We investigate the impact of fog, rain and snow effects on the transmitted optical signal by evaluating their attenuation behaviour based on measurement data collected at Graz, Milan, Nice and Prague. The data used in the analysis for Graz, Milan, Nice and Prague consists of six months (September 2005–February 2006), two months (January 2005 – February 2005), eight days (24 June 2004 – 01 July 2004) and two months (September 2007 & December 2007), respectively.

II. THEORETICAL BACKGROUND

Transmitted optical pulses in free space are mainly influenced by two main mechanisms of signal power loss – absorption and scattering. Absorption is mainly due to water vapours and carbon dioxide, and depends on the water vapour content that is dependent on the altitude and humidity. By appropriate selection of optical wavelengths for transmission the losses due to absorption can be minimised.

It was found that scattering (especially Mie scattering) is the main mechanism of optical power loss as the optical beam loses intensity and distance due to scattering. The beam loss due to scattering can be calculated from the following empirical, visibility range dependent, formula:

$$\alpha_{\text{scat}} = \frac{17}{V} \left( \frac{0.55}{\lambda} \right)^{\lambda V}$$  \hspace{1em} (1)

where $V$ is visibility range in km, $\lambda$ is transmission wavelength in nm. Visibility range is typically defined as the distance at which the transmitted optical intensity is attenuated to 5% of its original value $[5]$. The visibility range $V$ can be calculated from transmittance ($\tau$) according to the formula mentioned in the following equation $[8]$:

$$V(m) = \frac{\ln(\tau_d)}{\ln(\tau_m)} = -3.27m \frac{\ln(\tau_d)}{\ln(\tau_m)}$$  \hspace{1em} (2)

where $d$ is the link distance, $\tau_0$ and $\tau_M$ are the threshold of transmission (5%) and the measured percentage of transmission at a minute scale. To calculate the total received power and the link budget, following link equation:

$$P_r = P_t \left( \frac{d_T^2}{\Theta_T^2 L} \right)^{\tau_0 \tau_M \tau_{\text{scat}} \tau_{\text{atm}} \tau_{\text{agg}} \tau_{\text{agg}} \tau_{\text{agg}}}$$  \hspace{1em} (3)

where $d_T$ is the transmitter aperture diameter, $\Theta_T$ is the transmitter beam divergent angle, $L$ is the link distance,
\( \tau_{\text{ex}} \) is the atmospheric transmission factor, and \( \tau_t \) \& \( \tau_x \) are the transmitter and receiver optics efficiency, respectively.

To determine the probability of attenuation that it is equal to or exceeds a certain threshold value \( x \) dB during an arbitrary time interval \( t_0 \) such that the optical link is unavailable, is \( PA_\text{tot}(x) \) given by the following relationship [13]:

\[
PA_\text{tot}(x) = P[A_\text{tot}(t) \geq x] = E_\text{tot}(x)
\]  

where \( x \) is the normalized link margin such that \( x=x^*/L \) (dB/km) and its value also represents the highest value of the atmospheric attenuation, and \( x^* \) is the link margin whose upper bound is determined by the dynamical range of the receiver having a typical value of about 30-40 dB. \( PA_\text{tot}(x) \) is the cumulative distribution of the total attenuation and \( E_\text{tot}(x) \) is the cumulative exceedance probability of the atmospheric attenuation. The percent availability of the FSO links such that it fulfills the quality of service (QoS) requirements can be expressed by the following equation:

\[
\text{Availability} = (1 - PA_\text{tot}(x)) \times 100\%
\]  

In order to determine the reliability and the quality of the free space link, the attenuation coefficient \( \alpha_\text{tot} \) is considered a stochastic process whose distribution is empirically defined about a lognormal distribution. It is important to mention here that the availability and quality of service (QoS) of FSO links is strongly dependent upon and is influenced by various weather effects especially fog, rain and snow besides the wavelength used for transmission purpose [4, 5].

