Bands in the millimeter wavelengths above 30GHz are being allocated for various wireless links including communications, radars and stand-off remote sensing. Most recently, the standards for the 5th generation of the cellular communications, consider the possibility to utilize millimeter waves for short range links operating in small cells. This new spectrum presents more bandwidth, enabling for realization of high bitrate wireless network with low latencies.

Unfortunately, wireless communication operating in such extremely high frequencies, requires line-of-sight links, suffering from a decreased link-budget due to atmospheric absorption. The availability of such a link is further reduced in foggy or rain weather conditions. In such conditions, liquid water content play a role in the absorption and scattering of the millimeter wave radiation.

In the current work the effects of different water form in the atmosphere (vapor, suspended droplets and ice particles) on the propagation of electromagnetic radiation at broadband millimeter wave spectrum, have been studied.

Introduction

Utilization of higher microwave and millimeter-wave spectrum at the Extremely High Frequencies (EHF) above 30GHz can meet the growing demand for broadband wireless communication links and the deficiency of wide frequency bands within the conventional spectrum. In addition to the fact that the EHF band (30-300GHz) covers a wide range, which is relatively free of spectrum users, it offers many advantages for the 5th generation of the cellular communications.

When millimeter-wave radiation passes through the atmosphere, it suffers from frequency-dependent absorptive and dispersive phenomena, causing distortions in amplitude and phase [1]. Several empirical and analytical models were suggested for estimating the millimeter and infrared wave transmission of the atmospheric medium [2]. Golovachev
et al. [3] presented a theoretical study on the millimeter wave propagation in fog conditions and an experimental verification with very low visibility artificial fog.

In current work, dielectric properties of the different forms of the water content in the atmosphere were studied. The physical model was compared with practical recommendation.

**The model**
Millimeter wave signals propagating in the atmosphere suffer frequency-dependent absorptive and dispersive phenomena, causing distortions in amplitude and phase. The Millimeter-wave Propagation Model (MPM) is employed for prediction of the atmospheric frequency response.

**Electromagnetic Wave Propagation through a Dielectric Media**
The parameters of a radio wave are modified on propagation through a dielectric media. In general, such influences are due to refraction, absorption and scatter. Both phase and amplitude responses of a plane radio wave propagating the distance $d$ at frequency $f$ follow from

$$E(d) = E_0 \exp[-jk(f)d]$$  \hspace{1cm} (1)

where $E_0$ is the initial amplitude, $c$ is the speed of light in vacuum, $k(f)$ is the *propagation factor* and $n(f)$ is the *refractive index*.

$$k(f) = \frac{2\pi f}{c} n(f)$$  \hspace{1cm} (2)

The complex *refractive index*, is a measure of the interaction of electromagnetic radiation with the medium:

$$n(f) = 1 + N(f) \times 10^{-6}$$  \hspace{1cm} (3)

The refrectivity depends on the frequency and medium properties and is given in .

$$N(f)[ppm] = N_0 + N'(f) - jN''(f)$$  \hspace{1cm} (4)
where the nondispersive part $N_0$ is real and positive and $N$ is a function of frequency.

**The Medium Effect**

The distortions in amplitude and phase during the Millimeter wave signals propagation are presented as attenuation factor, and group delay. The refractivity is converted into path-specific propagation rates.

The imaginary part of $N$ leads to attenuation factor:

$$\alpha(f) = -\text{Im}\{k_z(f)\} = \frac{2\pi f}{c} N^n(f) \times 10^{-6}$$  \hspace{1cm} (5)

and the real part to phase dispersion or the wavenumber of the field:

$$\beta(f) = \text{Re}\{k_z(f)\} = \frac{2\pi f}{c} \left[ 1 + N_0 \times 10^{-6} + N'(f) \times 10^{-6} \right]$$  \hspace{1cm} (6)

The group delay at a distance $d$ is defined via the derivative of the wavenumber:

$$\tau_d = \frac{d}{2\pi} \frac{d\beta}{df} = \frac{d}{c} + \frac{d}{c} \left[ N_0 + N'(f) + f \frac{dN'}{df} \right] \times 10^{-6} = \tau_0 + \Delta \tau_d(f)$$  \hspace{1cm} (7)

where $\Delta \tau_d(f) = \tau_d(f) - d/c$.

