The Effect of Weather Conditions on Millimeter Wave Propagation

Yosef Golovachev, Ariel Etinger, Gad A. Pinhasi, and Yosef Pinhasi

***Abstract*—** Electromagnetic wave propagation in the atmosphere is affected by the composition of the air and by meteorological conditions like fog and rain. In the current work the effects of different phases of water in the atmosphere (vapor, suspended droplets, fog and rain) on the propagation of electromagnetic radiation at broadband millimeter wave spectrum, have been studied. Analytical expressions are derived for the attenuation and group delay along the path of propagation. Using the derived expressions a modified millimeter-wave propagation model (MPM) is employed for the prediction of the suspended water droplets and rain effects.

***Keywords*—** Atmospheric wave propagation, Dielectric permittivity of water, Dispersive complex refractivity, Extremely high frequency, ITU recommendations, Millimeter waves.

I. 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]. However most of the proposed models addressed only to the attenuation effect and not to the phase dispersion and group delay effects. Consequently, comprehensive models are needed for propagation predictions.

Golovachev et al. presented a theoretical study on the millimeter wave propagation in fog conditions and an experimental verification with very low visibility artificial fog [3,4,5]. Using a modified millimeter-wave propagation model (MPM) the calculated results showed a good agreement with experimental measurements with respect to attenuation and time delay effects.

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In current work, a space-frequency theory for modeling wireless communication channels operating in the EHF band is presented. The model was used to study the effect of clouds, fog and rain on the electromagnetic signal, in particular the attenuation and time delay.

Analytic expressions of dielectric medium parameters like permittivity, refractivity, and susceptibility, and the relation between them are presented. Using the derived expressions a modified millimeter-wave propagation model (MPM) is employed for the prediction of the suspended water droplets and rain effects.

The model results were compared with the practical ITU recommendations. The model was used to predict the results for the ongoing experimental study.

II. Propagation through a Dielectric Media

Millimeter wave signals propagating in the atmosphere suffer frequency-dependent absorptive and dispersive phenomena, causing distortions in amplitude and phase.

A. Electromagnetic Wave Propagation factors

The parameters of a radio wave are modified while propagating 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

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

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*.

$$k(f) = \frac{2\pi f}{c} n(f) \tag{2}$$

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

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

The refractivity depends on the frequency and medium properties and is given in

$$N(f)_{[ppm]} = N_0 + N'(f) - jN''(f) \quad (4)$$

where the nondispersive part N_0 is real and positive and N is a function of frequency.

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*:

$$\alpha(f) = -\operatorname{Im}\{k(f)\} = \frac{2\pi f}{c} N''(f) \times 10^{-6} \quad (5)$$

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

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

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

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

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

B. 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 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 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 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: Different water forms in air

Type	Size [µm]	Number concentration [cm^{-3}]
Cloud droplet	5-50	10^2-10^3
Drizzle drop	~100	~10^3
Ice crystal	10-10^2	10^3-10^5
Rain drop	500-4000	10-10^3

C. Dispersive Complex Refractivity

Liebe millimeter propagation model (MPM) is used for calculation of the atmospheric frequency response under foggy conditions [3]. 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,

$$N = (N_L + N_d + N_c) + N_W + N_R \quad (8)$$

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 (1989) [6].

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 $x = 2\pi R_p/\lambda << 1$). In the case of particles with dimensions greater than the wavelength, ($x \gg 1$) 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:

$$N_W = W\left(\frac{3}{2}m_{W,i}\right)\frac{\varepsilon_W - 1}{\varepsilon_W + 2} \quad (9)$$

where $m_{W,i}$ is the specific weight of the particle material (for liquid water = 1) and ε_W is dielectric permittivity of the suspended material - water (in distinction to the permittivity of the medium).

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

$$N_{W0} = \frac{3}{2}W\left(1 - \frac{3}{\varepsilon_0 + 2}\right) \quad (10)$$

$$N'_W(f) = \frac{9}{2}W\left(\frac{1}{\varepsilon_0 + 2} - \frac{\eta / \varepsilon''_W}{1+\eta^2}\right) \tag{11}$$

$$N''_W(f) = \frac{9}{2}W\frac{1}{\varepsilon''_W(1+\eta^2)} \tag{12}$$

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

D. Complex Dielectric Permittivity

The complex *dielectric permittivity* of the suspended material ε_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

$$\varepsilon_m(f) = \frac{\varepsilon_0 - \varepsilon_\infty}{1 - j(f/f_r)} + \varepsilon_\infty \tag{13}$$

where ε_0 is the static dielectric constant, ε_∞ ($f\rightarrow\infty$) high-frequency constant and f_r the relaxation frequency. For water ε_W, an expression containing two relaxation frequency is used, "double-Debye model" (5 parameters)

$$\varepsilon_m(f) = \frac{\varepsilon_0 - \varepsilon_1}{1 - j(f/f_p)} + \frac{\varepsilon_1 - \varepsilon_2}{1 - j(f/f_s)} + \varepsilon_2 \tag{14}$$

