Original scientific paper
https://doi.org/10.33180/InfMIDEM2024.301

Informacije MIDEM
Journal of Microelectronics, Electronic Components and Materials
Vol. 54, No. 3(2024), 167 – 175

High Resolution Rain Intensity Measurement and its Application on Free Space Optics

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Abstract: Thunderstorms affect our everyday life. Among the various types of precipitation, it is extremely important to determine rain intensity both for scientific and for economic reasons. Various traditional meteorological methods and other techniques, such as radio measurements can be applied to this. The fluctuation of the received signal level, occurring on radio connections, especially in the shorter millimeter wavelength range, strongly depends on the rain intensity. Thus, the fading phenomenon is also suitable for measuring the rain intensity indirectly. We present our new method of producing calibrated attenuation time series from the measured data of the received signal level, which can be used to directly express the rain intensity. It is concluded that the method is suitable for the detection of rapid and instantaneous changes in rain intensity due to the high sampling rate. Our results have many possible applications: from high-resolution detection of time-varying rainfall intensity to adaptive communication control systems with short reaction times. We present the effect of heavy rainfall on free-space optical connections, an important secure and high data rate link type. We assume that high-intensity rain would result in the disturbance of optical connections and worst-case it would result in its interruption. We analyzed the magnitude of deterioration by the probability of fade. Based on our results, we draw attention to the fact that nowadays increasingly frequent, high-intensity precipitation bursts can damage optical connections. We advise some solutions to eliminate the harmful effects of intense rain.

Keywords: mmW; high resolution measurement; rain intensity sensing; FSO link; outage probability

Merjenje intenzivnosti dežja z visoko ločljivostjo in njegova uporaba v optiki prostega prostora

Izvleček: Nevihte vplivajo na naše vsakdanje življenje. Med različnimi vrstami padavin je iz znanstvenih in gospodarskih razlogov izjemno pomembno določiti jakost dežja. Pri tem lahko uporabimo različne tradicionalne meteorološke metode in druge tehnike, kot so radijske meritve. Nihanje ravni sprejetega signala, ki se pojavlja na radijskih povezavah, zlasti v krajšem območju milimetrskih valovnih dolžin, je močno odvisno od intenzivnosti dežja. Zato je pojav bledenja primeren tudi za posredno merjenje intenzivnosti dežja. Predstavljamo našo novo metodo izdelave umerjenih časovnih vrst slabljenja iz izmerjenih podatkov o ravni sprejetega signala, ki se lahko uporabijo za neposredno izražanje intenzivnosti dežja. Ugotavljamo, da je metoda zaradi visoke stopnje vzorčenja primerna za zaznavanje hitrih in trenutnih sprememb intenzivnosti dežja. Naši rezultati se lahko velikokrat uporabijo: od zaznavanja časovno spremenljive intenzivnosti dežja z visoko ločljivostjo do prilagodljivih sistemov za nadzor komuniciranja s kratkimi reakcijskimi časi. Predstavljamo vpliv močnega deževja na optične povezave v prostem prostoru, ki so pomembna vrsta varnih povezav z visoko hitrostjo prenosa podatkov. Predpostavljamo, da bi močno deževje povzročilo motnje optičnih povezav, v najslabšem primeru pa bi povzročilo njihovo prekinitev. Velikost poslabšanja smo analizirali z verjetnostjo izginotja. Na podlagi naših rezultatov opozarjamo na dejstvo, da lahko dandanes vse pogostejši, visoko intenzivni nalivi poškodujejo optične povezave. Svetujemo nekaj rešitev za odpravo škodljivih učinkov intenzivnega dežja.

