Propagation Characteristics and Availability Performance Assessment for Simulated Terrestrial Hybrid 850 nm/58 GHz System

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Abstract. *Results of a propagation study on a free space optical link at 850 nm on a path 853 meters long and on a parallel 58 GHz radio link obtained over a 3-year period of observation are presented. The cumulative distributions of attenuation due to all of the hydrometeors combined as well as due to individual hydrometeors were obtained for both paths. The availability performances of the FSO link, the RF link and the simulated hybrid FSO/RF system were assessed. Significantly higher availability performance was achieved for the simulated hybrid FSO/RF system than for the FSO link alone. The diversity improvement factor reached significant values for attenuation greater than 5 dB and a significant diversity gain was obtained for the percentages of time smaller than 2%.*

Keywords

Free space optical link, radio link, hybrid system, availability performance.

1. Introduction

Free space optical (FSO) links can be used as affordable last mile broadband solutions. Their advantages are easy installation, rapid deployment time and significant cost savings. The disadvantages of FSO links are that their availability performances are seriously affected by lower atmospheric visibility which is significantly influenced mainly by fog, snow and their combinations [1], [2]. Novel radio frequency (RF) digital systems operating in the frequency bands above 50 GHz are able to transmit a signal with a bit rate of up to 10 Gbit/s [3], [4]. In contrast to FSO systems, heavy rainfalls have a significant impact on the availability performance of RF systems. A hybrid FSO/RF system, i.e. an FSO link backed up by an RF link, uses the strengths of each system to overcome each others´ weaknesses. It can achieve a higher link availability performance than a particular FSO or RF link due to the fact that the RF part of a hybrid FSO/RF system can mitigate the influence of dense fog events and the FSO part can mitigate heavy rainfall events [5]. The selection and calculation of certain design parameters of a hybrid FSO/RF system, switching and some results obtained during short-term experiments are given in [6], [7].

Fog seems to be the most important impairment factor for FSO links. Fog-only events as well as combinations of fog with hydrometeors like fog with rain, fog with snow or fog with rain and snow significantly reduce the atmospheric visibility [8]. Long-term measurements of visibility are carried out at meteorological stations and airports by means of transmissometers or diffusiometers and therefore these visibility data are usually used for the assessment of fog attenuation. However, these measurements do not differentiate between fog-only events and the combination of fog with other hydrometeors. Fog-only visibility data should be used for the conversions of visibility to the specific attenuation due to fog. Conversely, both the fog-only events and the combinations of fog with other hydrometeors should be used for the assessments of availability performances of FSO links. Therefore, the influence of combinations of fog with hydrometeors on the total fog attenuation is shown.

The parallel experimental FSO/RF paths are realized in a collaboration of the Czech Metrology Institute (CMI) with the Institute of Atmospheric Physics of the Academy of Sciences of the Czech Republic (IAP AS CR). Both propagation characteristics and availability performances of the FSO link, RF link and simulated hybrid FSO/RF system were examined on our experimental paths.

2. Experimental Set-Up

The experimental set-up consists of an FSO path, a parallel RF path, meteorological measurements near the receiver sites, data gathering and data processing.

2.1 FSO Path

The commercially available FSO system operates at 850 nm on a path about 853 metres long. The transmitted power is about 16 dBm, the divergence angle is 9 mrad and the optical Rx aperture is 515 cm^2. The recording optical fade margin is about 17 dB.

2.2 RF Path

The commercially available RF system operates at 57.670 GHz with V polarization on the same experimental path as the FSO system. The transmitted power is about 5 dBm and the recording fade margin is about 27 dB.

2.3 Terrain Profile

The terrain profile of the path between the IAP AS CR and the CMI is line-of-sight. The elevation angle from IAP AS CR to CMI is about 2.2°, and the difference of altitudes is about 33 m.

2.4 Meteorological Measurements

Meteorological conditions were identified by means of data obtained from a weather observation system located near the receiver sites and from color video-camera images of the space between the transmitter and the receiver sites. The system uses Vaisala sensors for the measurement of temperature, humidity, air pressure and the velocity and direction of the wind. The rain intensities were measured using a dynamically-calibrated heated tipping-bucket rain gauge with a collector area of 500 cm^2, and the rain amount per tip was 0.1 mm. The Vaisala PWD11 device was used for the measurement of visibility in the range from 2000 m up to 50 m. The meteorological data were synchronized in time with the measurement of hydrometeor attenuation.