III. EMPIRICAL AND THEORETICAL ATTENUATION MODELS

In FSO systems, modulating the instantaneous intensity of a laser source data are transmitted and the received intensity is detected with a photodiode. During propagation of optical pulses in free space, photons are absorbed and scattered by the atmospheric particles, such as fog, rain and snow droplets. Generally, these droplets have radii in a range between 1 \( \mu \text{m} \) to 5000 \( \mu \text{m} \), with drop-size concentration decreasing sharply with increasing drop sizes [9] and cause varying attenuation depending on their distribution. However, the droplets

The Beer-Lambert law defines the optical power loss through the atmosphere that varies on the order of hours [10]. The appropriate model for the attenuation coefficient \( \alpha \) varies depending on the presence of precipitation. Normally, the optical links in free space measure visibility data with the attenuation coefficient. In order to calculate the attenuations caused by fog, rain and snow usually we rely on two approaches – empirical approach and the theoretical approach (microphysical models). The empirical approach is very easy and quick to implement whereas, the theoretical approach is somewhat difficult and time consuming. The one very commonly adopted empirical approach concerns computing signal attenuations based on the visibility range estimate. In the case of clear or foggy weather with no rain, hail or snow, Kim’s model is employed to compute the attenuation due to fog \( \alpha_{\text{fog}} \), that is very accurate for the narrow wavelength range between 785 – 1550 nm [10],

\[
\alpha_{\text{fog}} = \frac{2.91}{V} \left( \frac{\lambda}{550} \right)^{-q}
\]  

where \( q \) is the parameter related to size distribution of the droplets

\[
q = \begin{cases} 
1.6 & (V > 50 \text{ km}) \\
1.3 & (6 \text{ km} < V < 50 \text{ km}) \\
0.66V + 0.34 & (1 \text{ km} < V < 6 \text{ km}) \\
V - 0.5 & (0.5 \text{ km} < V < 1 \text{ km}) \\
0 & (V < 0.5 \text{ km})
\end{cases}
\]  

In the case of rain, the optical power loss is relatively wavelength insensitive. For rain, an accepted empirical model based on the visibility range from [11] is,

\[
\alpha_{\text{rain}} = \frac{2.9}{V}
\]  

The attenuation in case of snow can be more severe than the attenuation in case of rain due to the much larger droplet size. Based on [12], the attenuation for snow based on visibility range is,

\[
\alpha_{\text{snow}} = \frac{58}{V}
\]  

The underlying electromagnetic theory behind the theoretical (microphysical) models is well known. For these models, we assume that multiple scattering is negligible, and all the scatterers are acting independently and are distributed uniformly along the atmospheric transmission path. For fog, the attenuation of optical pulse is mainly due to Mie scattering effect and the loss effects due to absorption can be ignored. Therefore the extinction coefficient is evaluated by,

\[
\beta_{\text{fog}} = \int_{r_{\text{min}}}^{r_{\text{max}}} \pi r^2 Q_{\text{ext}}(m, r/\lambda)n(r)dr \quad \text{[dB/km]}
\]  

Where \( m \) and \( r \) are the refractive index and radius of the fog droplets, respectively. \( Q_{\text{ext}} \) is the extinction efficiency and \( n(r) \) is the size distribution (i.e., modified gamma) of the fog droplets. For rain conditions the usual equations are:

\[
\beta_{\text{rain}} = 4.34 \int_{r_{\text{min}}}^{r_{\text{max}}} \alpha_{\text{scat}}(r)n(r)dr \quad \text{[dB/km]}
\]  

Where \( n(r) \) and \( r \) is the gamma distribution and radius of the rain drops, respectively. The rain rate can be calculated as,

\[
R = 4.8 \int_{r_{\text{min}}}^{r_{\text{max}}} r^2 v(r)n(r)dr \quad \text{[mm/hr]}
\]  

and the terminal velocity \( v(r) \) of rain droplets in stagnant air is given by,

\[
v(r) = 9.65 - 10.3e^{-2r} \quad \text{[m/s]}
\]  

The model dealing with snow attenuations is,

\[
\beta_{\text{snow}} = 0.3619 \frac{\rho_s R}{C_v^3 v_i} \quad \text{[dB/km]}
\]  

where terminal velocity \( v_i \) of the snowflakes is,

\[
v_i = 0.1155 \sqrt{\frac{gC_v}{\rho_s C_s}} \quad \text{[m/s]}
\]  

Here, \( \rho_s \) is the water density in g/cm\(^3\), \( R \) is snowfall rate in mm/hr, \( C_s \) is the thickness of snowflakes in g/cm\(^2\), \( \rho_s \) is the air density in g/cm\(^3\), \( C_v \) is the drag coefficient for snow.