Ključne besede: mmW; merjenje visoke ločljivosti; zaznavanje intenzivnosti dežja; povezava FSO; verjetnost izpada

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How to cite:
A. Farkasvölgyi et al., "High Resolution Rain Intensity Measurement and its Application on Free Space Optics", Inf. Midem-J. Microelectron. Electron. Compon. Mater., Vol. 54, No. 3(2024), pp. 167–175

1 Introduction

Rain intensity is a very important physical quantity whose measurement is fundamental in many areas. Meteorological observations, agricultural purposes, flight safety, and even the quality of terrestrial or satellite radio communication at millimetric wavelengths (mmW) are closely related to the amount of liquid precipitation [1-3]. Various types of measurement devices are suitable for measuring precipitation, including rain intensity, from simple tipping bucket gauges or drop counter sensors to real-time sensors or radar-based measurements [4]. In general, the devices for measuring rain intensity work with a certain integration time, which can be several minutes long. The measurement result provided by these devices is expressed as the rain intensity in [mm/h] detected at the geographic location of the measuring system. Considering mmW radio connections, the received signal power is affected by precipitation, especially by the attenuation of intensive rainfalls [2, 3]. On the other hand, this phenomenon can be used to determine the magnitude of the rain intensity from the rain attenuation [5], for which the appropriate calculations can be found in the relevant recommendations of ITU, the International Telecommunications Union [6]. On longer radio connections, we must account for the difference between the effective and the real path lengths [7]. However, on very short connections, it can be assumed that the rain affects the whole path length with uniform rain attenuation. Consequently, in this article our findings are also based on this assumption. We present a new method based on a computation of rain intensity from the change in signal level, measured on a very short radio hop operating in the 58 GHz band. The great advantage of the method is that the instantaneous rain intensity can be determined with high resolution, which is limited only by the sampling rate of the received signal level (RSL). The process provides a solution for the rapid detection of precipitation conditions and many practical application possibilities can be assigned for our new detection process.

The rest of the paper is organized as follows. Section 2 briefly introduces the applied measurement setup, using an experimental millimeter wave wireless radio link. Section 3 explains the data processing method of the measured received power level time series, in order to obtain the required attenuation time series. Section 4 introduces the inverse method to get rain attenuation time series from the attenuation time series data. Sections 5 and 6 present the impact of high-intensity precipitation on Free Space Optical (FSO) links by estimating the deterioration of outage probability. Finally, the application areas, remarks and conclusions are given in Sections 7, 8 and 9.

2 The measurement setup

The primary objective of this paper is to estimate the intensity of rainfall by analyzing the received signal power level of a radio link. The measurements are carried out by an experimental full-duplex *V*-band radio link. The used Nokia MetroHopper wireless access link has been originally designed for dense microcellular networks [8, 9]. This 58 GHz radio is set up to function over short distances to establish a low-latency connection to base stations. The main parameters of the implemented link are listed in Table 1., while the location and the outdoor radio unit can be seen in Fig. 1.

Table 1: Radio link parameters

Location	Budapest
Path length	d = 118 m
Frequency	f = 57.725 GHz
Link polarization	Vertical (V)
Typical TX output power	+5 dBm
TX/RX antenna gain	G = 34 dBi
BER=10^{-3} threshold	-75 dBm
BER=10^{-6} threshold	-73 dBm
Link capacity	4 x 2 Mbit/s

The radio indoor units have been installed at both ends of the link, providing a local management interface and ports for the 4x2 Mbit/s capacity. In our experimental setup payload data was not transmitted, only the received signal strength was monitored in [dBm] and logged with a granularity of 1 sample/second via the scripting tool of the management interface.

Figure 1: MetroHopper link between two buildings.

The free space path loss (FSL) of the experimental link is [3, 10]:

$$FSL^{[\mathrm{dB}]} = 92.4^{[\mathrm{dB}]} + 20\log_{10}\left(f^{[\mathrm{GHz}]}\right) + 20\log_{10}\left(d^{[\mathrm{km}]}\right) \quad (1)$$

Where *f* is the link frequency in [GHz] and *d* is the hop length in [km]. With the parameters of Table 1, *FSL*=109 dB. There is an additional attenuation due to the atmospheric gases, especially the effect of oxygen adds a further 1.1 dB [7, 11].