2.5 Data Processing

Both the received FSO and RF signal levels were measured, recorded synchronously on a PC hard disk, and statistically processed. All the recorded individual attenuation events were compared with the concurrent meteorological conditions and were carefully categorized according to the types of individual hydrometeors that occurred. Attenuation events due to individual types of hydrometeors, i.e. rain (R), rain with snow (RS), snow (S), fog only (F), fog with rain (FR), fog with snow (FS), fog with rain and snow (FRS) were identified. Rain intensities contained in the observed FR events, FS events and FRS events were always smaller than 3 mm/h. On the FSO link this rain intensity, however, could cause the maximum attenuation of about 2.5 dB/km during an FR event, about 8.6 dB/km for a wet snow event and about 25.3 dB/km for a dry snow event during the FS events, respectively [9]. Therefore, the fog events were ranked minutely. Only those attenuation events which were unambiguously identified due to their origin were statistically processed. It should be noted that the cumulative distributions of attenuation due to snow as well as due to rain with snow might be influenced by additional attenuation due to snow particles settled down on both the shield of the FSO system's lens and the RF system's antenna radomes.

The obtained attenuation data were processed over a 3-year period from December 2006 to November 2009. The cumulative distributions (CDs) of attenuation due to hydrometeors were obtained for the individual months and the individual year periods over the 3 year period of data processing.

3. Attenuation due to Hydrometeors on FSO Path

The obtained monthly CDs of attenuation due to all of the hydrometeors combined (R, RS, S, F, FR, FS, FRS) for the individual 1-year periods of observation on FSO path are given in Figs. 1-3.

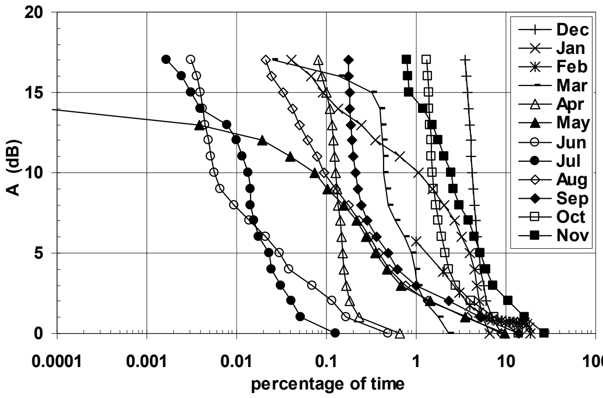

Fig. 1. Obtained monthly CDs of attenuation due to all of the hydrometeors combined on the FSO path for the 1st year period.

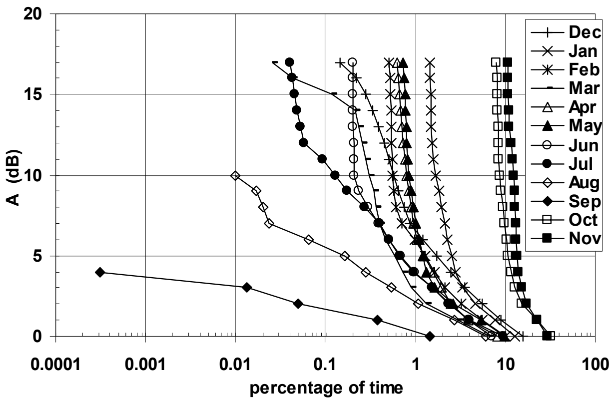

Fig. 2. Obtained monthly CDs of attenuation due to all of the hydrometeors combined on the FSO path for the 2nd year period.

The large month-to-month variability of these distributions can be observed. The CD of attenuation due to all of the hydrometeors combined for the worst month of the 1st year period is formed by the pertinent parts of the CDs for November and December. For the 2nd year period, the CD of attenuation due to all of the hydrometeors combined is formed by the CD for November.

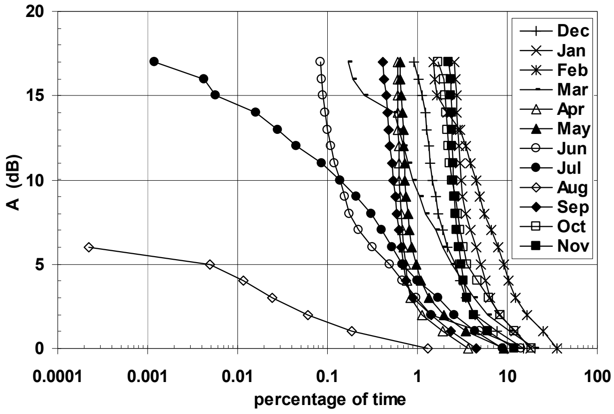

Fig. 3. Obtained monthly CDs of attenuation due to all of the hydrometeors combined on the FSO path for the 3rd year period.