Although snowflakes have a very complicated shape, yet they do not exhibit any preferred dimension, hence assuming the spherical shape of snow droplets seems reasonable. Additionally, the sizes for rain droplets can be much larger.
than 5 mm, but since they are hydro-dynamically unstable so they tend to break into relatively smaller dimensions.

IV. IMPACT OF WEATHER EFFECTS AND THE ANALYSIS

Fall of the received optical power below the receiver sensitivity threshold introduces a fade. This fade can be described as short-term fade or the long-term fade depending upon the time duration of the optical power interruption. The type of fade that occur due to rain, fog and snow is the long-term fade whose duration could be a few minutes or it can reach up to several hours. In this contribution we would focus our discussion only on the long-term fades introduced by fog, rain and snow conditions to the FSO link in free space. We analyse here one month rain attenuation data from Prague, one snow event.

Fig. 1 shows an empirical simulation of the rain, snow and fog attenuation effects against visibility range. From this plot it is evident also that fog, rain and snow cause significant propagation losses to the optical signals transmission in free space.

![Fig. 1: Simulation of empirical model for fog, rain and snow conditions for FSO link at 950 nm](image)

We will analyze here first the attenuations caused by rain to the propagation of optical pulses transmitted in free space. We take a rain event recorded at Prague for the transmission of 850nm pulses on 850 m link. From the analysis of this measured rain event data, it was observed that rain attenuation occurs for percentages of time smaller than 0.66% and the maximum measured value of 18 dB corresponds to 0.0005% of time of year. The minimum measured visibility during rain events is 1000 m.

Fig. 2 shows two sample rain events occurred during the attenuation measurement campaign of year 2006 – 2007 on 18.09.2006 at Prague and at Milan during year 2005-2006 measurement campaign on January 17th 2005. The maximum rain rate during this particular rain event was recorded to be about 44 mm/hr and the maximum attenuation reached during this rain event was 8.5 dB/km at Prague. The maximum change in specific attenuations during the rain events recorded were about ± 1.70 dB/km averaged on a minute scale. While for Milan the maximum attenuation reached was 65 dB/km, a mean attenuation of about 8 dB/km and with a change in specific attenuation of about ± 16 dB/km. Figure 3 below, shows the time series of these particular snow events on a second scale. It is concluded that the optical signal loss effects due to snow attenuations are much higher when compared with the rain attenuations.

![Fig. 2: Rain attenuations against a rain rate in mm/hr from rain events at Prague and Milan for FSO links operating at 850 nm and 785 nm](image)

In order to assess the optical signal loss effects due to snow, we analyze three snow events that were recorded; one long snow event at Graz during 25 – 28 November 2005 and the two in Milan on 18.01.2005 and 28.01.2005. The maximum attenuation measured for snow at Graz reached to 55 dB/km with a mean attenuation of about 3 dB/km averaged on a minute scale. While the changes in specific attenuation occurred around ± 15 dB/km & ± 18 dB/km on a minute and second scales, respectively. Whereas, for Milan the maximum attenuations reached to 65 dB/km, a mean attenuation of about 8 dB/km and with a change in specific attenuation of about ± 16 dB/km. Figure 3 below, shows the time series of these particular snow events on a second scale. It is concluded that the optical signal loss effects due to snow attenuations are much higher when compared with the rain attenuations.

From the knowledge of the Mie scattering theory, we know that fog is the biggest attenuating effect to the propagation of optical signal transmission especially in the troposphere. The time series analysis of the measured fog (radiation and advection) attenuations for Graz (Austria), Milan (Italy), La Turbie Nice (France) and Prague (Czech Republic) have been already reported and discussed in details [4, 6, 13, 14]. From these analyses, it was concluded that the
Fog attenuations are strongly dependent on the local climate and the fog microphysics as the fog attenuations vary spatially and temporally with time. It was also observed that on the average the changes in fog specific attenuation values occur about ±6 – ±8 dB/km in case of moderate continental fog conditions like as in Graz, Milan and Prague.

