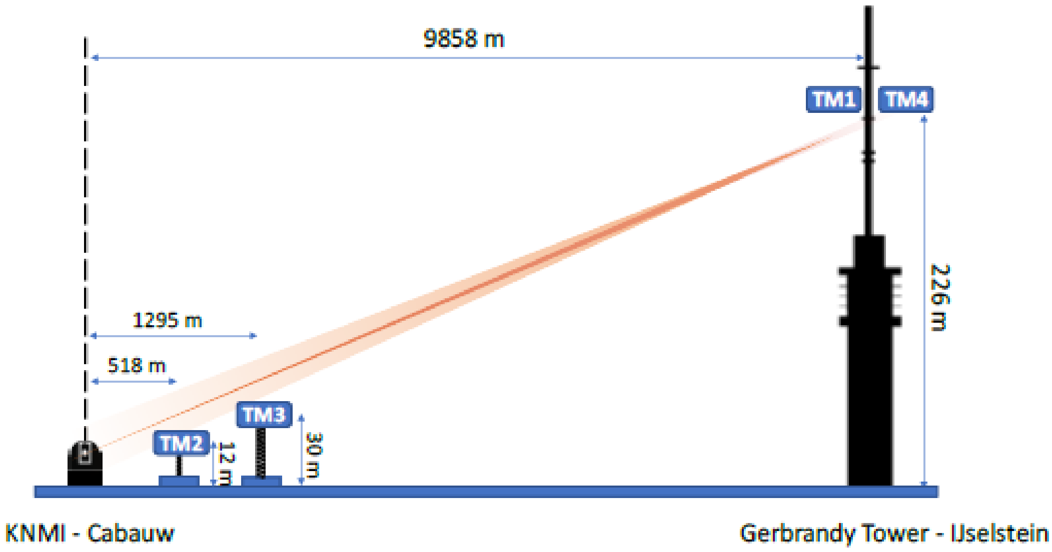

Figure 1; Illustration of the field test configuration with link path, ground station, space terminal and turbulence monitors (TM).

Figure 2; Photographic impression of satellite terminal (left) and ground station (right).

During the test campaign three types of tests have been performed. First, a single channel communication test consisting of an AO pre-compensated channel at a single wavelength of 1553.33 nm. Second, a multi-channel test which adds two dummy channels (1551.72 and 1554.95 nm) on top of the single channel communication, to verify the operation of the free-space high optical power

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Bulk Multiplexer [Silvestri] and on top of that the wavelength separation at the demultiplexer. The dummy channels with random bit streams are generated by two Acacia modules (CFP2-DCO). In a third test sequence the transmitter and receiver modem are included to facilitate the full RF end-to-end communication link.

The AO pre-compensation strategy is based on a 'classic' AO post-correction system of the incoming downlink optical beam. The underlying assumption here is that such a correction is also effective for the uplink optical beam to satellite. Inherently, it is assumed that the angular anisoplanatism caused by the point-ahead angle leads to a limited degradation of the correction performance. To investigate the impact of the anisoplanatism, the system can switch between a point-ahead angle of 0 and 18 µrad. Furthermore, the number of AO modes of the pre-compensation has been made tuneable.

During the field test, a predetermined sequence of measurements has been performed with various system configurations. For each measurement cycle a fixed Point Ahead Angle (PAA) and Wavelength Division Multiplexing (WDM) mode is chosen, whereas the communication mode and AO mode is being varied. Table 1 gives an overview of the test parameters during the single – and multi-channel tests. A total test cycle covers approximately 1 hour, in which each configuration is measured over 30 seconds.

Table 1; Optical and AO system configurations during the test procedures

Parameter	SETTING	DESCRIPTION
AO modes	2, 8, 16, 28	Number of pre-compensated AO modes
Point-ahead angle	0, 18	Point-ahead angle in µrad
Wave Division Multiplexing	1	Single wavelengths at 1553.33 nm
	3	Multiple wavelengths at 1551.72, 1553.33 and 1554.95 nm

The AO tip-tilt configuration (2 modes) serves as a reference for assessing the improvement achieved by correcting higher-order AO modes. The configuration without AO pre-compensation has not been tested, as the expected losses were too high to establish the communication link.

The end-to-end communication test consists of two parts. First, a multi-channel real-time 28Gbps per wavelength test with various coding rates and interleaver depths is performed. Second, assuming that the link budget is met, a demonstration of real-time error-free transmission of DVB signals over the digital transparent OFL is carried out.

a) Evaluation results

AO pre-compensation behaviour [Broekens]

As a first assessment, the downlink Adaptive Optics post-correction performance has been verified. This AO system performed as expected and shows a good match with simulated performance results in terms of residual wavefront phase error variance.