The CD of attenuation due to all of the hydrometeors combined for the worst month of the 3rd year period is formed by the pertinent parts of the CDs for February and January. It can be seen that the dominant attenuation events occurred mainly during the period from November to February, i.e. during the winter months. The insignificant attenuation events, i.e. the small or short-term attenuation events occurred from May to September.

The obtained annual CDs of attenuation on the FSO path due to both all of the hydrometeors combined and the individual hydrometeors separately are shown in Figs. 4-6.

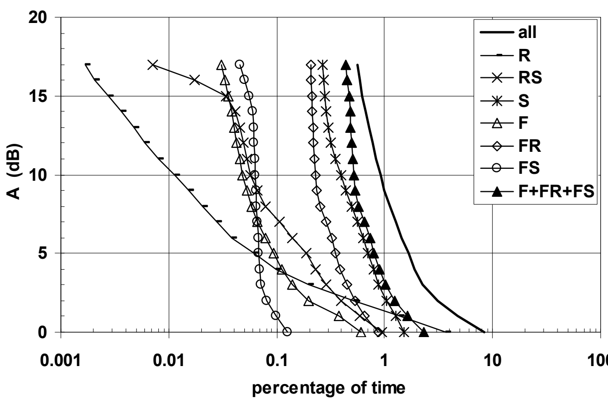

Fig. 4. Obtained CDs of attenuation due to individual hydrometeors on the FSO path for the 1st year period.

It follows from Figs. 4-6 that the dominant attenuation events were caused by fog events combined (F+FR+FS+ FRS) while the FR events were most significant of these for the 2nd and the 3rd year period. For the 1st year period, the snow events were more significant than the fog-only events.

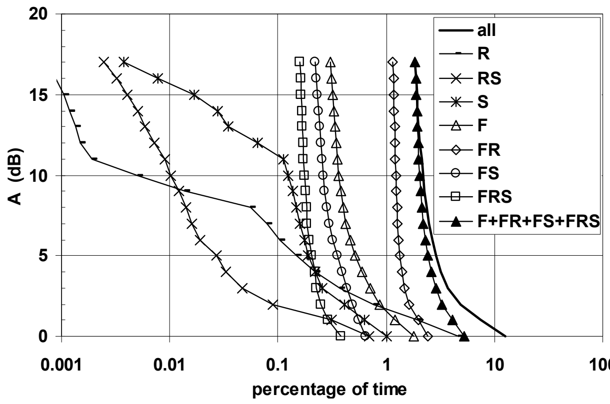

Fig. 5. Obtained CDs of attenuation due to individual hydrometeors on the FSO path for the 2nd year period.

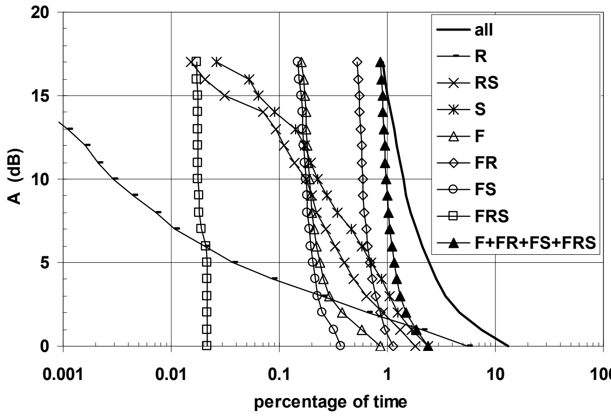

Fig. 6. Obtained CDs of attenuation due to individual hydrometeors on the FSO path for the 3rd year period.

4. Attenuation due to Hydrometeors on RF Path

The obtained monthly CDs due to all of the hydrometeors combined (R, RS, S, F, FR, FS, FRS) for the individual 1-year periods of observation on the RF path are given in Figs. 7-9.

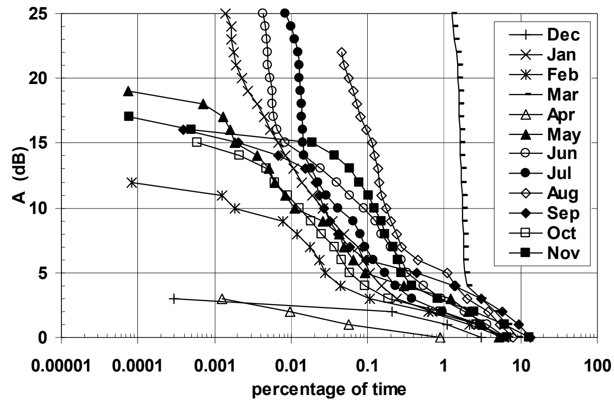

Fig. 7. Obtained monthly CDs of attenuation due to all of the hydrometeors combined on the RF path for the 1st year period.