After rationalization the expressions of the real and imaginary parts are

$$\varepsilon'_W(f) = \frac{\varepsilon_0 - \varepsilon_1}{1 + (f/f_p)^2} + \frac{\varepsilon_1 - \varepsilon_2}{1 + (f/f_s)^2} + \varepsilon_2 \tag{15}$$

$$\varepsilon''_W(f) = (f/f_p)\frac{(\varepsilon_0 - \varepsilon_1)}{1 + (f/f_p)^2} + (f/f_s)\frac{(\varepsilon_1 - \varepsilon_2)}{1 + (f/f_s)^2} \tag{16}$$

where $\varepsilon_0 = 77.66 + 103.3(\theta - 1)$; $\varepsilon_1 = 0.0671\varepsilon_0$; $\varepsilon_2 = 3.52$.

The principal f_p and secondary f_s relaxation frequencies are in GHz

$$f_p = 20.20 - 146(\theta - 1) + 316(\theta - 1)^2 \tag{17}$$

$$f_s = 39.8 f_p \tag{18}$$

where $\theta = 300/T$, T is the absolute temperature [K]. A Broadband model for an extension range up to 30THz is presented in [2] using the double-Debye model with addition of two Lorentzian terms.

III. The Effect of the Rain

The wave propagating through the volume of rain is attenuated by means of scattering and absorption on or in water droplets. If the multiple scattering is neglected as the first approximation the radiation intensity is decreasing with the distance x according to the relation:

$$I(x) = I(0)e^{-\alpha x} \tag{19}$$

where α is absorption coefficient that proportional to the number of droplets in a unit volume. Also it depends on the extinction cross section C_{ext} of the droplet which depends on the refractive index of water at particular frequency and also on the shape and size of the droplet.

The absorption coefficient (1/km) can be calculated by adding extinction cross sections of all droplets in a unit area

$$\alpha = 10^{-3}\int p(r)C_{ext}(r, f, n_W)dr \tag{20}$$

where r (mm) is the droplet radius, C_{ext} (mm^2) is the extinction cross section of a droplet with radius r, with complex refractive index of water n_W and for frequency f. The function $p(r)$ ($m^{-3}mm^{-1}$) denotes the drop size distribution and defines the number of droplet with radius r in a unit volume 1 m^3 per unit interval of droplet radii.

The drop size distribution (DSD) $p(r)$ can be found by the classical Marshall-Palmer (MP) model

$$p(r) = 16000e^{-8.2R^{-0.21}r} \tag{21}$$

where R (mm/h) is rain rate (intensity).

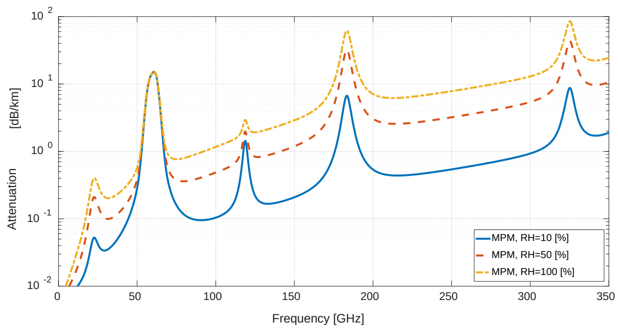
IV. ITU Propagation Models

A. The ITU Fog Attenuation Model

The International Telecommunication Union (ITU) presented a recommended model for attenuation due to clouds and fog in [dB/km] [4].

$$\gamma_{fog}(f) = 0.819W\frac{f}{\varepsilon''_W(1 + \eta^2)} \tag{22}$$

where f is the frequency [GHz].



