Performance analysis of mmWave/sub-terahertz communication link for 5G and B5G mobile networks

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Abstract: Millimeter (mmWave) and sub-terahertz communication is a key technology to support high data rate requirements of 5G and B5G mobile networks. However this field is still in its initial development stage because of the various technical difficulties in its practical implementation due to inherently distinct propagation properties of mmWave/sub-terahertz frequencies. A thorough investigation of mmWave/sub-terahertz communication link is required in order to successfully deploy these frequency bands in 5G and B5G mobile networks. This paper investigates the effect of atmospheric conditions like dry air, humidity, rain, snow, fog and foliage on the performance of the mmWave/sub-terahertz link. The work also presents a mathematical analysis of the coverage of mmWave/sub-terahertz communication link and investigates the effect of various parameters like frequency, bandwidth, transceiver antenna gain, path loss coefficient (LOS, NLOS case) and system noise on its performance.

Keywords: 5G; B5G; coverage; mmWaves; snow attenuation; sub-terahertz

1 Introduction

Wireless communication has always witnessed a trend towards the use of high frequency spectrum. Early continuous wave communications used frequencies having wavelengths of the order of kilometers which soon were followed by medium wave (MW) communications in the “500–1600 KHz” spectrum [1]. Due to the rising spectrum congestion and discovery of ionospheric reflection in the twentieth century, the focus of communication switched to the use of the shortwave (SW) band spectrum having wavelengths of the order of meters. Satellite and terrestrial communication applications which needed larger bandwidths used ultra-high frequency (UHF) band up to “1 GHz” [2]. The exponential growth of cellular networks in the last two decades has shifted the focus towards centimeter band. Modern cellular systems use frequencies in the range of 2–5 GHz (corresponding wavelength of 15–6 cm) [3]. However, even the relatively wide channels with bandwidth of 160 MHz using IEEE 802.11 standards are proving insufficient to meet the current user demand of high speed wireless communication [4].

In the recent years mmWave/sub-terahertz band has gained popularity due to their capability to support high data rates of the order of Gbps and Tbps for 5G and B5G wireless network applications [5, 6]. MmWave/sub-terahertz band refers to the frequency range of 30 GHz–300 GHz. The standard sub-bands within mmWave/sub-terahertz spectrum include 28–40 GHz (Ka-band), 57–64 GHz (V-band), 71–76 GHz (E-band), 92–115 GHz (W-band) and 130–175 (D-band) where W-band and D-band belong to the category of sub-terahertz spectrum (90–300 GHz) [7, 8]. The main motivation of using these frequency bands for 5G and B5G networks is the availability of huge unexploited bandwidth which can be used to provide the high speed networks with data rate of Gbps and Tbps. Other motivations include device compactness, higher degree of spectrum sharing, better spatial resolution that are achieved at these frequencies. However despite so many advantages, these frequency bands (especially W and D band) have not been practically utilised due to their fundamentally different propagation characteristics [9–11]. Therefore in order to implement these frequency bands successfully in 5G and B5G networks, mmWave/sub-terahertz communication link needs to be rigorously investigated and attempts need to be made to improve its performance. In practice mmWave/sub-terahertz communication link experiences different environmental/weather conditions depending on the application scenario. These conditions mainly include dry air, humidity, rain, snow, fog and foliage. This research work evaluates the effect of these factors on performance of the mmWave/sub-terahertz communication link. The work also presents the mathematical analysis of the coverage of mmWave/sub-terahertz

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communication link in a 5G and B5G mobile network scenario.

The paper is organised as: Section 1 gives the introduction. Section 2 evaluates the effect of dry air, humidity, rain, snow, fog and foliage on the link performance. Section 3 provides the mathematical analysis of the coverage of mmWave/sub-terahertz communication link considering various link parameters. Finally, Section 4 concludes the paper.

2 Effect of atmospheric conditions

The feasibility of mmWave/sub-terahertz communication in outdoor application scenarios depends on various atmospheric/environmental conditions which include dry weather (dry air or humidity), rain, snow, fog and foliage. In this section, performance of mmWave/sub-terahertz band communication link is investigated under the effect of these conditions and discussed below:

2.1 Dry weather conditions

In dry weather, apart from the atmospheric gases mmWave/sub-terahertz frequencies are attenuated mainly due to the absorption of the signal by water vapour or humidity present in the atmosphere especially at the lower altitudes. This frequency dependent attenuation under the conditions of dry air and humidity is computed using standard ITU Recommendations ITU-R P.676-3 [12] and plotted in Figures 1 and 2.