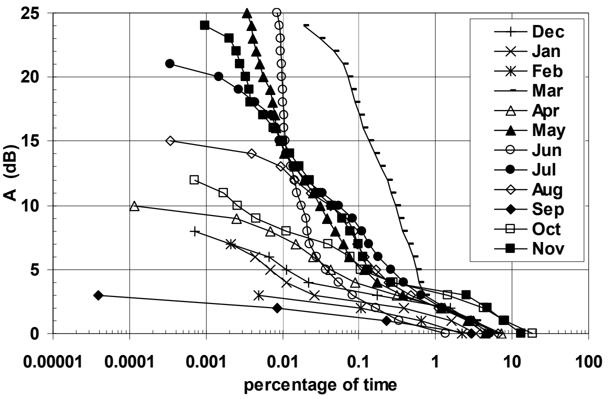

Fig. 8. Obtained monthly CDs of attenuation due to all of the hydrometeors combined on the RF path for the 2nd year period.

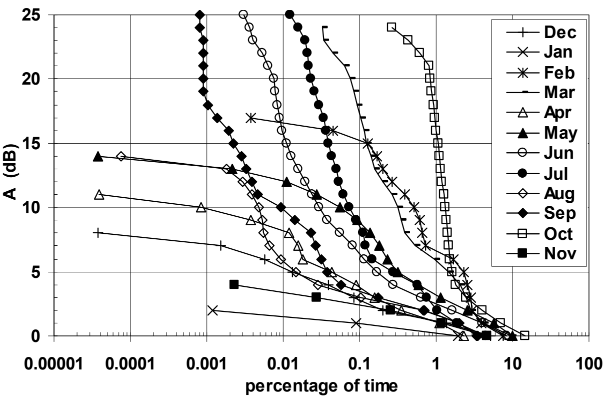

Fig. 9. Obtained monthly CDs of attenuation due to all of the hydrometeors combined on the RF path for the 3rd year period.

The large month-to-month variability of these distributions can also be observed. The CD of attenuation due to all of the hydrometeors combined for the worst month of the 1st year period is formed by the pertinent parts of the CDs for March and September. For the 2nd year period, the CD of attenuation due to all of the hydrometeors combined is formed by the pertinent parts of the CDs for March and November. The CD of attenuation due to all of the hydrometeors combined for the worst month of the 3rd year period is formed by the pertinent parts of the CDs for October and February. The insignificant attenuation events, i.e. the small or short-term attenuation events occurred during the winter months, i.e. from November to February.

The obtained annual CDs of attenuation on the RF path due to both all of the hydrometeors combined and the individual hydrometeors separately are shown in Figs. 10-12.

It follows from Figs. 10-12 that the dominant attenuation events were caused by RS and R events for the 1st and 2nd year period and by S, RS and R events for the 3rd year period. It can be seen that the F, FR, FS and FRS events only caused insignificant attenuation events.

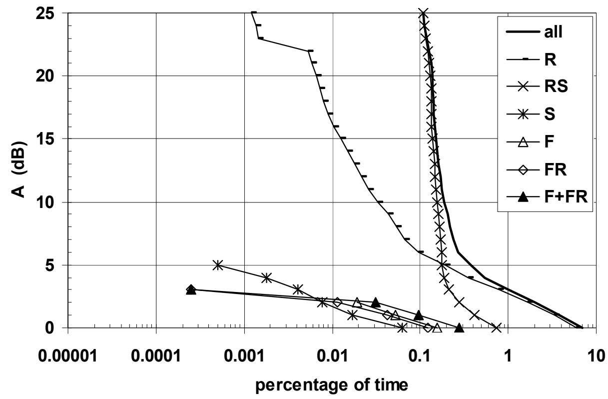

Fig. 10. Obtained CDs of attenuation due to individual hydrometeors on the RF path for the 1st year period.

