WaveComBE

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Precipitation effects and potential interference between mmW radio links

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[1] CO = Confidential, only members of the consortium (including the Commission Services)
PU = Public

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2 Executive Summary

MmWaves short range fixed links point to point and point to multi-point transmission can carry a mixture of low, medium to high data rate between two locations such as between buildings or lampposts. However, Radio wave propagation is characterized differently in each frequency band and the electromagnetic wave suffers from atmospheric effects, i.e., water (H2O), oxygen (O2), free space loss, material penetration loss, Doppler effect, propagation mechanisms, such as refraction, diffraction, scattering, reflection, attenuation from foliage, and rain. During channel modelling, these propagation effects should not be neglected. For frequencies above 10 GHz, the quality of the radio link is largely affected by rain, snow, and vegetation attenuation. Wavelengths in the range of 10 mm at 30 GHz decreasing to 1 mm at 300 GHz, suffer from scattering by raindrops. Thus, rain causes significant attenuation due to absorption and scattering at these frequency bands. Therefore, the study of precipitation attenuation caused by the interaction between the propagating waves and the rain droplets or snow at mmWaves band is important for deployment of 5G fixed link communication networks.

In the current study, a high-performance PWS100 disdrometer is used to collect weather data, including rain rate and rain drop size distribution (DSD). The custom-designed continuous wave (CW) channel sounder is utilized to record mmWave radio data to study and model rain attenuation at 25.84 GHz and 77.54 GHz over a direct and a side 36 m links and a commercial RF head set up to operate at 77.125 GHz over a 200 m to simulate building to building transmission. DSD and ITU models are implemented for prediction and verifying the measurement data. The results show that the measured attenuation agrees well with the calculated attenuation at most of the rain events while data show higher attenuation than the predicted values when a mix of snow grains and raindrops occurs. The condition of using the ITU-R P.530-17 maximum distance factor restriction of 2.5 has also been analysed using the long-term data. The results indicate that the 2.5 factor restriction is not suitable for the measured short-range fixed links as it excessively underestimates attenuation. The results were submitted to the ITU SG3 meeting in June 2021 which led to the modification of ITU-R P.530 to delete the upper limit of r=2.5. The effect of raindrops diameter between 0.1 and 4 mm was also investigated which indicate that the dominant raindrops have considerable influence on the measured attenuation, especially at light and moderate rainfall events. The scattering effect by raindrops throughout the measurement period using Mie theory is evaluated.

3 List of figures

4 List of Acronyms and Abbreviations

DSD	Drop Size Distribution
CW	Continuous Wave
IP	Internet Protocol
ITU	International Telecommunications Union
NLOS	non-Line of Sight
CCDFs	Complementary Cumulative Distribution Functions

1. Introduction

Rain attenuation studies need long term measurements and analysis over several years [1-2] to provide telecommunication network providers with accurate and useful results to plan and optimize reliable 5G radio links during precipitation events. Two rain attenuation prediction models are generally used. These are the regression model which uses rain rate and path attenuation statistics data for rain attenuation modelling at a specific region; and the physical model [3] which uses statistical information on rainfall and scattering caused by rain drops for providing accurate prediction that can be implemented in different regions. It is recognized that the physical models depend mainly on precipitation conditions. Due to the unpredictable behavior of rain distribution and weather conditions, this imposes significant challenges. Therefore, a universal drop size distribution (DSD) is not feasible as it differs between regions: tropical region, dry, polar, continental, and coastal region [4]. Several works have reported rain attenuation prediction using rain statistics. In [4] a DSD model is used to quantify rain attenuation at 57, 97, 135, and 210 GHz at Chilbolton and Singapore. Their results indicate that the DSD differs with climatic conditions levels of pollution. At higher frequencies and high rain fall rate, inconsistency and fluctuations were observed between the ITU model and the DSD attenuation model, with lower attenuation values predicted by the ITU-R model. In [5], rain attenuation measurements were conducted for 22, 23 and 31.4/30 GHz in a tropical region: Kolkata in India and Belem in Brazil for two years. Results show good agreement between DSD attenuation model and the ITU-R model for rain fall rate below 100 mm/h, with slight differences below 30 mm/h. It is assuming a log-normal distribution for the DSD, both the DSD model and the ITU-R model gave similar results for frequencies below 30 GHz with a maximum rain fall rate of up to 30 mm/h in tropical regions.

In this work, a PWS100 Weather Sensor station has been installed at Durham University to record precipitation data. It can determine each individual particle type from accurate size and velocity measurements. The station is controlled remotely to store data through the campus wireless network and the CR1000 data acquisition over an internet protocol (IP) address once every minute. The weather data are used for rain attenuation prediction over long term measurements in parallel with a mmWave channel sounder which operates at 25.84 GHz (K band) and 77.54 GHz (E band) over two 36 m links: a direct link and an indirect link. Another link with a commercial RF head is set up for CW transmission at 77.125 GHz (E band) for attenuation measurements. Measurements are conducted from October to December 2020, and January 2021 for all three links. Since the rainfall rate is insufficient for the prediction of attenuation in the higher frequency bands, more accurate precipitation data are needed which include: rainfall rate, rain drop diameter, drop size distribution, rainfall velocity, particle speed, and water permittivity. Such data can be obtained using a high end disdrometer station as used in the present study. The results of the attenuation prediction and measurement can be applied for regions with similar weather conditions.

In section 2, rain statistics are presented for the period of 2018 and 2019 and the implementation of this data for rain attenuation prediction using ITU and DSD models. In section 3, measurement results using the short-range fixed link datasets and the PWS100 disdrometer precipitation data are presented and compared for discussion.

2. Rain attenuation modeling using rain statistics

2.1 Weather data

Fig. 1 shows the complementary cumulative distribution functions (CCDFs) of the yearly rain intensity and worst month rain intensity that is exceeded for the given probability. Most of the rain intensity is below 40 mm/h. On average, the worst month was August with a maximum rain intensity that exceeded 150 mm/h and 105 mm/h in 2018 and 2019, respectively.