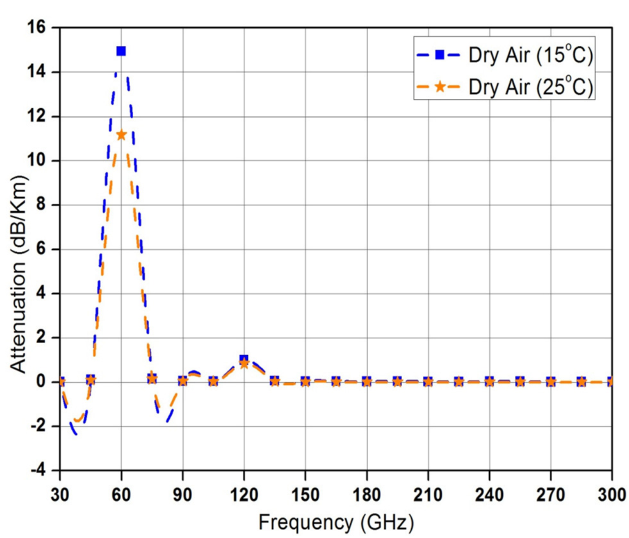

Figure 1: Effect of dry air on mmWave/sub-terahertz communication link.

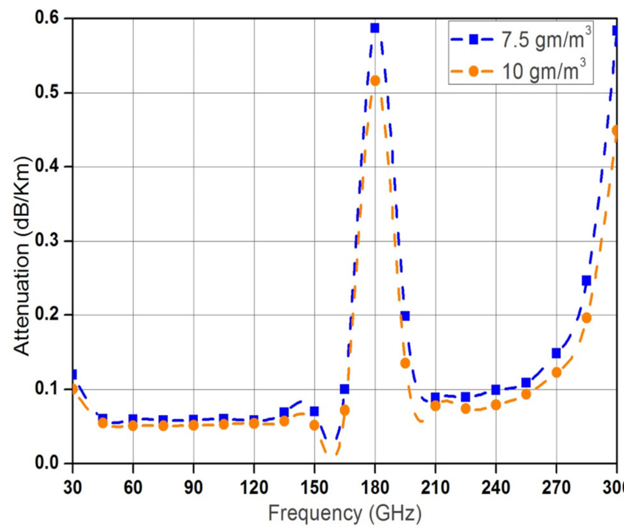

Figure 2: Effect of humidity (water vapour) on mmWave/sub-terahertz link.

2.2 Rain attenuation

In heavy and moderate rainfall, mmWave/sub-terahertz signals get absorbed or scattered as the wavelength of the signal is comparable to the size of raindrops. This result in the significant attenuation of the signal referred as 'Rain attenuation' ('γ_r'). The rain attenuation for specific frequency and rain rate is given by standard power law relationship as [13]:

$$\gamma_r = k \cdot R_r^{\alpha} \,(\mathrm{dB/km}) \tag{1}$$

where, 'R_r' denotes the rate of rainfall in mm/h, 'k' (k_h or k_v) and 'α' (α_h or α_v) are frequency-dependent coefficients. 'k_h' and 'α_h' correspond to horizontal polarisation and 'k_v' and 'α_v' correspond to vertical polarisation. The values 'k' and 'α' are determined using following standard relations [14]:

$$\log_{10} k = \sum_{i=1}^{4}\left(a_i \exp\left[-\left(\frac{\log_{10} f - b_i}{c_i}\right)^2\right]\right) + m_k \log_{10} f + c_k \tag{2}$$

where

$$m_k = \begin{cases} -0.1896 \text{ for } k_h \\ -0.1639 \text{ for } k_v \end{cases}$$

and

$$c_k = \begin{cases} 0.7114 \text{ for } k_h \\ 0.6329 \text{ for } k_v \end{cases}$$

The coefficients a_i, b_i and c_i (for i = 1 to 4) are given in Table 1.

Similarly the value of 'α' is computed as:

Table 1: Coefficients a_i, b_i and c_i for k_h and k_v.

i	k_h			k_v		
	a_i	b_i	c_i	a_i	b_i	c_i
1	−5.33	−0.10	1.13	−3.80	0.57	0.81
2	−0.35	1.27	0.45	−3.44	−0.23	0.51
3	−0.24	0.86	0.15	−0.39	0.73	0.12
4	−0.94	0.65	0.17	−0.50	1.07	0.27

$$\alpha = \sum_{j=1}^{5}\left(a_j \exp\left[-\left(\frac{\log_{10} f + b_j}{c_j}\right)^2\right]\right) + m_\alpha \log_{10} f + c_\alpha \quad (3)$$

where

$$m_\alpha = \begin{cases} 0.67850 \text{ for } \alpha_h \\ -0.0537 \text{ for } \alpha_v \end{cases}$$

and

$$c_\alpha = \begin{cases} -1.955 \text{ for } \alpha_h \\ 0.8340 \text{ for } \alpha_v \end{cases}$$

The coefficients a_j, b_j and c_j (for j = 1 to 5) are given in Table 2.