The typical (and nonadjustable) output power of the radio units is P_{TX} = +5 dBm [8]. The link polarization is vertical. After the alignment of the outdoor units, with the device parameters listed in Table 1., during clear sky conditions the measured received signal power level is roughly -56 dBm at the receiver side. According to the MetroHopper radio User's Manual [8], the minimum required RSL is -75 dBm (for *BER* = 10^{-3}) resulting a 19 dB fade margin for the measurement setup. Considering the very short hop length, this fade margin is sufficiently high to detect even the most intensive rain events in Budapest.

3 Processing of the received signal level data

For this study we processed the received power measurements on the experimental link between 1st of January to 28th of February 2023, when the availability of the data was 93%. This period was noticeably rainy in Hungary and the temperature was always above 0°C, therefore all precipitation was in liquid form. In Fig. 2. the time series of measured received power is depicted for January 2023:

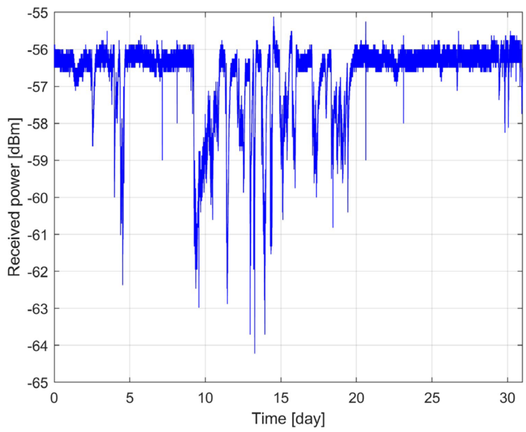

Figure 2: Received power time series for January 2023 (with one second resolution).

ITU-R P.838-3 [6] gives the relationship between specific attenuation γ_R and rain intensity *R* as:

$$A^{[\mathrm{dB}]} = d^{[\mathrm{km}]} \cdot \gamma_{\mathrm{R}}{}^{[\mathrm{dB/km}]} = d \cdot k_{\mathrm{H/V}} \cdot R^{\alpha_{\mathrm{H/V}}} \quad (2)$$

where *d* is the length of the radio link in [km], *R* is the rain rate in [mm/h]. Constants *k* and α are frequency and polarization dependent values according to ITU-R P.838-3 [6]. In the case of our vertically (V) polarized experimental 58 GHz link, these constants are k_V=0.8129 and α_V=0.7552.

When we apply the inverse form of the equation (2) given in ITU-R P.838-3, the momentary value of rain intensity R_i can be expressed as:

$$R_i^{[\mathrm{mm/h}]} = 10^{\frac{\log_{10}\left(\frac{A_i}{d \cdot k}\right)}{\alpha}} \quad (3)$$

where A_i is the i^{th} value of the path attenuation time series in [dB], and *d* is the link length in [km] as in Eq. (2). We note that because of the very short link, the effective path length and the actual path length can be considered equal in our case.

Please note, that the momentary value of R_i is calculated from a high-resolution data collection. Even though according to Eq. (2)-(3), the unit of R_i is given in [mm/h], R_i represents values obtained from very frequent measurements of 1 sample/second R_i^* as discussed in part 4. When hourly rain volume is required, the R_i^* sample/second values can be converted to mm/h values as:

$$R_i^{[\mathrm{mm/h}]} = \frac{1}{3600} \sum_{i=1}^{3600} R_i^{*[\mathrm{mm/h}]} \quad (4)$$

Path attenuation cannot be directly measured; it is the difference between the clear sky level and the momentary measured received signal power RSL_i in [dBm]. As the simplest solution, the clear sky level can be determined as the median of the received power during a precipitation-free day. In equation (2) the attenuation, and indirectly the clear sky level appears in the exponent of the equation, thus the resulting rain intensity value is very sensitive to this parameter. However, even a daily clear sky level may slightly vary due to the temperature variation of the air or the outdoor radio units, or due to the changes in the air humidity or the concentration of the atmospheric gases. This may introduce an uncertainty to the process.