The DSD is recorded with 300 values of the number of drops corresponding to the diameter from 0.1 mm to 30 mm with 0.1 mm resolution.

The DSD in unit of ($m^{-3}\ mm^{-1}$) can be calculated as:

$$N(D_i) = \sum_{j=1}^{300} \frac{n(D_I, v_j)}{v_j} \cdot \frac{1}{S \cdot \Delta t \cdot dD_i} \qquad (1)$$

where S = 40 cm^2 is the measurement surface of the laser beam of the PWS100 disdrometer, t = 60 s is the integration time, n(D_i, v_j) is the number of particles registered within the classes with mean diameter D_i (mm) and mean speed v_j (m/s), dDi (mm) is the class width associated with the diameter Di.

As shown in Fig. 2, the maximum DSD is around rain drop size of 0.9 mm to 2 mm for 2018 and 2019.

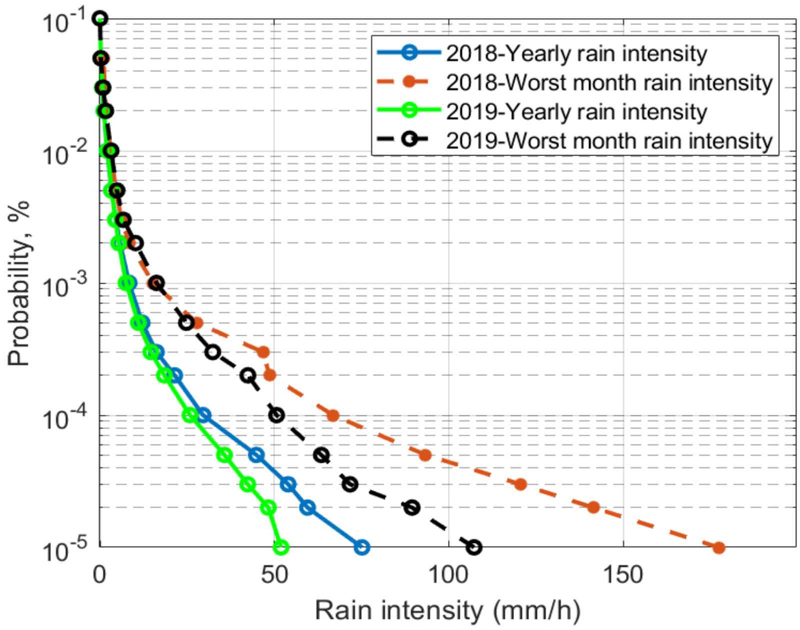


Fig. 1. The measured yearly rain intensity CCDF for 2018 and 2019.

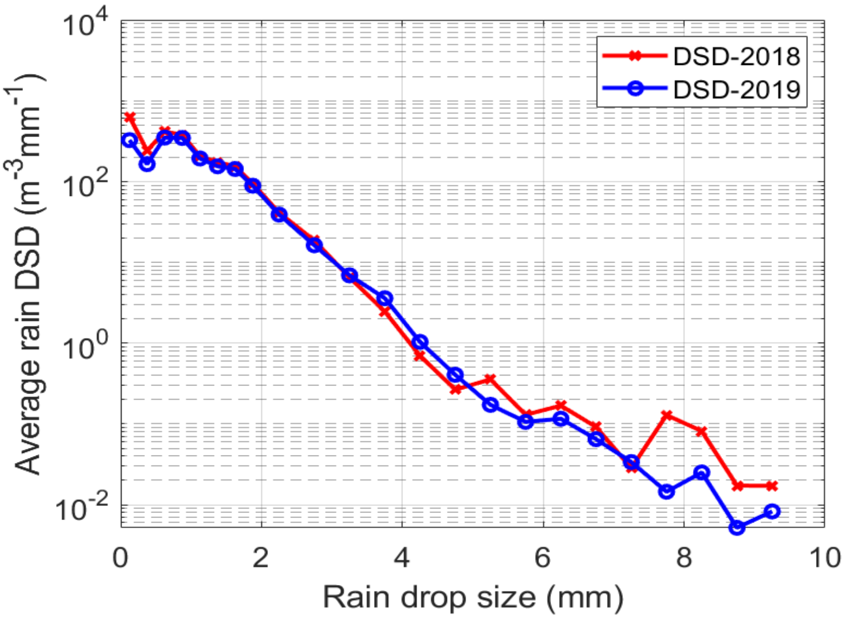


Fig. 2. The measured DSD over 2018 and 2019.

2.2 Prediction models

It is vital to have accurate and reliable propagation models for predicting rain attenuation using precipitation data such as rain fall rate, DSD, velocity, temperature, and water permittivity. The prediction models used in this study are the ITU-R P.838-3 model and the DSD model which use frequency parameters, wavelength, water permittivity, and raindrop distributions. The ITU model is given as:

$$\gamma = k\mathrm{R}^{\alpha} \qquad (2)$$

where R is the rain fall rate (mm/h), k and α are model parameters dependent on the frequency *f*, and is the specific attenuation in dB/km. The ITU model provides a look-up table for the parameters for different frequencies and polarizations. The total attenuation for a specific distance depends on the effective path length d_{eff}, between the Tx and Rx antennas is expressed as:

$$A = \gamma d_{eff} \qquad (3)$$

where the effective path length, d_{eff}, of the link is obtained by multiplying the actual path length *d* by a distance factor *r*, given in the ITU-R P.530-17 model as

$$r = \frac{1}{0.477 d^{0.633} R_{0.01}^{0.073\alpha} f^{0.123} - 10.579(1 - \exp(-0.024d))} \qquad (4)$$

where R0.01 is the rain rate exceeded for 0.01% of the time with an integration time of 1 minute.