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Also, for the downlink the residual phase variance decays by increasing the number of AO-modes corrected. In the uplink pre-compensation case, this no longer holds. For a point-ahead angle of 18 µrad, the additional performance of higher-order AO mode correction is limited and brings a minor advantage over controlling the AO tip and tilt modes only; see Figure 3. Performance differences between the various AO mode cases are relatively small (<1 dB). This is due to the strong turbulence conditions of the tests and the increasing sensitivity to angular anisoplanatism with (Zernike) mode order. For this near-horizontal link setting, the point-ahead angle value of 18 µrad has turned out to be severe and not representative for the more vertical GEO-satellite link case.

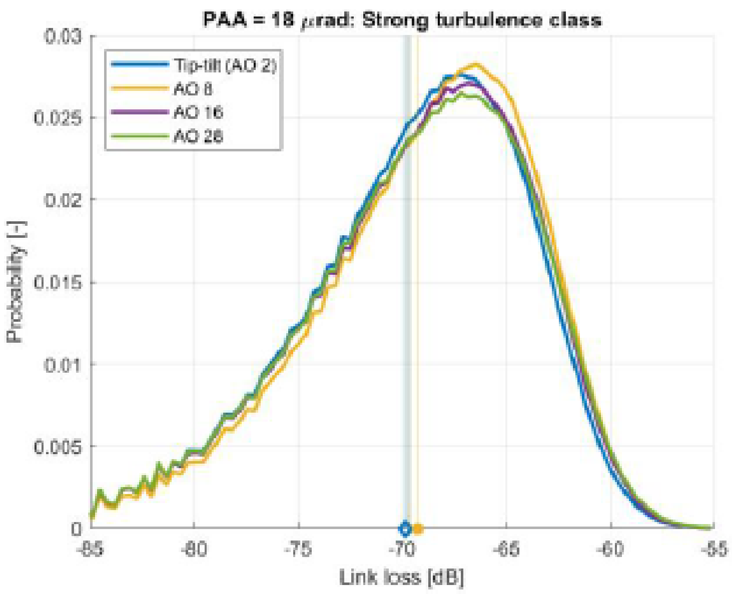

Figure 3: Probability distribution of link losses for strong turbulence conditions and 18 µrad point-ahead angle.

With respect to mean fade duration, AO pre-compensation with higher order modes is more advantageous; see Table 2. The outcomes show that correcting 28 AO modes leads to a significant reduction of the mean fade times, compared to correcting AO tip-tilt modes. A similar conclusion holds for the standard deviation of the fade durations. Also, the mean of the fade durations clearly decreases with increasing turbulence strength by 20-30%, which indicates that although the fades become deeper they last for a shorter period (on average).

Table 2; Mean fade durations in strong turbulence for 2 AO configurations and various outage %'s.

Fade duration – strong turbulence		
Outage %	**Mean [ms]**	
	2 AO modes	28 AO modes
10 %	6.52	4.59
5 %	4.86	3.37
1 %	2.67	1.92
0.5 %	2.17	1.56

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End-to-end communication performance [Korevaar]

1. Real-time 28Gbps/wavelength PRBS test

Under lab conditions, with the complete end-to-end system operating at 28Gbps, without fading, a BER of 1E-3 is obtained at a received optical power of about –37 dBm. For a BER of 1E-6, an optical power of -32 dBm is required. Adding a Reed Solomon code (255,223) yields to a coding gain of about 6.5 dB, resulting in a power of -38.5 dBm at 1E-6 BER. Under strong fading, as simulated in the lab and described by the gamma-gamma intensity probability distribution, about 20 dB more power is required to meet equivalent error levels.

In the field test, similar performance numbers have been found. The characteristic BER waterfall curves are depicted in Figure 4 using RS(255,223) together with interleaver lengths of 100 ms and 366 ms. Due to the severe fading, a long interleaver is required to spread out the bursts of errors over sufficient time to let the RS decoders fix the (evenly spread) bit errors. By lowering the coding rate to 0.75, and thus enhancing the error correction capability, the post-FEC BER is improved and practically all post-FEC measurements are below the target BER of 1E-6, when the receive optical power is higher than -28 dBm, as shown in Fig. 4(c).