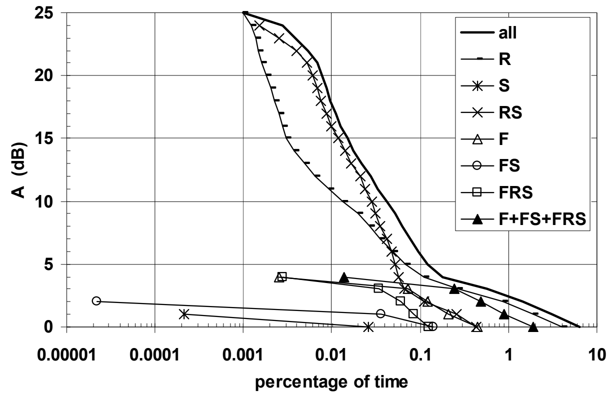

Fig. 11. Obtained CDs of attenuation due to individual hydrometeors on the RF path for the 2nd year period.

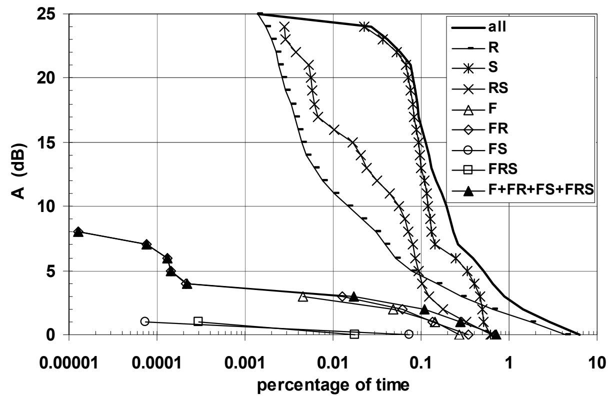

Fig. 12. Obtained CDs of attenuation due to individual hydrometeors on the RF path for the 3rd year period.

5. Yearly CDs of Attenuation due to Hydrometeors on FSO and RF Paths

The obtained CDs of attenuation due to all of the hydrometeors combined on the FSO and RF paths for the individual year periods and the average year over the 3-year period are displayed in Figs. 13 and 14.

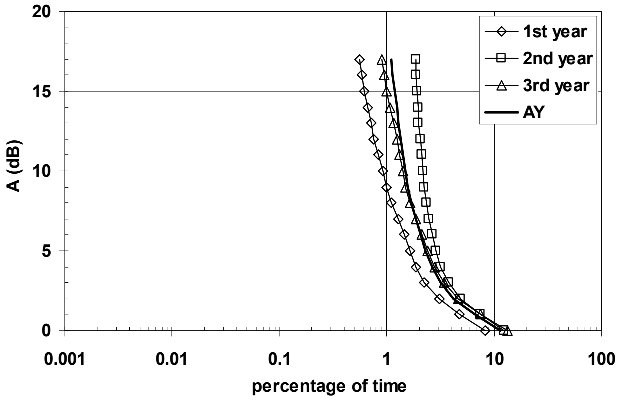

Fig. 13. Obtained CDs of attenuation due to all of the hydrometeors combined on the FSO path for the individual year periods and the average year.

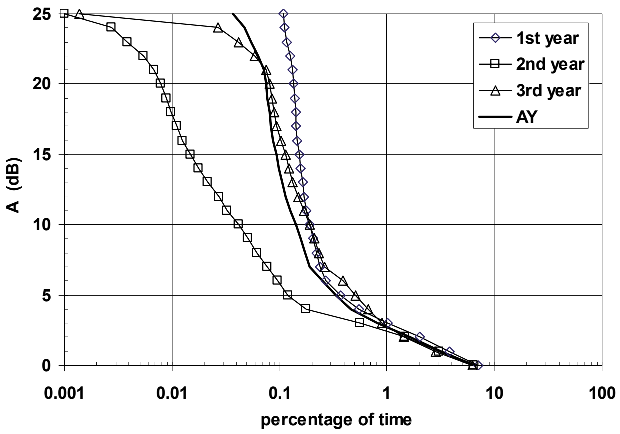

Fig. 14. Obtained CDs of attenuation due to all of the hydrometeors combined on the RF path for the individual year periods and the average year.

It can be seen that the dominant attenuation events occurred on the FSO path during the 2nd year of observation while the dominant attenuation events on the RF path occurred during the 1st year of observation.

6. Availability Performance of Hybrid FSO/RF System

Availability performances [10] of FSO links are mainly limited by dense fog events while availability performances of RF links are influenced predominantly by heavy rainfall events. A simple diversity technique can be simulated, so either the FSO part or the RF part of the hybrid FSO/RF system is active depending on instantaneous values of the optical and radio path attenuation. It can be assumed that the RF part of the system mitigates non-rain events and the FSO part mitigates rain events. The availability performances of the FSO link, the RF links and the simulated hybrid FSO/RF system can be assessed from the CDs of attenuation due to all of the hydrometeors combined which are given in Figs. 15-17 for the individual year periods of observation.