The DSD model is given as:

$$\gamma = 4.343 \times 10^{3} \int_{0}^{\infty} \delta_{ext}(D) N(D) dD \qquad (5)$$

where γ is the specific attenuation in dB/km, $\delta_{ext} = \pi(\frac{D}{2})^2 Q_{ext}$ is the extinction cross section (m^2) for water drops of diameter D (mm), and N(D) is the drop size distribution value ($m^{-3}\ mm^{-1}$) at diameter D. The extinction efficiency Qext can be calculated from Mie scattering or Rayleigh scattering theory depending on the size parameter x = π D/λ, where λ is the wavelength.

The following analyzes gives the estimated rain attenuation using only the disdrometer weather data. Figures 3 and 4 display the estimated specific attenuation in dB/km versus rain fall rate in mm/h for two continuous years (2018 and 2019) at 26 GHz and 77 GHz.

The estimated attenuation from the DSD using Mie scattering theory and the ITU model increase as a function of rain intensity at all frequencies. At 26 GHz, the horizontal ITU-R specific attenuation shows slightly higher attenuation than the DSD Mie scattering model for most rainfall events. The estimated attenuation from the measured raindrops distributions exhibits lower attenuation for rain events bellow 35 mm/h by 3 dB difference compared to the ITU model.

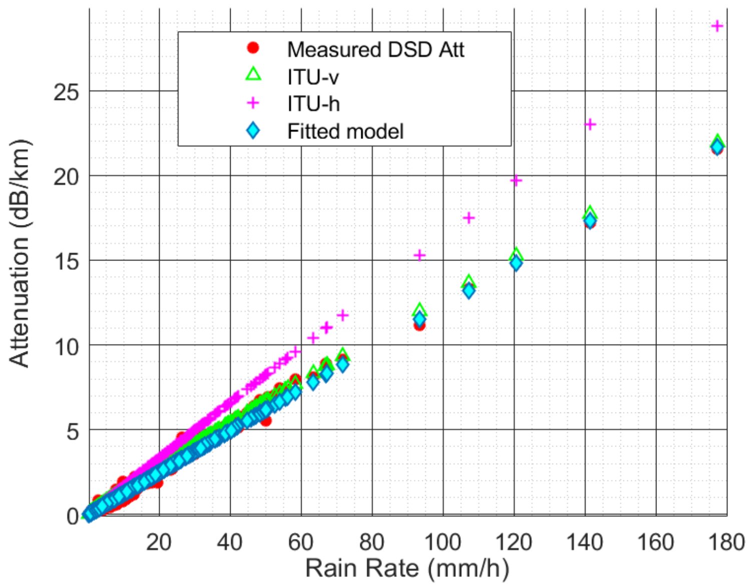


Fig. 3. Calculated and predicted rain specific attenuation at 26 GHz.

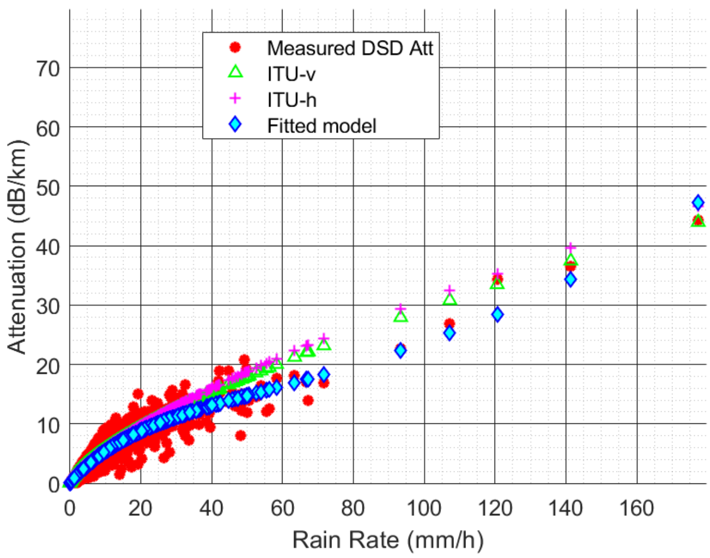


Fig. 4 Calculated and predicted rain specific attenuation at 77 GHz.

Figures 5 and 6 display the worst month estimated attenuation with the DSD Mie scattering model in 2018 and 2019. This provides useful information of the performance of a communication system and link margin. The maximum attenuation for the worst month in 2018 (July) is around 20 dB/km and 44 dB/km for 26 GHz and 77 GHz, respectively. In 2019, the worst month (August), the attenuation has a maximum of 13 dB/km and 26 dB/km, for 26 GHz and 77 GHz, respectively. For probability between 0.001 and 0.0001, the attenuation is higher (~10-25 dB) which is the case for sudden and torrential rain events.

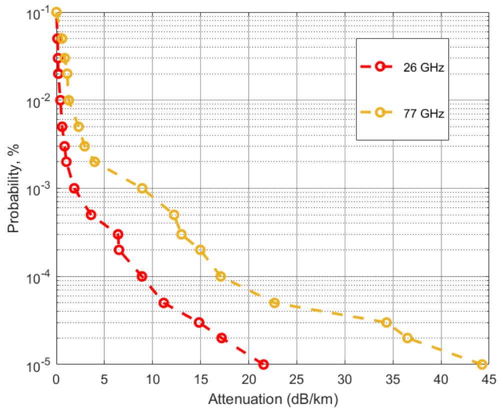


Fig. 5. Worst month calculated attenuation using measured raindrops distribution and Mie theory in 2018.

