SHORT TERM SCIENTIFIC MISSION (STSM) – SCIENTIFIC REPORT

The STSM applicant submits this report for approval to the STSM coordinator

Action number: COST CA15127 Action, STSM reference number: 40335
STSM title: FSO channel modelling and characterization in terms of various atmospheric turbulence conditions as well as fog effect
STSM start and end date: 24/03/2018 to 31/03/2018
Grantee name: Hristo Ivanov

PURPOSE OF THE STSM/

Due to various advantages Free Space Optical (FSO) systems gain more and more popularity among the other available wireless communication technologies. However, optical wireless communications can be easily deteriorated in the presence of different atmospheric effects. In general the main atmospheric effects responsible for the attenuation and blockage of the FSO systems are Mie scattering (fog and clouds) and turbulence. In case of fog and clouds, the size of water droplets is comparable with the optical wavelength which leads to attenuation due to Mie scattering. On the other hand, turbulence effect caused by random changes of the atmospheric refractive index, leads also to fading and deformation of the transmitted optical beam. Atmospheric turbulence can be divided into two different effects, namely scintillations and beam wondering. Beside this, its characteristics strongly depend on the chosen scenario.

Based on the above discussion, Mie scattering (fog and clouds) and clear-air turbulence effect can introduce severe impairments reducing FSO channel availability and reliability. The investigation of both parameters is very crucial for Working Group 2 (WG2), which main goal is to increase the reliability and capacity of the FSO in the presence of weather-based disruptions which also includes preliminary examination of the mentioned atmospheric effects leading to optical signal impairments. Consequently, further investigation of the atmospheric influences over FSO channel can be considered as an important task which is directly related to WG2.

To sum up, the present STSM in frame of COST action CA15127 RECODIS is very narrow related to WG2. It will provide more detailed information in terms of different turbulence conditions and their effects over broad range of possible FSO communication scenarios such as terrestrial and space one. Moreover also Mie scattering will be considered. In this way the reliability and capacity of FSO system can be improved and in this way fully contribute to WG2.

DESCRIPTION OF WORK CARRIED OUT DURING THE STSMS

In the frame of the current STSM I have a scientific research stay in Sapienza University of Rome. There I have possibility to work with Prof. Frank Marzano who has excellent expertise in characterization of FSO communication channel including various atmospheric effects. During our intensive discussions we defined a few main topics which cover various aspects related to the atmospheric conditions influencing optical

wireless communications. In addition, a detailed work plan was created which is completely considered during my current research. The three main STSM topics together with their subtasks are as follows:
1) Modelling satellite Free-Space Optical channels by means of a physical approach

- Preliminary update survey of literature
- Investigating the possible location for deploying FSO communication links, which is mainly important in terms of deep space FSO communications.
- Appling radio sounding datasets for the chosen locations. The radio sounding data for various locations around the world are provided by university of Wyoming, USA. In general, the Wyoming weather databases content two times per day measurements for each of the locations.
- The simulations should be executed in Matlab based on formulas in Section II of F. Marzano et al. [1]. In this way the power scintillation index and Rytov log amplitude variance will be obtained.
- Providing the plots of Section IV related to paper [1] for the chosen locations.

2. FSO time-correlated channel model for implementing end-to-end hardware emulator

- Detailed definition of the problem together with preliminary update survey of literature
- Simulation in Matlab environment of the FSO Gamma-Gamma channel model which can represent significantly well all kind of turbulence conditions. The simulations are based on formulas in Section II of paper [2].
- Accomplishing Fourier transform of the covariance function provided in [2]. The covariance function gives the relationship between received optical irradiance values where different turbulence atmospheric conditions are applied.
- Verification if the Fourier transform of the covariance function can provide the scintillation filter function.
- Verification if a hardware filter with appropriate frequency response characteristic can be used to replicate the turbulent channel.
- Providing simulated dataset based on the developed turbulence conditions.
- The calculated attenuation data can be verified based on already developed channel emulator incorporating Variable Optical Attenuator in OptiKom Group, TU-Graz [3].