**Water in the atmosphere**

The current work focus on dielectric properties of different phases of water content, such as moist air, fog and rain.

**Moist air**

Moist air is gaseous state of water present in the air. Concentration of water in the gas phase in air called humidity. Quantitative characteristic of the moist air could be relative humidity RH [%], which is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature.

**Fog**

Fog is aerosol consisting of liquid droplets suspended in the air. Quantitative characteristic of the fog could be liquid water content $W$ [g/m$^3$]. Droplet scale of fog is 5-50 µm.
Rain

Rain is liquid water in the form of droplets that have condensed from atmospheric water vapor. Quantitative characteristic of the rain could be rainfall rate $R$ [mm/h]. Raindrop sizes typically range from 0.5 mm to 4 mm.

Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Size [μm]</th>
<th>Number concentration [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud droplet</td>
<td>5-50</td>
<td>102-103</td>
</tr>
<tr>
<td>Drizzle drop</td>
<td>~100</td>
<td>~103</td>
</tr>
<tr>
<td>Ice crystal</td>
<td>10-102</td>
<td>103-105</td>
</tr>
<tr>
<td>Rain drop</td>
<td>0.5-4</td>
<td>102-103</td>
</tr>
</tbody>
</table>

Propagation through the Atmosphere

Liebe [2] millimeter propagation model (MPM) is used for calculation of the atmospheric frequency response under foggy conditions. Contributions of dry air, water vapor, suspended water droplets (haze, fog, cloud), and rain are addressed.

The Dispersive complex refractivity can be represented by five terms,

$$N = (N_L + N_d + N_c) + N_W + N_R$$

(8)

where $N_L$ moist air resonance contributions, $N_d$ dry air non-resonant spectra, $N_c$ water vapor continuum spectrum, $N_W$ suspended water-droplet refractivity and $N_R$ rain approximation. The current work we presents the suspended water droplets effect in details, where the detailed model can be found in Liebe [4].

The Effect of Suspended Water Droplets

The suspended water-droplet refractivity term, $N_W$ is developed from Mie scattering theory using Rayleigh approximation, which applies for the case when the scattering particle is small relative to the wavelength (i.e. size parameter $x = 2\pi R_p/\lambda \ll 1$). In the case of particles with dimensions greater than the wavelength, ($x \approx 1$) Mie's scattering model can be used.
Using the Rayleigh approximation, the model provides both amplitude and phase information independent of the particle size distribution. The refractivity contributions, $N_w$, was found to be proportional to the suspended water droplet concentration, $W$, in [g/m$^3$] as

$$N_w = W \left( \frac{3}{2} m_{W,i} \right) \frac{\varepsilon_w - 1}{\varepsilon_w + 2}$$

(9)

where $m_w$ is the specific weight of the particle material (for liquid water $=1$) and $\varepsilon_w$ is dielectric permittivity of the suspended material- water (in distinction to the permittivity of the medium).

The refractivity in (9) be presented as sum of nondispersive, $N_0$, spectra, $N'$, and loss, $N''$, terms:

$$N_{w0} = \frac{3}{2} W \left( 1 - \frac{3}{\varepsilon_0 + 2} \right)$$

(10)

$$N_w (f) = \frac{9}{2} W \left( \frac{1}{\varepsilon_0 + 2} - \frac{\eta / \varepsilon_w''}{1 + \eta^2} \right)$$

$$N_w'' (f) = \frac{9}{2} W \frac{1}{\varepsilon_w'' \left( 1 + \eta^2 \right)}$$

where $\eta(f) = [2 + \varepsilon_w'(f)]/\varepsilon_w''(f)$.