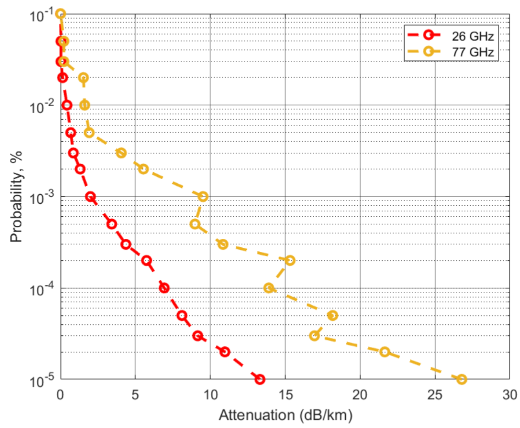


Fig. 6. Worst month calculated attenuation using measured raindrops distribution and Mie theory in 2019.

It is noticed that the estimated attenuation values using Mie theory are not all uniform with rain rate and theoretical predictions models. This is also observed in other works [6]. This could be due to several factors. Primarily, Mie theory assumes that rain drops are spherical, whereas it is not always the case within a real rainfall event since the DSD model uses real disdrometer data which is sometimes subject to severe weather conditions that reduces its collection capability. Additionally, for light rain rate, the disdrometer might not be able to count small raindrops in higher windy situations. Other factors that may affect the collected rain data are the humidity and temperature variability in space and time. In our estimation, we used the average yearly value of temperature and we neglected the humidity. The raindrops size and rain events distributions are not uniform within space and time due to the variability of raindrop distribution and the particle size correspond to the number of each dominant raindrop diameter, rainfall speed and particle speed.

3. Rain Attenuation Measurement Using Short-Range Fixed Link

3.1 mmWave Fixed Link Setup

The experimental fixed link setup using Durham University's channel sounder used for collecting fixed link data for real rain attenuation investigation is shown in Fig. 7. The first two links are set up over a direct path and side path over 36 m links and located on the roof-top of the Engineering department. Two antennas with vertical and horizontal polarizations are used for the E band and a dual polarized antenna is used for the K band for the direct link. To study the effect of scattering and interference a second side link receiver was installed. For the side link Rx, single vertically polarized antennas were used for both the K band and the E band. Custom designed covers were installed for all the antennas to reduce the impact of the wet antenna effect on the measured attenuation. The fixed link operates on Continuous Wave (CW) transmission (building to building/lamppost to lamppost scenario). The third link which operates at 77.125 GHz is installed between Durham University Library roof at 62 m above sea level and the engineering department roof which gives a point to point 200 m path. The Tx/Rx for the 200 m link are commercial transceivers donated by Filtronic (Orpheus E-band modules) shown in Fig. 7 (d).

(a) Transmitter (b) Receiver-direct

(c) Receiver-side (d) Filtronic transceiver

Fig. 7. Fixed link RF heads of the measurement setup, (a) transmitter box for 36 m link, (b) receiver box for direct 36 m link, (c) receiver box for side 36 m link, (d) transceiver Filtronic box for 200 m link.

This section presents the measured attenuation at K band and E band over the two 36 m links between October 2020 and January 2021 and the 77.125 GHz band over the 200 m link from November 2020 - January 2021 adopting the ITU and DSD models for comparison with the measured rain attenuation. Vertical to vertical polarization which is common to all the three links is selected for the two bands over 252 hours of rain data. The attenuation is calculated and referenced using sunny clear sky days before and after the recorded data. Measurement days where snow occurs are compared to rainy days.

For accurate and reliable rain attenuation study, minutes corresponding to equipment transient behavior (rise and drop of the received power), the power flatness of the system, atmospheric attenuation, equipment icing, humidity, and wind are not used in the analysis. For each link, the best measured data sets and the most stable signal strength are used for the estimation of the attenuation.

3.2 Measurement analyses

The results of the measured attenuation as a function of rainfall up to 25 mm/h are presented. Figures 8, 9, and 10 show the received signal mapped against the rain intensity and snow particles for the three links: direct 36 m, 200 m, and side 36 m, respectively for the K and E band vertical to vertical polarization. The figures show that the signal strength follows the rainfall trend. During snow events, the signal takes more time to recover to the level following the end of rain/snow event due to antenna icing as can be seen in Fig. 9. This effect should be differentiated from the measurement by eliminating from the analysis of the icing events. Compared to the predicted-calculated attenuation the measured attenuation for the direct 36 m link during rain events without snow and before mid of December 2020 shows an average of 0.8-1.5 dB higher attenuation for heavy and very heavy rainfall at 26 GHz, while a difference of 0.4-1.3 dB at 77 GHz. However, higher losses up to 9.5 dB are recorded when a mixture between rain and snow occurs. The side link shows somewhat higher attenuation than the direct link 0.5-2.3 dB as the side link depends on non-Line of Sight (NLOS) reflected paths to receive the signal. Thus, the measured attenuation is affected by raindrops scattering mechanism. The K band side link exhibits 1.7 dB difference with respect to the predicted rain attenuation for light, moderate and heavy rainfall events. Measured rain attenuation for the 77 GHz 200 m link agrees well and follows the predicted attenuation for most rainfall events where 6 dB loss has been recorded for a maximum rain intensity of 20 mm/h.