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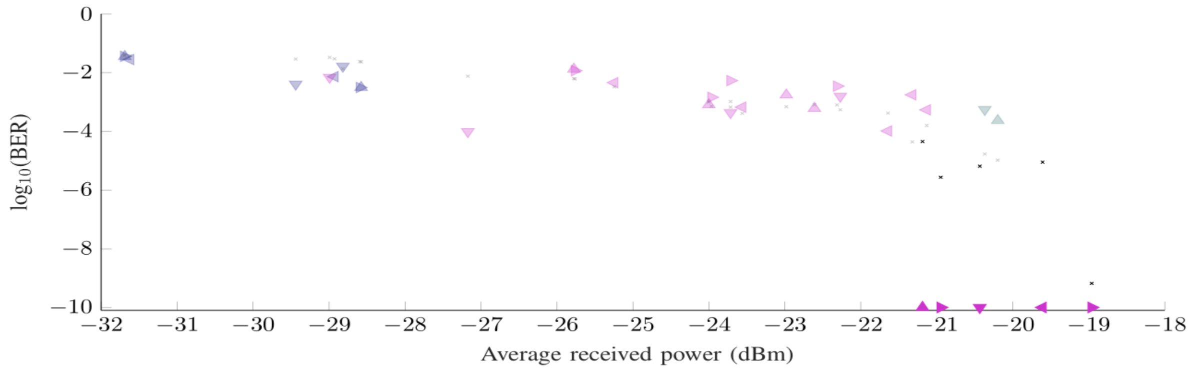
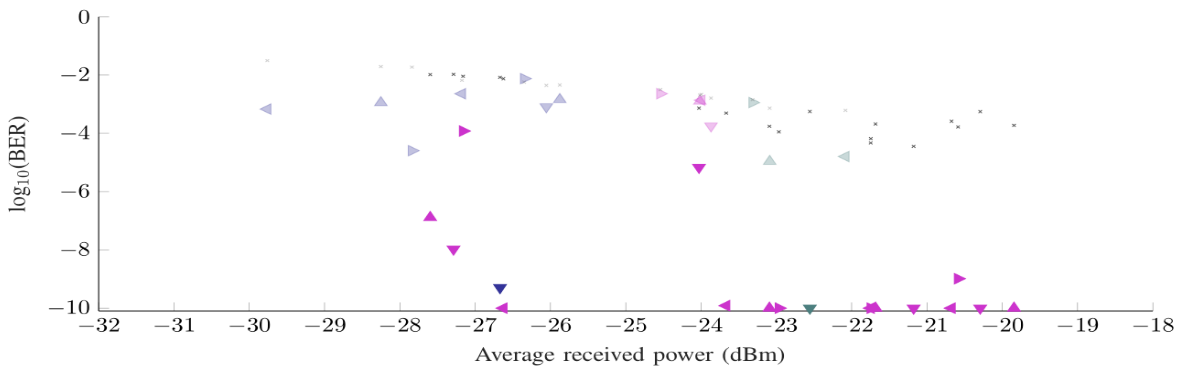
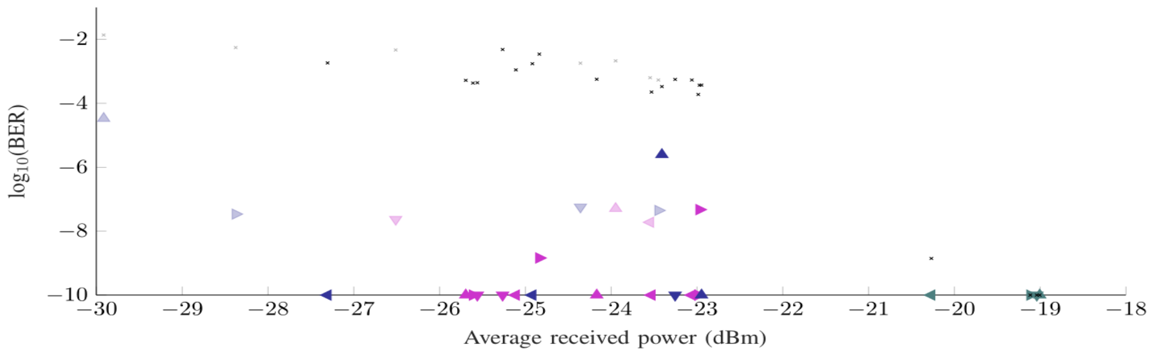