In order to get a calibrated result, concurrent measurement data of a weather station was applied, especially the total amount of rain for one month. This weather station is part of the MetNet network [12], collecting several meteorological data such as temperature, humidity, heat index, dew point, wind direction and speed, air pressure and rain intensity. The distance between the weather station and our radio link is only 763 m, therefore it can be expected that there is no significant difference between the total monthly amount of rain at the two different locations. The calibration method for January 2023 was as it follows:

1. select one clear sky day and determine the median of the received signal level (8th January): RSL_m=-56.3 dBm
2. transform received power time series to attenuation time series with $A_i = RSL_m - RSL_i$ [dB]
3. calculate the time series of rain intensity R_i with equation (3)
4. determine the total amount of rain R_{total} in [mm/month] during the whole month as:

$$R_{\text{total}}\left[\frac{\text{mm}}{\text{month}}\right]=\frac{1}{3600}\sum_{i=1}^{31\cdot 24\cdot 3600} R_i^*\left[\frac{\text{mm}}{\text{h}}\right] \quad (5)$$

5. get the total amount of rain for January from the MetNet data (R_M=102.9 mm/month)
6. modify the value of median RSL_m and repeat the process from step 2 until $R_M = R_{total}$ (in mm that has fallen during the entire month).

Applying the process described above, a calibrated time series of rain intensity can be determined for the whole month, as it can be seen in Fig. 3. The upper plot shows the rain intensity time series as resulted with the simple median value. The lower plot presents the rain intensity after calibration. Using the above recursive steps 2-6, the original median clear sky received power level for January was modified from -56.3 dBm to -60.65 dBm, resulting an identical value that was recorded by the MetNet station. Due to the stability of the radio connection and the meteorological station's equipment, it is enough to perform the calibration once, and it can also be applied correctly in case of further measurements.

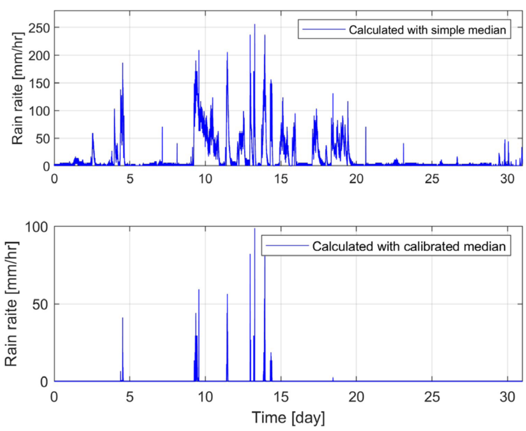

Figure 3: Time series of rain intensity for January 2023, calculated with simple median (top) and by using the calibration method (bottom).

4 Detecting rain attenuation with high resolution

In sections 2 and 3, we demonstrated that a short distance millimeter wavelength radio link can be utilized to sense the momentary rain intensity by measuring the received signal level and convert it to rain intensity time series. A supporting calibration process ensures the validity of the transformed rain intensity data. The most important advantage of the method is that the sampling rate of the resultant rain intensity time series is identical to the sampling rate of the *RSL* over the radio link. Actually, this is 1 sample/sec, therefore the fast changes in the rain intensity can be also detected, contrarily to the conventional sensors, that usually smooth the high peaks due to their integrating behaviour.

Fig. 4. depicts a typical rain event in January 2023 with a duration of approximately 5 minutes. In the center of the rainfall event a fast increase of the rain intensity is observable, having a duration of only 15 seconds.

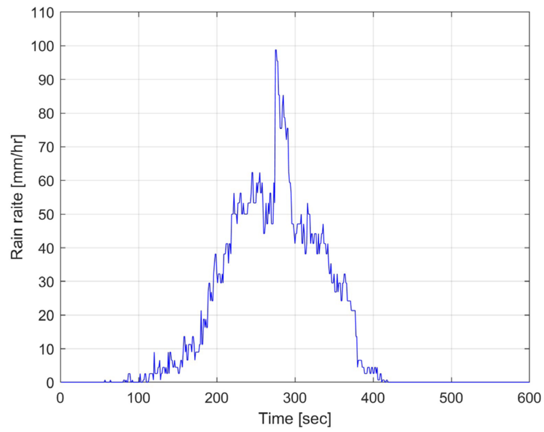

Figure 4: Single rain event with high instantaneous peak intensity. Measured on 13th of January 2023.