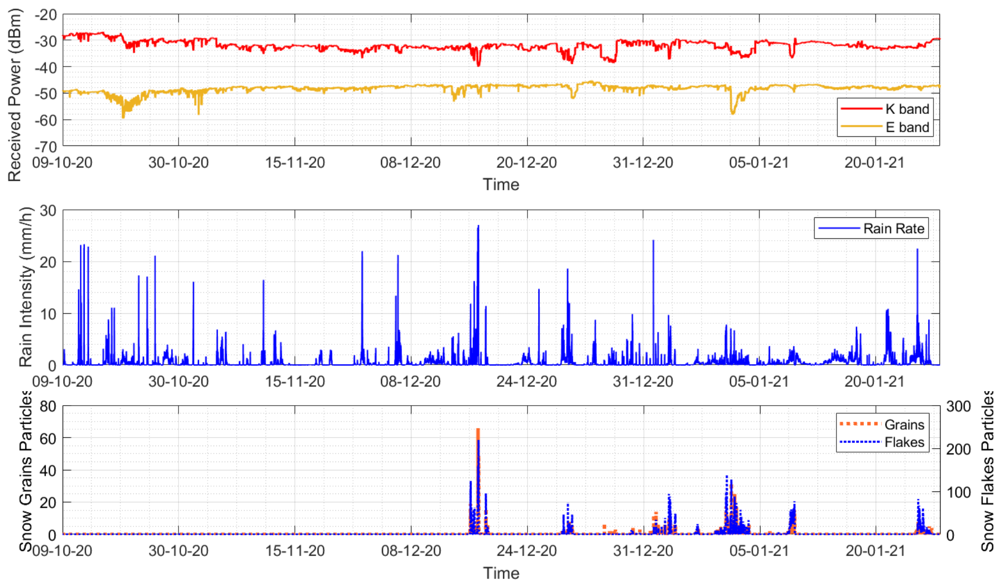


Fig. 8. Long term rain attenuation measurement for direct 36 m link at K and E band through dominant recorded rainy days between October 2020 and January 2021.

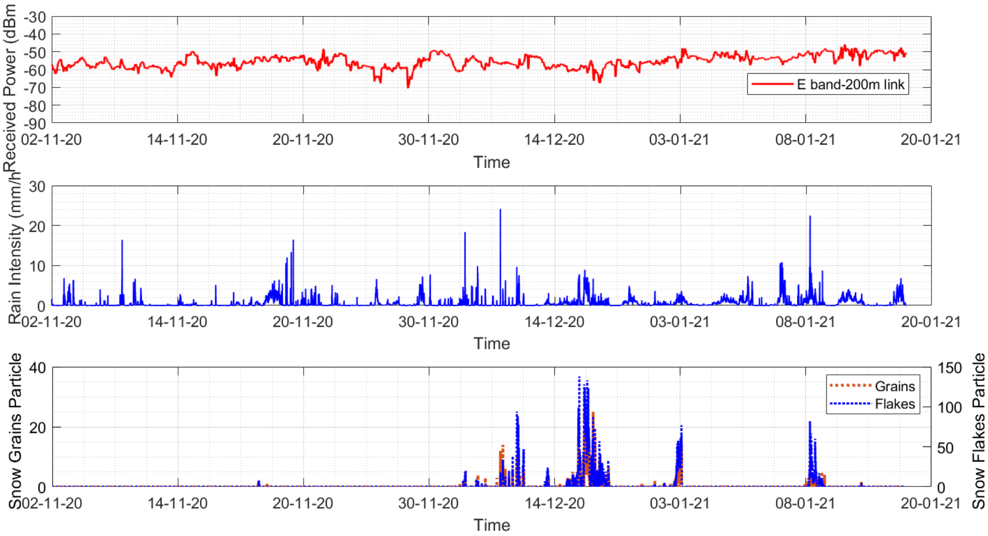


Fig. 9. Long term rain attenuation measurement for point to point 200 m link at E band through dominant recorded rainy days between November 2020 and January 2021