(a) RS 0.875 with 100 ms interleaver



(b) RS 0.875 with 366 ms interleaver



(c) RS 0.75 with 366 ms interleaver

Figure 4; BER waterfall plots based on combined measurements with various applied coding rates and interleaver durations. Measurements took place with various turbulence conditions (moderate, strong and very strong), AO settings

(◁ =2, ▷ =8, ▽ =16 and △ =28) and over multiple days, but always with 3 WDM channels and a point-ahead angle of 18 µrad. The average power is based on the power over the 30 second measurement interval. The small ‘x’ markers indicate

the estimated pre-FEC BER. The 4 markers show the post-FEC measurements. Transparent markers indicate that the BER checker has unlocked (at least once) during the 30 s measurement interval.

2. Real-time DVB test

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In the real-time DVB test the signal has been generated by a Viasat Hi-beam DVB modem. It is transported over the digital transparent OFL over 9.8 km and – after reconstruction – demodulated by a Newtek MDM6100 receive modem. The OFL is however limited by amplified spontaneous emission (ASE)-noise. In the case of severe fading with limited interleave depths, the risk of RS decoders unable to recover some codewords exists and the remaining optical bit errors lead to reconstruction errors of the DVB signals. To a high extent however, the receive DVB modem (due its own LDPC+BCH error correction) can handle the distortion due to reconstruction errors.

The parameter settings in this DVB test have been RS(255,223), point-ahead angle of 18 µrad, AO compensation for 28 modes and interleaver length of 366 ms. With a receive optical power of -20.9 dBm, an error-free run has been observed. This was temporarily interrupted, however, by a sudden jump of 875 DVB erroneous frames after 9 minutes. The packet error ratio observed was 5E-4 after 10 minutes. This above illustrates a typical test result. It is expected that the stability of transmission can be improved further by solving the occasional loss of a hyper-frame, and that error-free operations may be achieved at around -28 dBm, as shown for the PRBS tests.

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Fuchs, C. F. Moll, J. Poliak, A. Reeves, and C. Schmidt, “Optical satellite links at DLR,” in Free-Space Laser Communications XXXV, vol. 12413. SPIE, 2023, pp. 34–41.

Horst, Y. , B. I. Bitachon, L. Kulmer, J. Brun, T. Blatter, J.-M. Conan, A. Montmerle-Bonnefois, J. Montri, B. Sorrente, C. B. Lim et al., “Tbit/s line-rate satellite feeder links enabled by coherent modulation and full adaptive optics,” Nature - Light: Science & Applications, vol. 12, no. 1, p. 153, 2023.

Bonnefois et al. “FEELINGS, ONERA's optical ground terminal for AO pre-compensated GEO Feeder links demonstration”, Proceedings of the International Conference on Space Optics — ICSO 2022.

Walsh, S.M. et al.“Demonstration of 100 Gbps coherent free-space optical communications at LEO tracking rates”, Nature Scientific Reports volume 12, Article number: 18345 (2022)

Kudielka, K. et al. “Successful first optical feeder link demonstration between a ground station and a GEO satellite applying adaptive optics pre-compensation”, ,” IEEE International Conference on Space Optical System, 2023.

Hristovski, I.R. et al, “Pre-distortion adaptive optics: experimental results from bi-directional tracking links between DLR’s optical ground station and Alphasat’s TDP-1 terminal”, Proceedings of SPIE Conference 12877, 2024.

Silvestri, F. et al, “Beam multiplexing for satellite communication optical feeder links,” in Proc. SPIE Free-Space Laser Communications XXXII, 2020, pp. 1–9.

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Broekens, K.A. et al., “Field test demonstration of adaptive optics pre-correction for a terabit optical communication feeder link,” IEEE International Conference on Space Optical System, 2023.

Korevaar, W. et al., “Terabit Optical Feeder Links for DVB Satellite Systems: Real-time End-to-End Communication System Design & Field Test Results”, IEEE International Conference on Space Optical Systems 2023.