Another similar effect can be observed in Fig. 5., detected on 20th of February 2023 with a length of 50 seconds An extreme peak of the rain intensity is observable with only 5 seconds duration, when the rain intensity increased almost two times higher than in the surrounding periods.

5 Discussion of high-resolution detection

There could be several application areas of this kind of rain intensity sensing. In case of adaptive control of the modulation and coding over terrestrial or satellite communication links [13] high resolution and fast information about the momentary rain intensity may support the adaptive algorithm and higher throughput can be achieved. In case of a diversity systems, when several

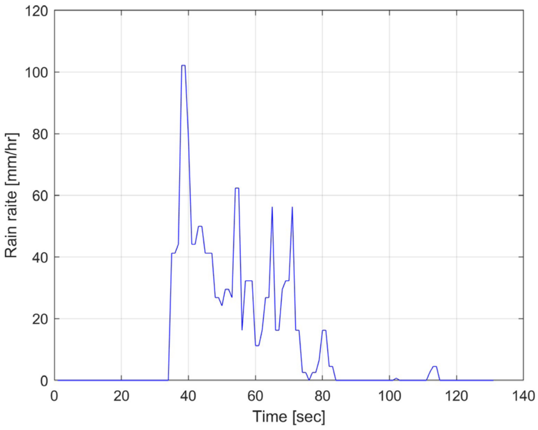

Figure 5: Single rain event with short duration peak intensity. Detected on 20th of February 2023.

radio stations are operated at multiple geographical locations, the perfect knowledge about the local rain rate changes may be very advantageous. Similarly, if diversity radio and free space optical links are concurrently operated over the same path, the fast-switching control of the two different media may increase the channel capacity and maintain the overall link availability. Applying legacy, constant bit rate mmW radios in the 58 GHz band for the continuous rain intensity monitoring has some advantages. Firstly, the high atmospheric attenuation reduces the maximum radio hop lengths in Europe, typically below 1 km [3, 7, 9, 15]. For the same reason, the probability of unwanted interference from other mmW transceivers is smaller. Secondly, the novel Gbit/s radios in *E*-band (80 GHz) switch adaptively when signal to noise ratio degrades due to precipitation or interference [3, 14]. Continuous switching between modulation modes would result in less accurate rain intensity measurement as different transmit power and received signal thresholds apply to different symbol rates [3, 7, 15]. Finally, in several countries, the *V*-band is either unlicenced or the frequency fees are moderate due to the high atmospheric losses around 58-60 GHz [7, 9]. Therefore, 58 GHz links can operate as a continuous backup for FSO links to provide guaranteed bit rates in foggy days when FSO capacity is reduced [27].

6 Impact of high-intensity precipitation on FSO communication links

Planning a new terrestrial wireless connection, the current environmental challenges caused by meteorological events of recent years must be taken into account. Some few years ago, intense rainfall was not a problem in this region of Central Europe. A decade ago, the outage probability of RF links due to rain were orders of magnitude less frequent than in recent years. This is why we must reconsider the effects of intense rain. Based on own long-term experience and measurements, the impact of short-term, very intense precipitation event which greatly deteriorates the availability of the connection becomes an increasingly serious problem. This point is confirmed by measurements from other research centers [16, 17]. The long-term statistics used previously do not include the effects of very short and very intense precipitation events. It is not enough to plan the terrestrial connections based only on average values of rainfall rate. Intensive precipitation events must be monitored and compensated rapidly and adaptively. For this monitoring and compensation method, the instantaneous rainfall rate is required at very short intervals. To measure rapid precipitation events, the measurement of rainfall-rates averaged over minutes or hours is unfortunately not sufficient. The rainfall intensity determination method, presented in part 3 is suitable for a quick determination of the instantaneous rain intensity, by which the outage probability of the connection can be reduced, and such the reliability improved. Note, that even though the average rainfall intensity has negligible influence on the FSO connections, the intense precipitation significantly decreases the availability of the connection. Therefore, because of the recent climate changes in our environment, we should manage this new influence and deal with the effect of intense rain on the FSO link. Compensating the effect of intense precipitation on FSO links is less demanding than on RF hops. This is because rain affects FSO much less than RF links, which is validated by our calculations. In the FSO connection, the outage probability of fade does not alter if the transmitted signal is pre-compensated at the transmitter. The simplest method to manage this process is to reduce the data rate to a suitable level since the instantaneous data rate is proportional to the allocated bandwidth. Based on our calculation, the connection will not be interrupted by heavy rain if the applied data rate does not exceed 100 Mbps.