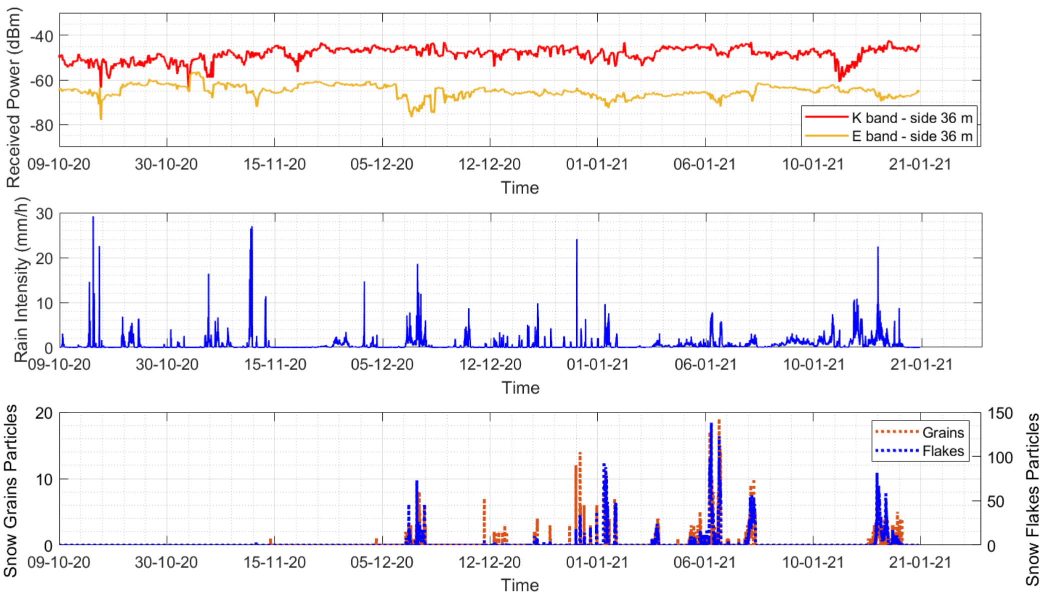
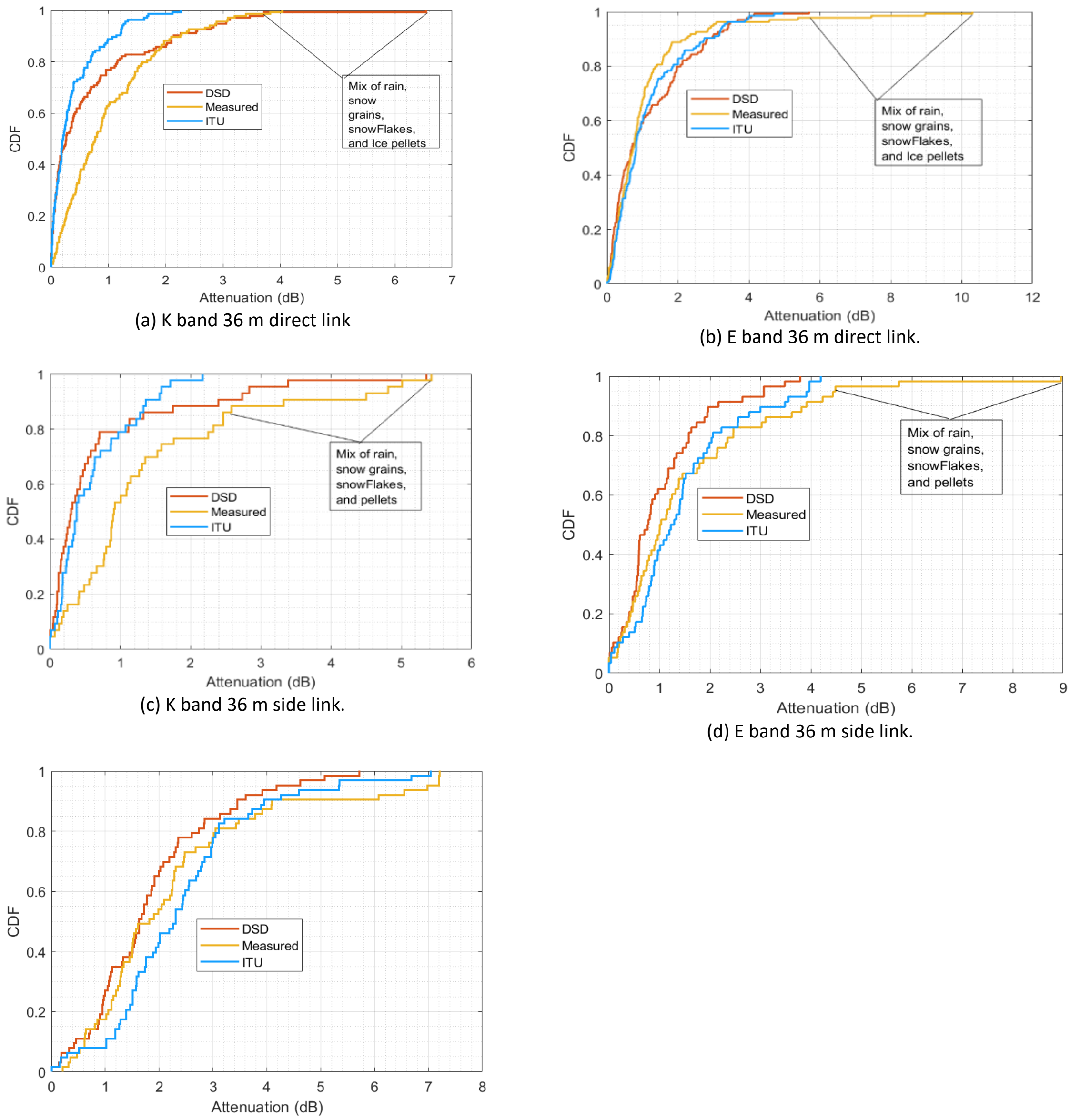


Fig. 10. Long term rain attenuation measurement for side 36 m link at K and E band through dominant recorded rainy days between October 2020 and January 2021.

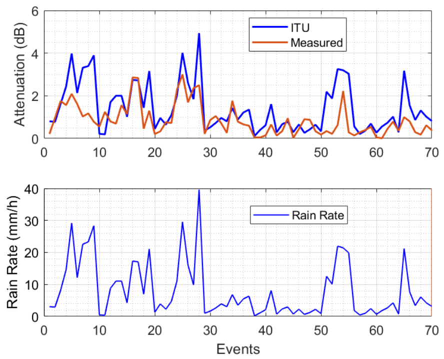
In Fig. 11 the measured CDFs are compared with the predicted CDFs from the ITU and DSD models. Good agreement between measured and calculated attenuation is obtained at 77 GHz for the direct, side, and Filtronic links. A notable difference occurs at the lower frequency band at 26 GHz between the measured and the theoretical values for the side link where the measured attenuation has larger values.



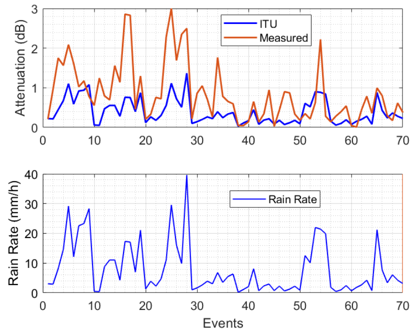
(a) K band 36 m direct link
(b) E band 36 m direct link.
(c) K band 36 m side link.
(d) E band 36 m side link.
(e) E band 200 m Filtronic link.

Fig. 11. CDFs of the measured and the predicted rain attenuation for the three links.

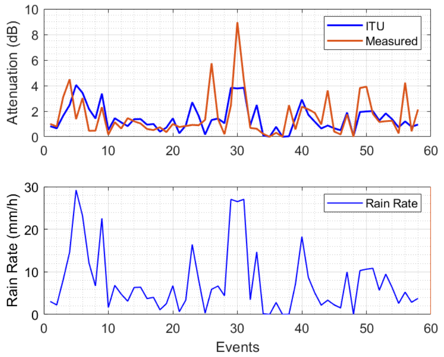
mmWave short-range fixed links require accuracy and reliability of prediction. The ITU-R P.530-17 model uses the effective path length for estimating the rain fade and *r* distance factor which is derived from long range measurements. It is recommended in the model to use a maximum value of 2.5. The recommended value is implemented into the calculation, and thereafter investigated for the three links within its corresponding frequency bands. Fig. 12 and 13 show a full and detailed comparison between the measured and ITU predicted rain attenuation using the maximum recommended distance factor and without using it for the E and K bands, respectively. When implementing the ITU distance factor *r*, it is noticed a larger difference between the measured and the predicted values for all the links at 77 GHz and 26 GHz. Accordingly, the ITU-R P.530-17 maximum distance factor restriction of 2.5 highly underestimated the attenuation with respect to the measurements for both the 36 m and 200 m links. Consequently, using this recommended distance factor is inappropriate for short-range fixed links.