3. Microphysical characterization of Free Space Optical link due to hydrometeor and fog effects

- Preliminary updated survey of literature where main emphasis will be put on paper [4]. More specifically the simulations should be based on Section II, Section III and Appendix A of paper [4].
- Selection of particle size distributions (PSDs) which are already available from previous measurement campaigns. The measurements are accomplished within OptiKom Group of TU-Graz, Austria in cooperation with Koruza Company, Slovenia.
- Having the PSDs, formula (A5) from paper [4] should be applied to compute water content W_p.
- In addition, formula (7) should be used to compute the extinction coefficient in km^{-1} for radiation/advection fog (also cloud, rain, snow) at 1550 nm (or 850 nm) wavelength.
- Finally the channel attenuation should be calculated based on the dB formulation of Lambert-Beer law.
- The calculated attention data can be verified based on already developed simulator incorporating Variable Optical Attenuator in OptiKom Group, TU-Graz [3].

Based on the above created work plan, together with Prof. Marzano we established one excellent collaboration during which I had a possibility to initiate a joint research and to examine the influence of different tropospheric weather conditions over the transmitted optical beam. Although Mie scattering (fog) is also considered during my STSM, the main emphasis is put on the clear-air turbulence effect which can introduce severe impairments reducing FSO channel availability and reliability. Nevertheless, investigation of the both atmospheric effects is very important for WG2. In other words, the current work as well as the established collaboration can significantly contribute to COST action CA15127 RECODIS.

DESCRIPTION OF THE MAIN RESULTS OBTAINED

Regarding to the described tasks and the discussed work plans, in this part more detailed information in terms of the carried out research is provided. Although the terrestrial FSO is also considered, the main focus is concentrated on deep space optical links. The deep space FSO ground stations are located only in specially selected locations where the atmospheric influences are enough favorable. In other words, the selected areas should have the lowest possible probability for occurrence of thick clouds. In addition, they should be deployed at high altitudes and far enough from cities or residential areas. In conclusion, the ideal optical ground station locations is at the top of a hill (mountain) combined with least possible amount of clouds. However, these conditions are usually very problematic to be met. After intensive research two different places are selected as good locations for deep space communications. One very suitable area for establishing deep space communication link in Canary Islands, where the mean cloud probability is 0.3 which leads to overall link availability of 70%. Moreover, another place which is considered to be a good location for a deep space links is Hawaii islands. The sounding data for both locations are provided by university of Wyoming. The description of the sounding columns is as follows: atmospheric pressure, geopotential height, temperature T, dewpoint temperature, relative humidity, mixing ratio, wind orientation, wind velocity, potential temperature, equivalent potential temperature, and virtual potential temperature. An extract from Canaries' and Hawaii's sounding data is provided in Table 1 and Table 2.

Table 1. Canaries' radio sounding datasets.

PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1008.0	12	23.6	21.9	90	16.72	180	3	296.1	344.4	299.0
1000.0	86	23.2	20.5	85	15.43	215	4	296.4	341.0	299.1
983.0	236	22.4	20.2	87	15.41	283	7	297.0	341.7	299.7
975.3	305	22.5	19.3	82	14.70	315	8	297.8	340.6	300.4
967.0	379	22.6	18.4	77	13.97	321	7	298.6	339.4	301.1
941.7	610	20.7	17.3	81	13.34	340	5	298.9	338.1	301.4
927.0	746	19.6	16.6	83	12.98	2	5	299.2	337.2	301.5
925.0	765	19.6	16.7	83	13.10	5	5	299.3	337.8	301.7
909.2	914	18.9	17.1	90	13.71	135	1	300.1	340.4	302.6
903.0	973	18.6	17.3	92	13.95	154	2	300.4	341.5	302.9
882.0	1175	18.2	16.2	88	13.31	221	4	302.0	341.5	304.4

Table 2. Hawaii's radio sounding datasets.

PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1015.0	56	18.6	9.6	56	7.44	195	2	290.5	311.9	291.8
1012.0	82	16.8	7.8	55	6.60	192	2	289.0	307.9	290.1
1000.0	187	15.8	7.8	59	6.68	180	2	288.9	308.1	290.1
925.0	841	9.8	5.6	75	6.20	150	2	289.3	307.2	290.4
850.0	1538	4.8	4.5	98	6.25	355	8	291.2	309.3	292.3
840.0	1634	3.8	3.4	97	5.85	345	8	291.1	308.1	292.1
838.0	1654	4.0	3.4	96	5.86	343	8	291.5	308.6	292.5
837.0	1664	4.8	4.1	95	6.17	342	8	292.4	310.4	293.5
834.0	1693	6.6	-9.4	31	2.26	339	8	294.6	301.7	295.1
831.0	1723	8.8	-13.2	20	1.67	336	8	297.3	302.6	297.6
820.0	1833	9.2	-15.8	15	1.37	325	8	298.8	303.3	299.1

After the two appropriate locations are already selected and related radio sounding datasets are downloaded, the data are processed. The block diagram of the applied MATLAB simulation code provided by research group of Prof. Marzano is shown in Fig. 1. These self-developed simulations provides very good results shown already in paper [1]. However they should be also adapted to our case, namely to the two new selected locations above. The main reason is that the way in which radio sounding measurements are accomplished it is not the same for the different locations. In other words there is necessity for special changes.

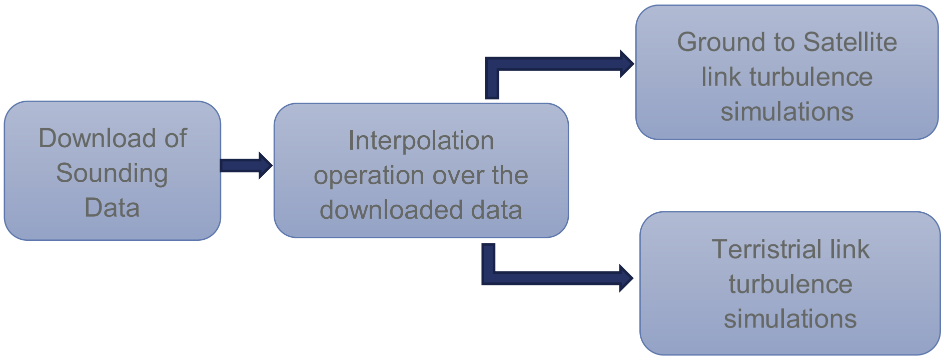

Fig.1 MATLAB simulation code

According to Fig. 1., the next step after the data are downloaded is applying an interpolation method. The linear interpolation procedure is used in order to avoid lack of data. In addition, the data have been interpolated at the same height levels. Finally the interpolated meteorological data are used for estimation of the scintillation index for both vertical and horizontal communication links. In this way both satellite (deep space) and terrestrial FSO links are considered. The calculations are accomplished based on well-established turbulence scintillation model from the theory. This includes also calculation of the atmospheric turbulence refractive index which is directly connected to the raw meteorological data presented in Table 1 and Table 2. Once the simulated results are accomplished, the link reliability and availability will be taken into account. In this way the strength of the weather-based disruption effects over optical channel will be evaluated, which is especially important in terms of WG 2.

The second phase of the research includes real hardware based simulations which must be prepared with help of specially selected filter. During the design phase the specific characteristics of the atmospheric turbulence scintillations should be taken into account. In general, when the sizes of the turbulence air pockets are smaller than the transmitted optical beam diameter, diffraction and ray bending leads to distortions in the laser beam wave front. Consequently temporal fluctuations in the laser beam intensity appeared, known as scintillations at the receiver with a frequency spectrum from 0.01 Hz to 200 Hz. Based on this we reached the conclusion that a proper turbulence representing with a low-pass filter is necessary which to cut the high frequencies. The basic architecture of the atmospheric turbulence emulator is presented in Fig. 2.