7 Calculation of FSO connection outage probability in case of heavy rain

7.1 FSO channel model

The required minimum received power of the FSO link depends on the sensitivity of the optical detector, the allocated bandwidth, and the signal-to-noise ratio. Accordingly, the minimum required received power can be determined, see in [18], by equation (6).

$$P_{\mathrm{req}} = NEP \cdot \sqrt{BW} \cdot SNR \tag{6}$$

where, *NEP* is photodetector noise equivalent power, *BW* is the applied bandwidth, and *SNR* is the minimum required signal-to-noise ratio, provided at the receiver. The required minimum signal-to-noise ratio depends on the type of modulation and the demanded bit error probability.

The effect of rain on the FSO link, i.e. the fading phenomenon on the propagating optical signal, can be demonstrated by outage probability. The magnitude of the received optical power varies depending on the intensity of the rainfall. In addition to increasing the total attenuation of an optical link, based on the recommendation of Kumar et. al, in [19], it can be taken into account that the structure parameter of the turbulent medium increases as a result of the rain. Our calculation is based on the modified Hufnagel-Valley (H-V) model (see in detail in [20]), which can be used adequately in heavy rain.

The fading margin of the optical connection can be determined by the ratio of the long-term average of the maximum signal power received in clear-sky, rain-free weather conditions and the required minimum received optical power. The amount of the fading margin is given by equation (7).

$$FM_{\mathrm{FSO}}^{[\mathrm{dB}]} = P_{\mathrm{FSO\ rec-avg}}^{[\mathrm{dBm}]} - P_{\mathrm{FSO\ req}}^{[\mathrm{dBm}]} \tag{7}$$

where $P_{\mathrm{FSO\ rec-avg}}^{[\mathrm{dBm}]}\Big|_{R_{\mathrm{rain}}=0\mathrm{mm/h}} = \mathbb{E}\left\{P_{\mathrm{FSO\ rec}}^{[\mathrm{dBm}]}\right\}$ is the average of the maximum received signal power. Therefore, the fading margin (FM) was calculated as the difference between $P_{\mathrm{FSO\ rec-avg}}^{[\mathrm{dBm}]}$ and $P_{\mathrm{FSO\ req}}^{[\mathrm{dBm}]}$.

The fading margin must be always greater than the highest level of rain attenuation, $FM_{\mathrm{FSO}} \geq max\left\{A_{\mathrm{rain}}^{[\mathrm{dB}]}\right\}$, where $A_{\mathrm{rain}}^{[\mathrm{dB}]}$ is the rain attenuation based on [21]. Accordingly, the value of the instantaneous received signal power above the threshold can be determined by the fading margin of the system and the instantaneous value of the attenuation caused by the rainy turbulent medium. The level of the average received power above the threshold value can be specified by equation (8).

$$\Delta_{\mathrm{p}}^{[\mathrm{dB}]} = P_{\mathrm{FSO\ rec-inst.}}^{[\mathrm{dBm}]} - P_{\mathrm{FSO\ req}}^{[\mathrm{dBm}]} - A_{\mathrm{rain}}^{[\mathrm{dB}]} \tag{8}$$

Note, that several options can be used to compensate for the effect of heavy rain. To effectively compensate, the current rain intensity and its short-term estimated value must be known. To compensate for the negative effect of rain, a closed-loop control system is required, which can pre-compensate the radiated optical signal according to the rainfall rate. Among several mitigation techniques, the most efficient is the accurate selection of bandwidth. Accordingly, using a lower data rate results in bandwidth efficiency, a smaller allocated bandwidth. Our paper does not deal with the strongly destructive effect of fog, which can only be compensated with hybrid FSO-RF systems [22, 29].