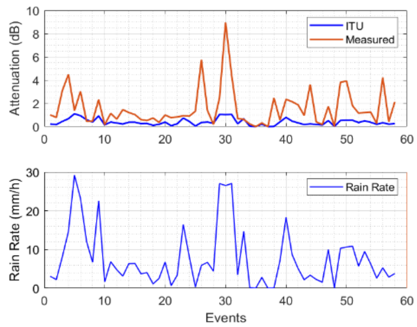
(a) E band 36 m direct link: without distance factor restriction.



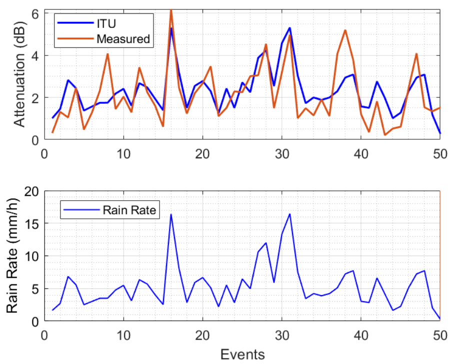
(b) E band 36 m direct link: with distance factor restriction



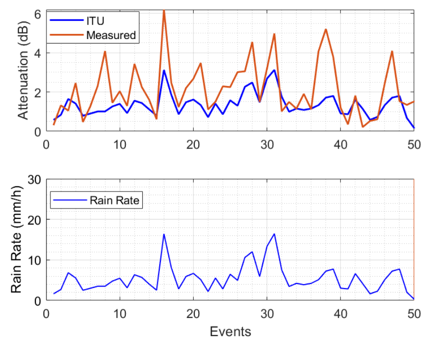
(c) E band 36 m side link: without distance factor restriction.



(c) E band 36 m side link: without distance factor restriction.

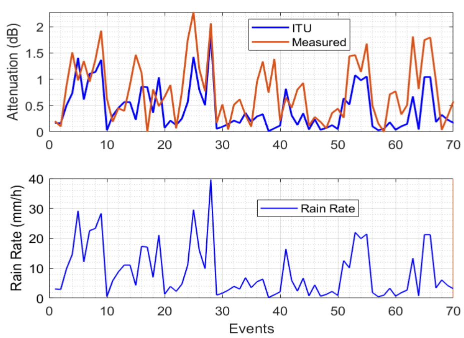


(e) E band 200 m link: without distance factor restriction.

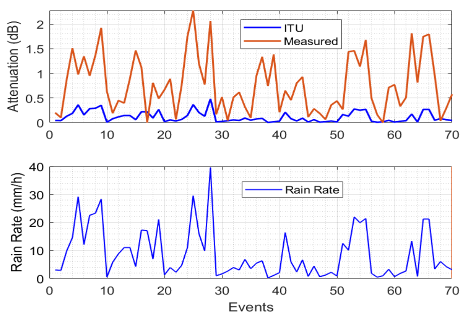


(f) E band 200 m link: with distance factor restriction.

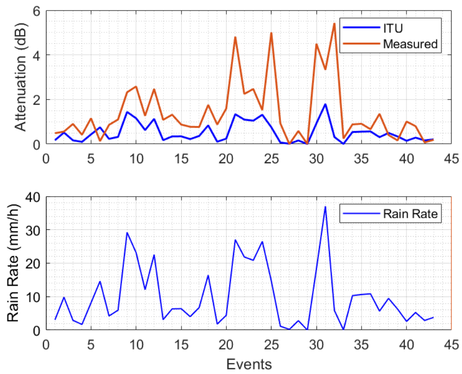
Fig. 12. Measured and ITU predicted rain attenuation for E band for the three links with and without using the maximum distance factor of 2.5.



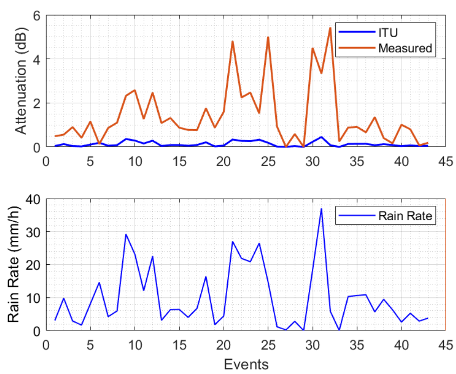
(a) K band 36 m direct link: without distance factor restriction



(b) K band 36 m direct link: with distance factor restriction



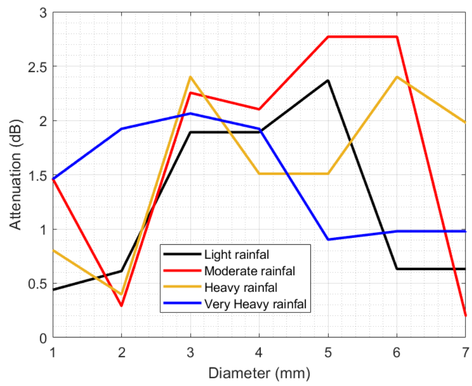
(c) K band 36 m side link: without distance factor restriction.



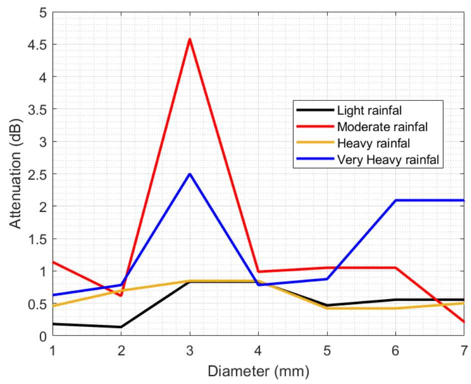
(d) K band 36 m side link: with distance factor restriction.