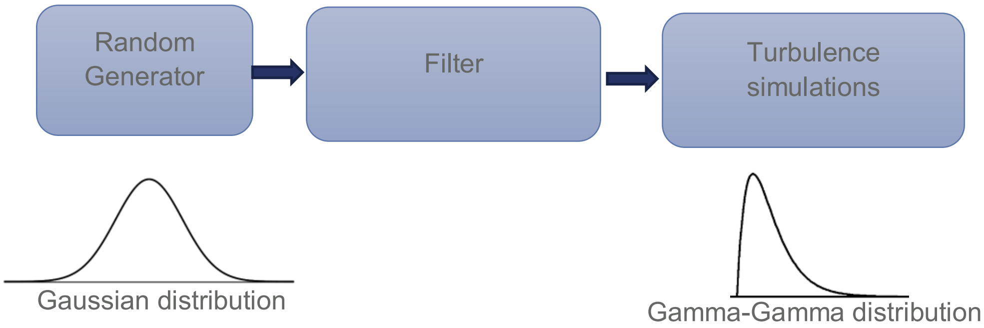

Fig. 2 Atmospheric turbulence emulator

Regarding Fig. 2., the input signal is provided by Gaussian random generator. In other words the transmitted electrical signal has Gaussian distribution. Once the signal is processed by the applied filter, we already have signal which is Gamma – Gamma distributed. In other words, in case the filter is properly selected the output signal should be characterized with the following covariance function:

$$B_I(\rho)=exp\left[\left(\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right){}_1F_1\left(\frac{7}{6};1;-\frac{k(\rho)^2\eta_x}{4L}\right)+\left(\frac{0.50\sigma_R^2}{\left(1+0.69\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}}\right)\left(\frac{k(\rho)^2\eta_y}{L}\right)^{\frac{5}{12}}K_{5/6}\left(\sqrt{\frac{k(\rho)^2\eta_y}{L}}\right)\right]-1 \quad (1)$$

Consequently the desired scintillation filter function is compared with the Fourier transform of the covariance function presented in (1). Once the hardware turbulence emulator is developed the turbulence based fading can be coupled into already developed FSO channel simulator of OptiKom Group, TU-Graz, Austria [3]. The simulator is based on Variable Optical Attenuator with which the attenuation in the artificially represented optical channel can be directly varied.

The final works includes Mie scattering investigation based on already measured particle size distribution of different artificially simulated fog effects. This task will be investigated in a later phase due to fact that the main topic is related turbulence effect.

FUTURE COLLABORATIONS (if applicable)

During my STSM in frame of COST action CA15127 RECODIS in Sapienza University of Rome, Italy, I obtained important knowledge in terms of FSO channel characterization. More specifically a work plan for detailed investigation of the atmospheric influence over FSO optical channel is developed. Although Mie scattering is also considered the main tasks are related to the investigation of the turbulence effect. Based on the work plan and the conducted research, reliability of (deep space) FSO communication links can be significantly increased in the presence of various deteriorative atmospheric effects (turbulence and Mie scattering). Consequently, the current problem is completely related to WG2 so I will continue the initiated narrow collaboration with Sapienza University of Rome, Italy. In other words, the FSO communications in terms of reaching higher reliability will be further examined. The future plans also includes publications in an appropriate conference and journal. The scientific papers will be related to three topics clearly presented above.

References

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[2] A. Ando, S. Mangione, L. Curcio, S. Stivala, G. M. Garbo, A. C. Busacca, G. M. T. Beleffi, F. S. Marzano, “Rateless codes performance tests on terrestrial FSO time-correlated channel model” International Workshop on Optical Wireless Communications (IWOW), 2012

[3] H. Ivanov, T. Plank, C. Pock, E. Leitgeb, "FSO System Performance Evaluation Based on Calibrated Atmospheric Channel Emulation", 14th International Conference on Telecommunications (ConTEL 2017), Zagreb, Croatia, 28th - 30th June, 2017

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