7.2 FSO outage probability due to fade

The probability of FSO link outage was calculated by the cumulative distribution function $F(\gamma)$ of the signal-to-noise ratio ($\gamma_{\mathrm{av\ opt}}$) measured at the receiver. It is defined as:

$$P_{\mathrm{out\ FSO}} = P_{\mathrm{r}}\left(\gamma_{\mathrm{opt\ avg}} < \gamma_{\mathrm{opt\ th}}\right) = F\left(\gamma_{\mathrm{opt\ th}}\right) \tag{9}$$

and approximated by lognormal distribution as:

$$P_{\mathrm{out\ FSO}} = 0.5\left(1 + \mathrm{erf}\left(\frac{0.5\sigma_{\mathrm{I}}^2 - \Phi_{\mathrm{T}}}{\sqrt{2}\sigma_{\mathrm{I}}}\right)\right) \tag{10}$$

In Equation (10) $\Phi_{\mathrm{T}} = \ln\left(\frac{\gamma_{\mathrm{opt\ avg}}}{\gamma_{\mathrm{opt\ th}}}\right)$ is the SNR of average and the threshold; $\sigma_{\mathrm{I}}^2\left(R_{\mathrm{Rain}}\right)$ is the normalized irradiance variance, the 'scintillation index'. The variance of the received signal level can be determined based on the modified structure parameter, which can be estimated based on the frequently used H-V model and with the Kumar's addition [19]:

$$\begin{aligned} C_{\mathrm{n}}^2(h) = {} & 5.94\cdot 10^{-53}\left(\frac{v}{27}\right)^2 \cdot \mathrm{h}^{10}\cdot \mathrm{e}^{-\left(\frac{h}{1000}\right)} + \\ & + 2.7\cdot 10^{-16}\mathrm{e}^{\left(-\frac{h}{1500}\right)} + \\ & + A\cdot \mathrm{e}^{\left(-\frac{h}{100}\right)} + R\cdot 10^{-16}\cdot \mathrm{e}^{\left(-\frac{h}{1000}\right)} \end{aligned} \tag{11}$$

In equation (11) *v* is the wind speed, in [m/h], *h* is the altitude above sea level, in [m], *A* is the structure parameter at sea level, $C_{\mathrm{n}}^2\left(h = 0\ \mathrm{m}\right)$ in $\left[\mathrm{m}^{-2/3}\right]$, and *R* is the rainfall rate in [mm/h]. The variance of the received signal is given by equation (12) as:

$$\sigma_I^2 = e^{\left(\frac{0.49\sigma_R^2}{\left(1+1.1\sigma_R^{12/5}\right)^{7/6}} + \frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{12/5}\right)^{7/6}}\right)} - 1 \tag{12}$$

where, σ_R^2 is the Rytov variance.

8 Results of the impact of rain on FSO link

Our calculated result is depicted in Fig. 6. We confirm that the optical link can be significantly impacted by short-term heavy rainfall events that have occurred frequently in the last few years. It can be seen that the effect of heavy rains (up to roughly 100 mm/h) can only be compensated by optimally reduced data rate. Based on Fig. 6, it is concluded that FSO links longer than 2 km are more exposed to interruptions caused by rain, as seen in [23, 24].

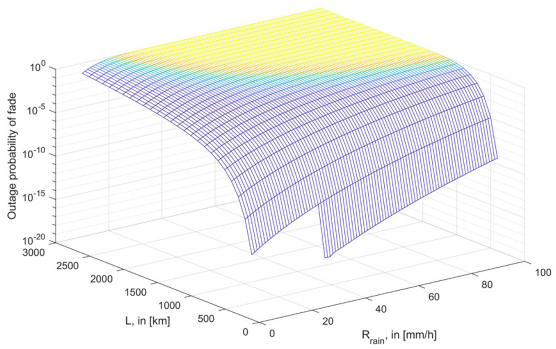

Figure 6: Outage probability of FSO link as a function of link distance *L*, and rainfall rate R_{rain}, with fade margin of M_{FSO} = 25 dB.