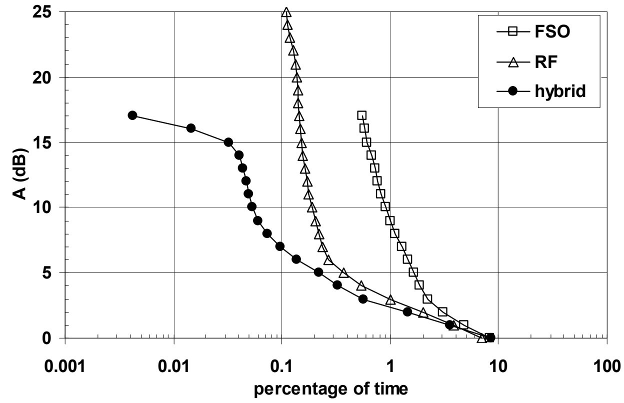

Fig. 15. Obtained CDs of attenuation due to all of the hydrometeors combined for the FSO path, RF path and simulated hybrid FSO/RF system for the 1st year period.

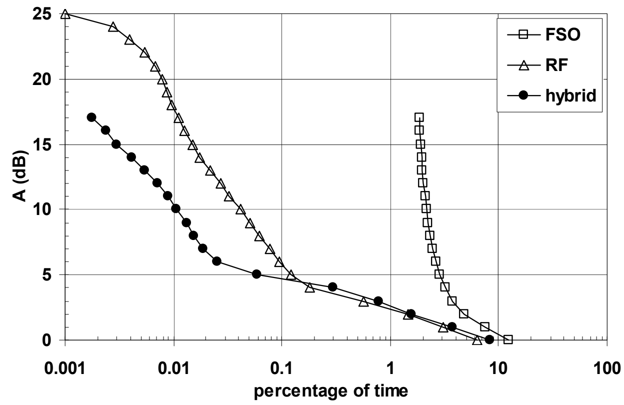

Fig. 16. Obtained CDs of attenuation due to all of the hydrometeors combined for the FSO path, RF path and simulated hybrid FSO/RF system for the 2nd year period.

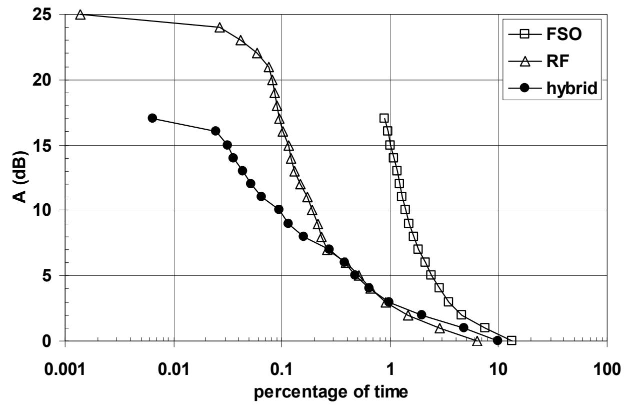

Fig. 17. Obtained CDs of attenuation due to all of the hydrometeors combined for the FSO path, RF path and simulated hybrid FSO/RF system for the 3rd year period.

The great year-to-year variability of these distributions can be observed in the 2nd year period. For the 2nd year period, the dominant attenuation events occurred on the FSO path while the attenuation events on the RF path were most favorable over the 3-year period. This is confirmed by Figs. 13 and 14. Therefore, the simulated hybrid FSO/RF system was the most efficient for the 2nd year period.

The obtained CDs of attenuation due to all of the hydrometeors combined for the FSO path, RF path and the simulated hybrid FSO/RF system over the 3-year period are shown in Fig. 18. The long-term availability performances of the FSO, RF and hybrid FSO/RF systems can be assessed from the figure.

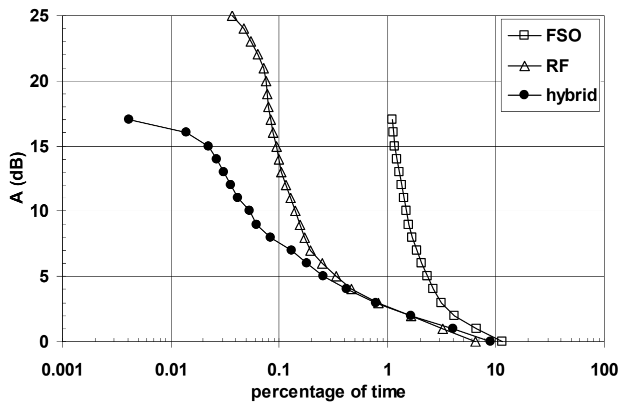

Fig. 18. Obtained CDs of attenuation due to all of the hydrometeors combined for the FSO path, RF path and simulated hybrid FSO/RF system over the 3-year period.