Fig. 13. Measured and ITU predicted rain attenuation for K band for the three links with and without using the maximum distance factor of 2.5.

To further examine the impact of other rain parameters on the link, the measured attenuation has been investigated with rain drop diameter size from 0.1 mm to 7 mm which were within different rainfall rates. The attenuation rises with the raindrop diameter. The highest attenuation is illustrated for the events where raindrops diameters range between 2-4 mm. The analysed results indicate that very heavy and moderate rainfall rate lead to higher attenuation values for both frequencies in the presence of large rain drops (above 2 mm) but larger drops do not contribute considerably to the entire maximum attenuation when the particle speed is 9 m/s to 10 m/s even with a number of particles lower than 20 drops, it results in higher and variable attenuation specially for very heavy rainfall higher than 20 mm/h where raindrops with size of 1-3 mm lead up to 4.5 dB higher attenuation. A diameter in the range of 4-7 mm contributes occasionally to the attenuation up to 2 dB for both frequency bands.



(a) 25.84 GHz



(b) 77.54 GHz

Fig. 14. Calculated attenuation versus raindrop diameter in mm

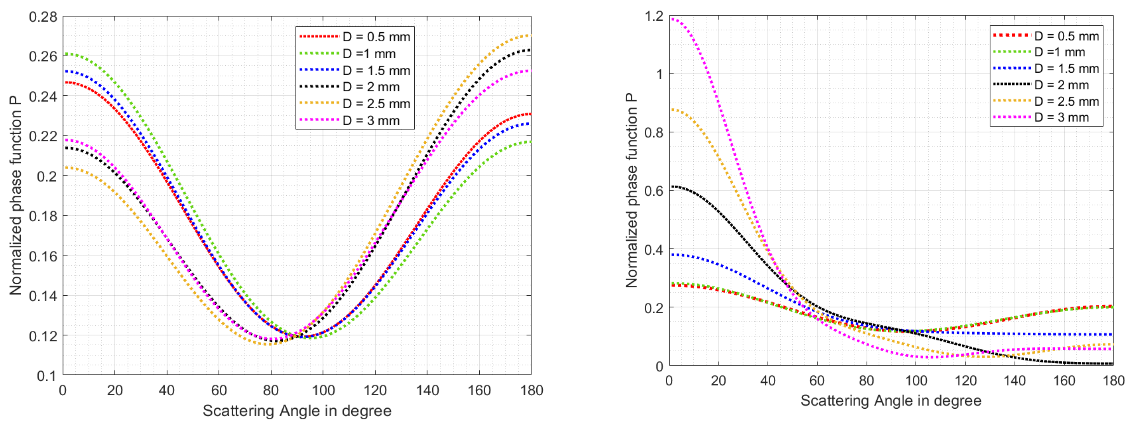
3.3 Raindrops induced scattering

Scattering due to raindrops has significant effect because rain scattering is considered one of the main sources of attenuation and interference. The rain scattering modelling which can be divided into single-scattering or multiple-scattering. In single scattering, the wave incident on the raindrops volume arrives after few interactions. When the density of scatterers or the scattering cross section increases, multiple scattering occurs. In the current analysis, the most common first order rain scattering approach is adopted. The regular model which is considered widely to cause interference between fixed links.

Spherical raindrops, Mie theory, and bistatic radar equation are considered for scattering functions calculations. One significant element that defines the prospect distribution of the scattered wave direction is the scattering phase function P (D; θ_s) defined by:

$$P(\theta) = \frac{|S_1(\theta)|^2 + |S_2(\theta)|^2}{\pi x^2 Q_{sca}} \quad (5)$$

where $S_1(\theta)$ and $S_2(\theta)$ terms are elements of the scattering amplitude matrix given by the Mie theory. Fig. 15 shows the scattering phase function versus the scattering angle for predefined raindrops diameter dominant in the disdrometer measurements. It is noticed from the figure that the 77 GHz band is considerably forward oriented pattern while at 26 GHz is titled to Rayleigh which explains the difference between the measured and predicted attenuation for the K band side link presented in the previous section when Mie theory was applied for all the calculations of both bands.



(a) 25.84 GHz. (b) 77.54 GHz.

Fig. 15. Normalized scattering phase function $P(\theta)$ at: (a) 25.84 GHz and (b) 77.54 GHz.

4. Conclusion

In this study, rain attenuation for millimeter wave 5G fixed links applications was investigated using long term rain statistics and radio data collected over three fixed links at Durham University. For most rain events, the attenuation follows the rain intensity with an exponential increase. Predicted attenuation values from the DSD and the ITU models have been analysed and compared to measured data at 25.84 GHz and 77.54 GHz for a direct and a side link over 36 m together with a 200 m point to point link at 77.125 GHz. The DSD proves that rainfall rates are insufficient to estimate rain attenuation values as other factors are involved such as the raindrops shape and distribution, number of dominant drops, diameter, and velocity. The drops diameter in the range of 0.1-2 mm contributes to the overall attenuation within all frequencies for particle speeds in the range between 1 m/s and 5 m/s. Larger raindrops contribute irregularly to the attenuation when the rainfall velocity and particle speed is in the range of (5-10 m/s). Measurement results using the long-term measurements over the short-range point to point fixed links indicate that the maximum distance factor of 2.5 in ITU-R P.530-17 is not suitable for rain attenuation prediction. The results were submitted to the ITU Study Group 3 meeting in June 2021 recommending deleting the upper limit on *r*. This was approved and will appear in ITU-R P.530-18 in due course. The results were also submitted to a special issue of Radio Science [7].

5. References

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