Nevertheless, we recommend avoiding long distance terrestrial optical links in Central Europe, where rain rates can exceed 50 mm/h and in short periods even may reach 100 mm/h [25].

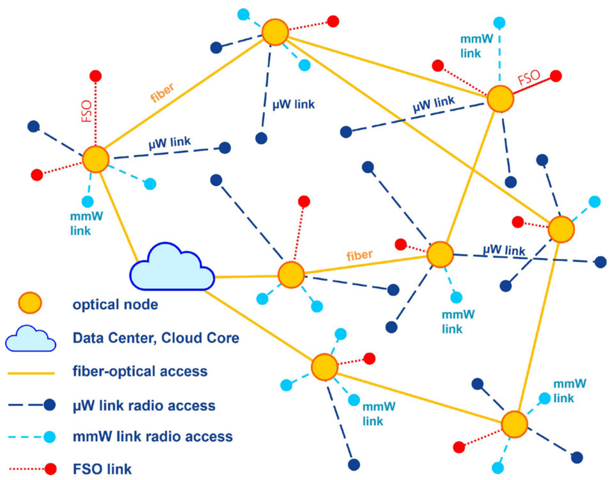

Figure 7: Meshed wireless RF/FSO network with fiber-optical backbone for 5G and future 6G access.

On the other hand, this restriction does not introduce a strict limitation for actual 5G and future beyond 5G anyhaul links. These access networks will use a mesh of fiber-optical, RF (microwave and mmW) and FSO links [26-31]. As shown in Fig. 7, the longer connections are fiber-optical or microwave links [7, 28, 30]. FSO and mmW links are mainly used for the dense urban connections that are typically shorter than 2 km [3, 7, 15, 29, 31].

9 Conclusions

In our paper, the deterioration of terrestrial communication links as a result of increasingly frequent heavy rainfall events in recent years has been discussed in detail. Precise and adequately frequent measurement of instantaneous rain intensity is becoming more important from both scientific and economic point of view. In our article, an indirect rain intensity measurement method is presented, based on the received signal level fluctuation of the radio receiver used in a millimeter wave link. To determine the rain intensity, we used a short-range experimental radio hop operating in at 58 GHz. Based on the received signal level data of the mmW connection, the instantaneous rain intensity was determined. The applied computation process has been presented: first, the attenuation time series must be calculated in a calibrated mode, then the rain intensity data can be generated based on the attenuation time series. It was shown that the new method is suitable for the detection of rapid, instantaneous changes in rain intensity due to the high sampling rate. Among the many application possibilities of our results, we present a relevant type of adaptive communication, the effect of intense rain on FSO connections. It was shown that the increasingly frequent high-intensity precipitation events can significantly deteriorate the free-space optical connections. The quality of the optical connection is shown by determining the probability of fade. We recommended a basic planning guideline to avoid the harmful effects of very intensive rainfalls in Central European areas. Finally, some few words on our future topic: the 5G and 6G networks in the future will be mixed mesh networks. As a result, mm-wave links will enmesh our environment. Therefore, the high-precision rain measurement will be continuously available, by 5G and 6G stations installed on top of buildings. The end users will access the system via adaptive FSO/mm-wave links, thus ensuring optimized data connection. We plan to determine the availability of the system in the case of hybrid connections, adaptive FSO/mm-wave, by which the spectral efficiency of the system can be improved over a service territory.

10 Conflict of Interest

The authors declare no conflict of interest.

11 Acknowledgments

The authors thank Dr. Levente Dudás and Viktor Fehérvári for the useful discussions and help in the *V*-band experiments. The research has been supported by the National Research, Development and Innovation Fund of Hungary under the 2020-1.1.2-PIACI-KFI funding scheme.

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Arrived: 16. 04. 2024
Accepted: 22. 05. 2024