Let us consider a hybrid system where both the FSO link and the RF link have the same fade margin FM = 17 dB. The obtained availability performances (AP) of the FSO link, the RF links and the simulated hybrid FSO/RF system are given in Tab. 1.

System	AP (%)
FSO	98.9000
RF	99.9171
hybrid FSO/RF	99.9958

Tab. 1. Availability performances of FSO, RF and simulated hybrid FSO/RF system.

It can be seen that a significant improvement of the availability performance (practically 2 decades) was achieved for the simulated hybrid FSO/RF system in comparison with the FSO system alone.

The improvement of the availability performances of the hybrid FSO/RF system can be assessed by the concept of diversity characteristics [11]. The improvement due to diversity used can be expressed as the diversity improvement factor $I(A)$ or the diversity gain $G(A)$ [11], [12] which are defined as:

$$I(A)= P_{\mathrm{FSO}}(A) / P_{\mathrm{d}}(A), \tag{1}$$

$$P_{\mathrm{d}}(A) = \min (P_{\mathrm{FSO}}(A), P_{\mathrm{RF}}(A)), \tag{2}$$

$$G(A) = A_{\mathrm{FSO}}(t) - A_{\mathrm{d}}(t), \tag{3}$$

$$A_{\mathrm{d}}(t) = \min (A_{\mathrm{FSO}}(t), A_{\mathrm{RF}}(t)) \tag{4}$$

where $P_{\mathrm{d}}(A)$ is the percentage of time in the combined diversity path with a fade depth larger than A, $P_{\mathrm{FSO}}(A)$ is the time percentage for the FSO path and $P_{\mathrm{RF}}(A)$ is the time percentage for the RF path. Similarly, $A_{\mathrm{d}}(t)$ is the fade depth in the combined diversity path occurring in time percentage t, $A_{\mathrm{FSO}}(t)$ is the fade depth for the FSO path and $A_{\mathrm{RF}}(t)$ is the fade depth for the RF path.

The diversity improvement factor $I(A)$ and the diversity gain $G(A)$ obtained for the individual year periods and the whole 3-year period of observation are given in Figs. 19 and 20.

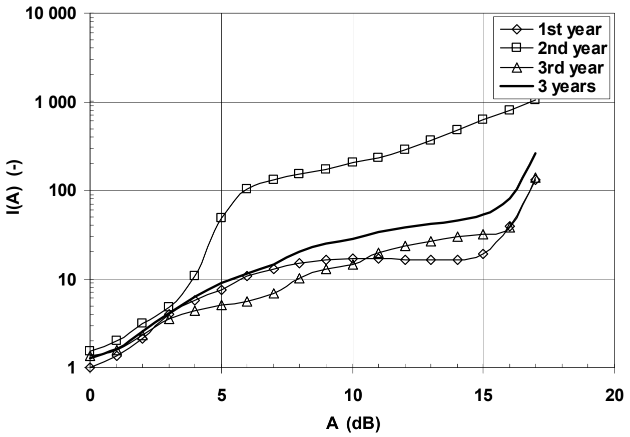

Fig. 19. Diversity improvement factor obtained.

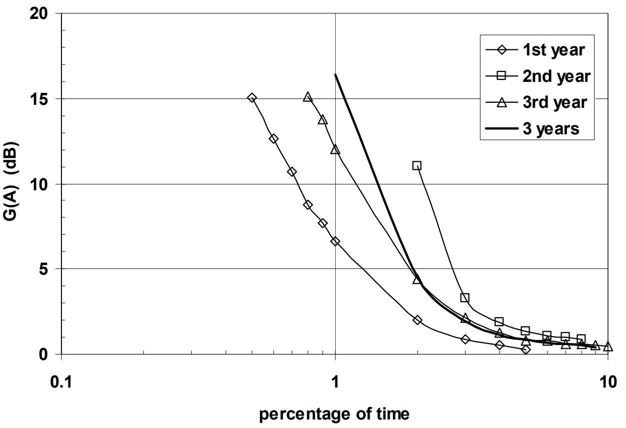

Fig. 20. Diversity gain obtained.