Fog can be classified into many types on the basis of its formation mechanism, climatic conditions and the drop size distribution. However, the two most common types of fog are continental and maritime fog. The fog conditions at Graz, Milan and Prague are the continental type while at La Turbie Nice it is the dense maritime fog. The fog microphysics of these two types of fog is very different, so is their attenuations to the optical signal transmissions in these fog environments. The attenuations in continental fogs reach up to 120 dB/km while in dense maritime fogs the average value is about 480 dB/km.

It is evident from the above plot that the changes in specific attenuation for dense maritime fog events are more concentrated around 0 dB/km suggesting that most of the time the fog was stable. We believe that the large changes observed in the changes were mainly due to the wind turbulence causing changes or the order of ±300 dB/km. The Table 1 below summarises some basic statistics of the optical links installed at the above mentioned four locations.

<table>
<thead>
<tr>
<th>Place</th>
<th>Link distance</th>
<th>Transmission wavelength</th>
<th>Max. attenuation</th>
<th>Avg. attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graz</td>
<td>79.6 m, 650 m</td>
<td>850 nm, 850 nm</td>
<td>124 dB/km</td>
<td>120 dB/km</td>
</tr>
<tr>
<td>Milan</td>
<td>390 m</td>
<td>785 nm</td>
<td>65 dB/km</td>
<td>25 dB/km</td>
</tr>
<tr>
<td>Nice</td>
<td>28.3 m</td>
<td>850 nm, 850 nm</td>
<td>590 dB/km</td>
<td>490 dB/km</td>
</tr>
<tr>
<td>Prague</td>
<td>550 m</td>
<td>850 nm, 850 nm</td>
<td>131 dB/km</td>
<td>122 dB/km</td>
</tr>
</tbody>
</table>

The apparent changes in the average and the maximum values of specific attenuations measured and mentioned under Table 1 (for Graz, Milan and Prague) for continental fog conditions are strongly dependent upon the fog microphysics and also due to the local weather conditions. However, despite Milan, Prague and Graz are located in the same temperate area, we feel that there are two major differences which are expected to affect to some extent the fog attenuation measurements: a) the climate during winter is colder in Graz than Prague and Milan, where daily temperature minima are often below 0°C, while in Milan temperature rarely falls below 0°C but average temperature in Prague during winter remains -0.4°C, and b) Milan and Prague are large cities the microclimate is that of a dense urban area. On the other side, Graz is a midsize town, with the optical link being located in a suburban environment with no tall buildings and many wide open areas around. Therefore it is reasonable that fog episodes are heavier in Graz than in Milan and Prague. We present in Table 2, some statistics of all the fog events measured during the September 2005 to February 2006 measurement campaign at Graz since the fog attenuations measured at Graz shows the worst case fog events as compared with the Milan and Prague fog attenuation events.