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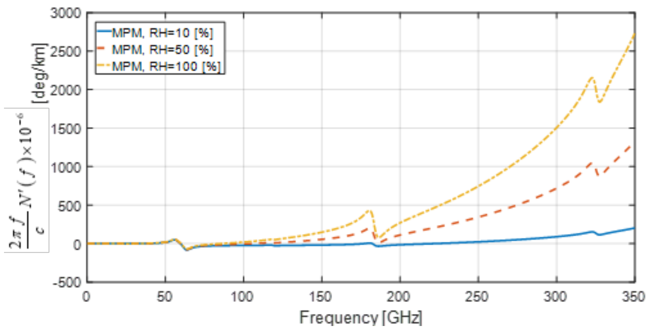

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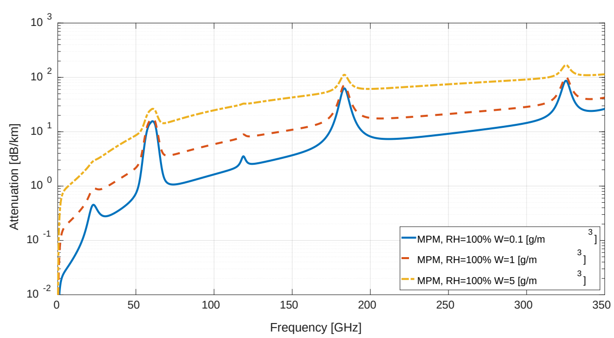
Fig. 1: (a) Attenuation and (b) incremental phase dispersion propagation factors in different conditions of relative humidity RH [%]



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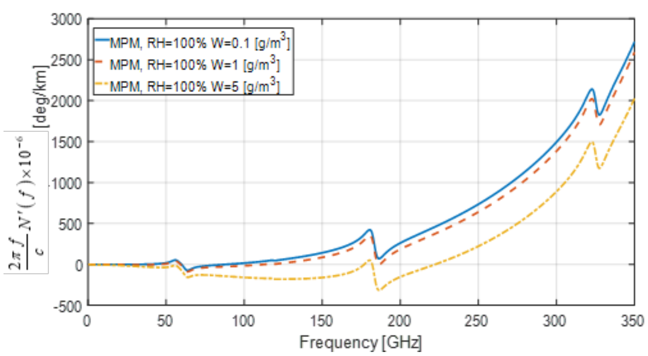

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Fig. 2: (a) Attenuation and (b) incremental phase dispersion propagation factors in different conditions of liquid water content W [g/m^3]

A. The ITU Rain Attenuation Model

The International Telecommunication Union (ITU) presented a recommended model for attenuation due to rain in [dB/km] [6]. The specific attenuation is obtained from the rainfall rate R (mm/h) using the power law relationship:

$$\gamma_{rain} = kR^{\alpha} \tag{23}$$

Values for the coefficients k and α are determined as functions of frequency, f (GHz), in the range from 1 to 1000 GHz, from the following equations, which have been developed from curve-fitting to power-law coefficients derived from scattering calculations:

$$\log_{10} k = \sum_{j=1}^{4} a_j \exp\left[-\left(\frac{\log_{10} f - b_j}{c_j}\right)^2\right] + m_k \log_{10} f + c_k \tag{24}$$

$$\alpha = \sum_{j=1}^{5} a_j \exp\left[-\left(\frac{\log_{10} f - b_j}{c_j}\right)^2\right] + m_\alpha \log_{10} f + c_\alpha \tag{25}$$

V. Simulation Results

The model predictions for the attenuation and phase dispersion are presented for various humidity, fog and rain conditions. The results were compered against the ITU recommendations.

A. Transmission characteristics

The transmission characteristics of the atmosphere at the EHF band, are presented for different relative humidifies, RH (%), (Fig. 1), different fog densities, W (g/m^3) (Fig. 2) and different rainfall rate, R (mm/h), (Fig. 3).

B. Comparison with ITU Recommendation

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 g/m^3 and R>50 mm/h. Thus, the ITU model refers to the attenuation only, and not for the group delay.

VI. Conclusion

This study discusses the absorptive and dispersive characteristics of moist air, fog and rain and their effects on the propagation factors of Millimeter Waves. In particular the attenuation and time delay emerging when the electromagnetic signal is propagating in the atmosphere due to clouds fog and rain. At millimeter wavelengths, the attenuation is a function of the water droplet concentration**.** Different phases of water content affect the dielectric properties of the atmospheric media. A comparison is made between the attenuation estimated by the ITU-P.840 [7] and the ITU-P.838 [8] recommendations and that obtained from the MPM [2].