**The Material (Water) Permittivity**

The complex dielectric permittivity of the suspended material $\varepsilon_w$ (water for fog and clouds) is given in the Debye shape. For single relaxation frequency $f_0$, the relation is in the form of

$$\varepsilon_m (f) = \frac{\varepsilon_0 - \varepsilon_\infty}{1 - j \left( f / f_r \right)} + \varepsilon_\infty$$

(1)

where $\varepsilon_0$ is the static dielectric constant, $\varepsilon_\infty$ ($f \rightarrow \infty$) high-frequency constant and $f_r$ the relaxation frequency. For water, $\varepsilon_w$, an expression containing two relaxation frequency is used, “double-Debye model” (5 parameters).
\[ \varepsilon_m(f) = \frac{\varepsilon_0 - \varepsilon_1}{1 - j \left( \frac{f}{f_p} \right)} + \frac{\varepsilon_1 - \varepsilon_2}{1 - j \left( \frac{f}{f_s} \right)} + \varepsilon_2 \]  

(2)

After rationalization the expressions of the real and imaginary parts are

\[ \varepsilon'_W(f) = \frac{\varepsilon_0 - \varepsilon_1}{1 + \left( \frac{f}{f_p} \right)^2} + \frac{\varepsilon_1 - \varepsilon_2}{1 + \left( \frac{f}{f_s} \right)^2} + \varepsilon_2 \]  

(3)

\[ \varepsilon''_W(f) = \left( \frac{f}{f_p} \right) \frac{(\varepsilon_0 - \varepsilon_1)}{1 + \left( \frac{f}{f_p} \right)^2} + \left( \frac{f}{f_s} \right) \frac{(\varepsilon_1 - \varepsilon_2)}{1 + \left( \frac{f}{f_s} \right)^2} \]

where \( \varepsilon_0 = 77.66 + 103.3(\theta - 1) ; \varepsilon_1 = 0.067 \varepsilon_0 ; \varepsilon_1 = 3.52 \).

The principal and secondary relaxation frequencies are in GHz

\[ f_p = 20.20 - 146(\theta - 1) + 316(\theta - 1)^2 \]  

(4)

\[ f_s = 39.8 f_p \]

where \( \theta = 300/T \), \( T \) is the absolute temperature [K]. A Broadband model for an extension range up to 30THz is presented in [5] using the double-Debye model with addition of two Lorentzian terms.

**The ITU model**

The International Telecommunication Union (ITU) presented a recommended model for attenuation due to clouds and fog in [dB/km] [6].

\[ \alpha(f) = 0.819W \frac{f}{\varepsilon''_W(1 + \eta^2)} \]  

(5)

where \( f \) is the frequency [GHz].

**Results**

The model predictions for the attenuation and phase dispersion are presented for various humidity and fog conditions. The results were compared against the ITU recommendations.
**Transmission characteristics**

The transmission characteristics of the atmosphere at the EHF band, are presented for different relative humidifies, RH (%), (Fig. 1) and different fog densities, W (g/m3) (Fig. 2)

![Graph 1](image1)

**Fig. 1.** (a) Attenuation and (b) incremental phase dispersion propagation factors in different conditions of relative humidity RH [%].
Fig. 2. (a) Attenuation and (b) incremental phase dispersion propagation factors in different conditions of liquid water content $W$ [g/m$^3$].

**Comparison against ITU Recommendations**

A comparative study between the comprehensive MPM and ITU recommendation reveals that although the absorption picks of water vapor and oxygen are not taken into account in the ITU model, there is good fit between the models for $W>5$ [7]. Thus, the ITU model refers to the attenuation only, and not for the group delay. Fig. 3 presents comparison of MPM and ITU-P.840 recommendation for different relative humidity RH [%] and liquid water content $W$ [g/m$^3$].
Fig. 3. Comparison of MPM and ITU-P.840 recommendation for different relative humidity RH [%] and liquid water content W [g/m³].

Summary
The paper discussed the absorptive and dispersive characteristics of moist air, fog and rain effects on the propagation factors at Millimeter wave regime. We find that different phases of water content affect differently on dielectric properties of the media. We compare ITU-P.840 recommendation and MPM attenuation factor estimations for fog conditions.

References