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of fog events</th>
<th>Total duration</th>
<th>50% %</th>
<th>99% %</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.09.2005</td>
<td>01</td>
<td>5.20</td>
<td>14.64</td>
<td>78.9</td>
</tr>
<tr>
<td>25.10.2005</td>
<td>02</td>
<td>3.28</td>
<td>45.23</td>
<td>95.43</td>
</tr>
<tr>
<td>26.10.2005</td>
<td>02</td>
<td>3.14</td>
<td>8.26</td>
<td>110.8</td>
</tr>
<tr>
<td>11.11.2005</td>
<td>01</td>
<td>4.32</td>
<td>11.18</td>
<td>52.5</td>
</tr>
<tr>
<td>12.11.2005</td>
<td>01</td>
<td>3.25</td>
<td>10.05</td>
<td>59.95</td>
</tr>
<tr>
<td>22.11.2005</td>
<td>01</td>
<td>2.05</td>
<td>7.32</td>
<td>105.5</td>
</tr>
<tr>
<td>29.11.2005</td>
<td>01</td>
<td>2.45</td>
<td>8.45</td>
<td>115.7</td>
</tr>
<tr>
<td>30.11.2005</td>
<td>01</td>
<td>1.91</td>
<td>13.42</td>
<td>109.18</td>
</tr>
<tr>
<td>13.12.2005</td>
<td>01</td>
<td>1.37</td>
<td>70.84</td>
<td>108.7</td>
</tr>
<tr>
<td>09.01.2006</td>
<td>02</td>
<td>1.11</td>
<td>73.13</td>
<td>112.06</td>
</tr>
<tr>
<td>16.01.2006</td>
<td>01</td>
<td>3.27</td>
<td>44.79</td>
<td>115.48</td>
</tr>
<tr>
<td>30.01.2006</td>
<td>01</td>
<td>3.28</td>
<td>22.50</td>
<td>125.5</td>
</tr>
<tr>
<td>31.01.2006</td>
<td>01</td>
<td>2.07</td>
<td>50.12</td>
<td>297.96</td>
</tr>
<tr>
<td>01.02.2006</td>
<td>02</td>
<td>4.34</td>
<td>25.04</td>
<td>199.10</td>
</tr>
<tr>
<td>02.02.2006</td>
<td>01</td>
<td>1.48</td>
<td>36.56</td>
<td>199.9</td>
</tr>
<tr>
<td>03.02.2006</td>
<td>01</td>
<td>2.16</td>
<td>32.02</td>
<td>195.46</td>
</tr>
</tbody>
</table>

Table 2: Fog episodes detected at Graz from September 2005 to February 2006. The last two columns show laser attenuation values measured during fog: alongside with the 50% and 99% percentiles of the attenuation distribution

For Nice, the fog conditions are dense maritime type that are not dependent on any particular season but are more
dependent on the marine environment. Fig. 6 as shown below, presents the scatter of the fog attenuation data during a fog event measured on 28th July 2004 with 950 nm wavelength as fog attenuations for Nice shows a worse fog attenuation scenario. The measured data points are compared with the four commonly used empirical models to measure the fog attenuations. It is apparent that the dependence of specific attenuation on visibility for dense maritime fog does not converge to a particular model.

Since the fog attenuations at Graz shows a worse scenario of fog attenuations under the moderate continental fog conditions, we draw a contour plot of the measured attenuations of six months duration in order to visualize their diurnal behaviour. This knowledge can be handful to identify the time intervals that can have the highest & lowest attenuation values for such type free space optical links. This information would consequently be useful in the link budget designs for locations having such fog environments.

We plotted the collected six months fog attenuations data for Graz in Fig. 7. From this contour plot we can see, that there are few individual high attenuation events scattered in the plot. However, it is difficult to conclude from this plot any particular time slots when the fog attenuations are particularly high. From this plot, it is clear that especially in October to end of January the overall attenuations are high most of the time in the range of 120 dB/km - 180 dB/km on a second scale. Also in the start of September and the end of February the attenuations are comparatively lesser as compared the other months. The reason could be that in these months winter starts to come and finish, respectively. So there is a very high likelihood of the less severe or a kind of very light fog conditions. Additionally, the very high attenuation individual events are mostly occurring during the evening and especially very late night hours (i.e., during the 18-24 time interval), while the attenuations are generally lesser in the 00-06 time interval. From this data set, however it is very difficult to clearly identify the regions and time events of very high attenuation levels.

V. Conclusions

This contribution explains the impact of rain, snow and fog effects on the propagation of optical wireless links in free space. It was found out that for optical wireless links in the troposphere, fog is the most limiting factor as compared with the losses incurred by rain and snow.

This paper provides some useful statistics of the fog attenuations from the measured attenuations of terrestrial optical wireless links. We also tried to evaluate the atmospheric environments of Graz, Milan, Nice and Prague on the basis of three weather conditions i.e., rain, snow and fog and studied their effect on the optical signal propagation. Obviously, more attenuation data is required to make an in depth analysis of these links under fog, rain and snow conditions. Additionally, we tried to figure out the time intervals of fog evolution, its dissipation and its occurrence based on the fog attenuation trends. This information can prove very useful when to apply a certain fade margin, that can have a significant impact on the optical wireless links availability and improving the quality of service (QoS) demands for applications requiring high data rates communication.

REFERENCES