4. Publications on WG4

[1] Ivanov, H.; Marzano, F.; Leitgeb, E.; Bekhrad, P. Testbed Emulator of Satellite-to-Ground FSO Downlink Affected by Atmospheric Seeing Including Scintillations and Clouds. Electronics 2022, 11, 1102. https://doi.org/10.3390/electronics11071102
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[4] M. Grillo, A. Dowhuszko, M.-Ali Khalighi and J. Hämäläinen, “Resource allocation in a quantum key distribution network with LEO and GEO trusted-repeaters,” in Proc. International Symposium on Wireless Communication Systems, Belin, Germany, pp. 1-6, September 2021. Doi: 10.1109/ISWCS49558.2021.9562139. (T4.2, T4.3)
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[6] A. Vavoulas, H. G. Sandalidis, N. D. Chatzidiamantis, Z. Xu and G. K. Karagiannidis, "A Survey on Ultraviolet C-Band (UV-C) Communications," in IEEE Communications Surveys & Tutorials, vol. 21, no. 3, pp. 2111-2133, thirdquarter 2019, doi: 10.1109/COMST.2019.2898946.
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[8] Itay Sartori, Avi Davis, Alon Berlinski, Raz Chengal, Amir Handelman,Effect of water-waves on recognition of speech signals transmitted over a wireless optical communication channel, Optics & Laser Technology, Volume 167, “Outage performance of satellite-to-ground terminal system containing selection relaying”
[9] C. Guerra-Yánez et al., "The Throughput Bottleneck of Quantum-secure Communication Links: Analysis and Mitigation," in IEEE Transactions on Communications, doi: 10.1109/TCOMM.2024.3394746

5. Other Activities

5.1. Training School

In addition, training school was organized in August 2022 in University of Prague covering the topics on WG3 and WG4. For WG4 following lectures/presentations were provided to educate but also to advertise what fields and topics are currently being investigated in research industries.

i. Free space Optical Communication activities in German Aerospace Center (DLR), Oberpffafenhofen, Amita Shrestha (DLR)

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ii. Seminar on Optical Communication for Space, Dr. Dirk Giggenbach (DLR)
iii. Embedded Systems Development within the framework of new Space, Dr. Julio Ramirez (DLR)

5.2. Short Term Scientific Mission

Moreover, several Short-term scientific missions were also done to maximize the collaborative work between different WG members.

I. „Modelling near-Earth FSO channels and atmospheric seeing affected by turbulence and clouds “, Hristov Ivanov (TU Graz) and Sapienza Universita di Roma. 2nd October -15th October 2021.
II. “Influence of EDFA on the satellite QKD channel Research, Ali Khalighi (ECM) and DLR. August 2022
III. „ Development of High-Performance Adaptive Optics Control Algorithms for Free Space Optical Communication “, Joana Torres (DLR) and Instit d‘Optique, April 2023 (planned)
IV. “Influence of ASE noise from EDFAs on a free space QKD channel”, Carlos Guerra Yanez (University of Prague), and DLR. June 2023 (planned)
V. „Emulation and Definition of Continuous Variable QKD systems “, Marc Amay CTU, April-May 2023.
VI. „ Outdoors Evaluation of the Crosstalk Between Classical and Quantum Signals in a Free Space Terrestrial Link“, Carlos Guerra-Yánez (CTU Prague-DLR), March 2024
VII. „Theoretical loss analysis for free space optical links”, Máté Galambos (Budapest University of Technolgy and Economics in HU to Scuola Superiore Sant’Anna -IT), September 2023
VIII. „Extending fiber-based quantum networks with non-terrestrial nodes”, András Mihály (BMU - CTUPrague), May 2024
IX. „Characterization of FSO cross-talk and impact on QBER”, Javier Garcia Olmedo (DLR-CTU Prague), June 2024
X. „Tomographic Reconstruction Algorithms for Lasere-Guide-Star-Assisted Pre-Distortion Adatptive Optics Systems“, Ilija hristovski (DLR-ESA Teide Observatory-ES), June 2024

5.3. White paper

Finally, second white paper is being prepared covering the topics for WG3 and WG4. Contributions from WG4 are:

iv. Giulio Cossu, Veronica Spirito, Michail P. Ninos, Ernesto Ciaramella, “Wavelength Division Multiplexing Free Space Optical Links”.
v. Joan Bas, Marc Amay, “Review of Hybrid Optical-Radio Inter-Satellite Links in 6G NTN Including Quantum Security”.
vi. Davide Orsucci, Florian Moll, Amita Shrestha, “Review of low-Earth orbit satellite quantum key distribution”.
vii. Davide Orsucci, Florian Moll, Amita Shrestha, “Perspectives for global-scale quantum key distribution via uplink to geostationary satellites”.

6. Conclusions

Various contributions to the milestone have been made in collaboration with different working group members in terms of input documents, short-term scientific missions and publications. For working

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group 4, short term scientific missions were particularly very popular and have helped establish knowledge transfer and collaboration between different institutes.

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