It may be seen clearly in Fig. 19 that the higher the attenuation on the FSO path is, the higher diversity improvement factor can be achieved. The diversity improvement factor reaches the significant values for the attenuation events greater than 5 dB. It should be stressed that the diversity improvement factor is mainly significant for the 2nd year of observation. It is thanks to the fact that the dominant attenuation events occurred on the FSO path while the attenuation events on the RF path were most favorable over the 3-year period of the observation. Therefore, the RF part of the hybrid system mitigated dense fog events and the FSO part mitigated heavy rain events. This is confirmed by results given in Figs. 13, 14 and 16.

It follows from Fig. 20 that the more significant diversity gain is obtained for the percentages of time smaller than 2%. Again, the most significant diversity gain was obtained for the 2nd year of observation.

7. Conclusions

The results of a propagation study on a free space optical link at 850 nm on a path 853 meters long and on a parallel 58 GHz radio link obtained over a 3-year period of observation are presented. Individual attenuation events were compared with the concurrent meteorological situations and were carefully classified according to the causes of their origin. The cumulative distributions of attenuation due to all of the hydrometeors combined for the individual months as well as due to individual hydrometeors for individual year periods were obtained for both paths. The yearly CDs of attenuation due to all of the hydrometeors combined for individual year periods and the average year over the 3-year period were also obtained. The large month-to-month and year-to-year variability of these CDs were observed on both paths. The availability performances of the FSO link, the RF link and the simulated hybrid FSO/RF system were assessed from the CDs of attenuation due to all of hydrometeors combined. For the 2nd year period, the dominant attenuation events occurred on the FSO path while the attenuation events on the RF path were most favorable over the 3-year period. Therefore, the simulated hybrid FSO/RF system was the most efficient for the 2nd year period when the dense fog attenuation events were eliminated by the RF system and heavy rain attenuation events were eliminated by the FSO system.

Up to about two decades of higher availability performance was achieved for the simulated hybrid FSO/RF system than for the FSO link alone. The diversity improvement factor reached significant values for attenuation greater than 5 dB and the significant diversity gain was obtained for the percentages of time smaller than 2%. Only a simple hard-switching was considered. Even during high attenuation events there is still atmospheric turbulence which can disturb mainly FSO communication. Near the threshold, the link availability performance will differ from theoretical curves obtained for a constant input power. In this case, soft switching may improve the combined link throughput significantly.

It was proved that a radio link working in the 58 GHz band can be used as a hitless backup for an FSO link. Limitations due to dense fog and heavy rain are significantly eliminated. The availability performance of the obtained hybrid FSO/RF system is much improved over that of either the FSO or 58 GHz systems. The utilizations of radio systems working in the higher frequency bands have other advantages such as small antennas and broadband transmission. Therefore, the high bit rate transmission need not be reduced.

It should be noted that the results obtained in Prague with the temperate climate of Central Europe are climatically dependent. Therefore, the conclusions on availability performance are valid only for Prague or the sites with similar climatic conditions.

Long-term experimental research is needed to obtain more detailed information about the influences of individual hydrometeors on attenuation and more reliable results about the availability performances of hybrid FSO/RF systems.

Acknowledgements

The Czech Science Foundation supported the described work under project No. 102/08/0851.

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About Authors ...

Vaclav KVICERA was born in Poděbrady in 1948. He received his M.Sc. and Ph.D. degrees in Electrical Engineering from the Czech Technical University in Prague, Czech Republic in 1971 and 1986, respectively. He is a senior researcher at the Dept. of Frequency Engineering of the Czech Metrology Institute. He is a senior member of IEEE. His research activities are aimed at electromagnetic wave propagation in the frequency bands of fixed terrestrial links, especially on the influence of hydrometeors in frequency bands above 10 GHz. His research interests also include optical wave propagation on free space optical links.

Martin GRABNER was born in Prague in 1976. He received his M.Sc. and Ph.D. degrees in Radio Electronics from the Czech Technical University in Prague, Czech Republic in 2000 and 2008, respectively. Since the year 2000 he was with TESTCOM then the Czech Metrology Institute working in the area of electromagnetic wave propagation in the troposphere. His research interests include the physical and statistical modeling of fixed wireless channels and the quality of telecommunication systems.

Ondrej FISER was born in Prague in 1952. He received his M.Sc. degree in 1977 in Electrical Engineering and his Ph.D. degree in 1986 in Electronics, both from the Czech Technical University in Prague. He works as a scientific researcher at the Institute of Atmospheric Physics, the Academy of Sciences of the Czech Republic, focusing on atmospheric radiowave propagation research and radar meteorology. He also teaches electrical engineering at the University of Pardubice.