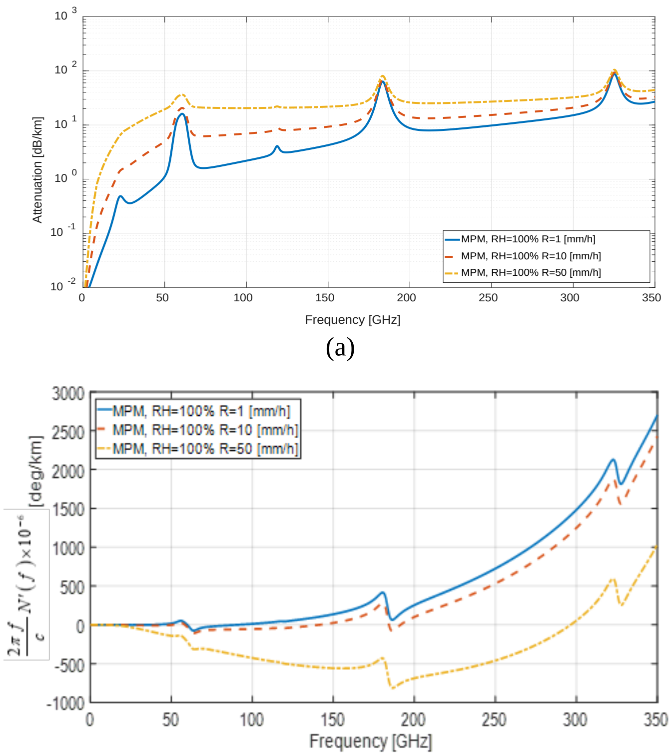

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Fig. 3: (a) Attenuation and (b) incremental phase dispersion propagation factors in different conditions of rainfall rate *R* [mm/h]

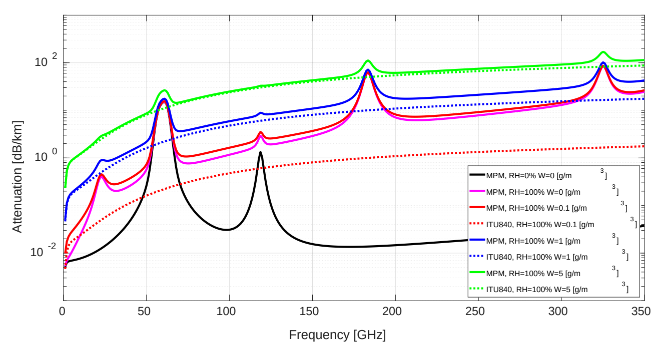

Fig. 4: Comparison of MPM and ITU-P.840 recommendation for different relative humidity RH [%] and liquid water content *W* [g/m^3]

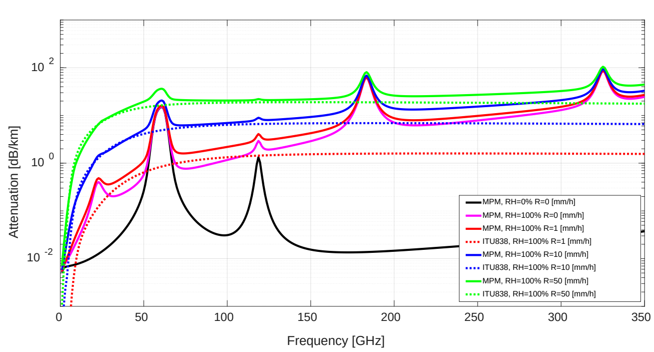

Fig. 5: Comparison of MPM and ITU-P.838 recommendation for different relative humidity RH [%] and rainfall rate *R* [mm/h].

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Yosef Golovachev received the B.Sc. degree in Electrical Engineering and M.Sc. degree in Telecommunication Systems Engineering from Jerusalem College of Technology (Lev Academic Center) in 2009 and 2015 respectively.

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Dr. Pinhasi is involved in numerical and experimental study of millimeter and sub-millimeter wave field in laboratory at Ariel University.

Yosef Pinhasi (M'89) was born in Israel on May 3, 1961. Received the B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from Tel-Aviv University, Israel in 1983, 1989 and 1995 respectively.

Currently, he is a Professor in Ariel University. In 1995 he joined Ariel University as one of the founders of the Department of Electrical and Electronic Engineering, and served as its head between the years 2004-2007. During 2010-2017 he has been the Dean of the Faculty of Engineering at the Ariel University.

Prof. Pinhasi investigates utilization of electromagnetic waves in a wide range of frequencies for various applications such as communications, remote sensing and imaging. The space-frequency approach, which developed by him, is employed to study propagation of wide-band signals in absorptive and dispersive media in broadband communication links, and wireless indoor and outdoor networks as well as in remote sensing radars and radiative power beaming operating in the millimeter wavelengths and Tera-Hertz regimes. He is also a radio amateur (call sign: 4Z1VC), member of the IEEE.