Using 'k_h', 'k_v', 'α_h' and 'α_v' computed from equation (2) and (3), the value of 'k' and 'α' is calculated as:

$$k = \frac{[k_h + k_v - (k_v - k_h)\mathrm{Cos}\, 2\,\psi \mathrm{Cos}^2\phi]}{2} \quad (4)$$

$$\alpha = \left[\frac{k_h\alpha_h + k_v\alpha_v - (k_v\alpha_v - k_h\alpha_h)\mathrm{Cos}\, 2\,\psi \mathrm{Cos}^2\phi}{k_h + k_v - (k_v - k_h)\mathrm{Cos}\, 2\,\psi \mathrm{Cos}^2\phi}\right] \quad (5)$$

where, 'ψ' is the polarisation angle and 'ϕ' is the path elevation angle. For mmWave/sub-terahertz range, 'k' and 'α' are computed and presented in Table 3. The variation of these frequency dependent coefficients is also plotted and shown in Figure 3.

Equations (1), (2) and (4) show that attenuation due to the rainfall increases with increase in frequency of operation and rainfall intensity. The effect of rain attenuation on mmWave/sub-terahertz signal in various rainfall scenarios (drizzle, light, medium and heavy rainfall) is also illustrated in Figure 4. The figure clearly depicts that the

Table 2: Coefficients a_j, b_j and c_j for α_h and α_v.

j	α_h			α_v		
	a_j	b_j	c_j	a_j	b_j	c_j
1	−0.143	1.824	−0.551	−0.078	2.34	−0.76
2	0.296	0.775	0.198	0.567	0.96	0.54
3	0.322	0.637	0.132	−0.202	1.15	0.27
4	−5.376	−0.962	1.478	−48.23	0.79	0.116
5	16.17	−3.299	3.439	48.58	0.79	0.117

Table 3: 'k' and 'α' for mmWave/sub-terahertz frequencies.

f (GHz)	k	α
30	0.2347	0.9307
60	0.8560	0.7571
90	1.2801	0.6911
120	1.4881	0.6624
150	1.5860	0.6480
180	1.6272	0.6392
210	1.6432	0.6381
240	1.6345	0.6323
270	1.6292	0.6301
300	1.6286	0.6279

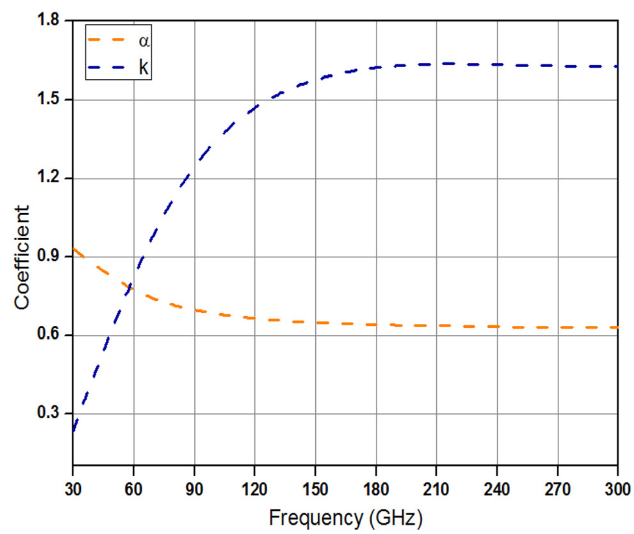

Figure 3: Variation of coefficients 'k' and 'α' with frequency.

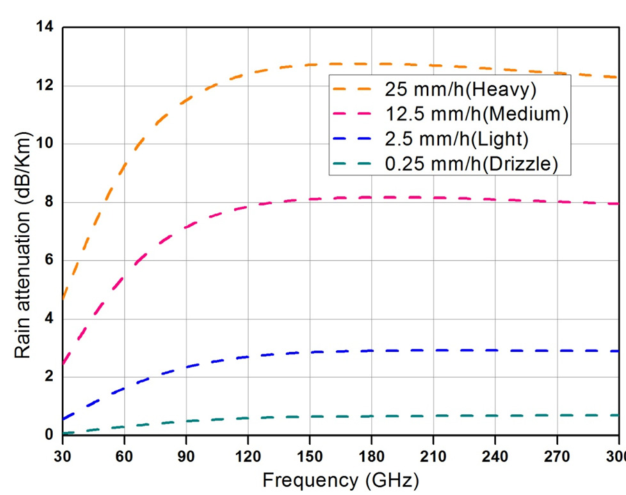

Figure 4: Effect of rainfall on mmWave/sub-terahertz link.

mmWave/sub-terahertz link is severely affected in medium and heavy rainfall and may even bring the status of the link to disconnected state for frequencies beyond 120 GHz in heavy rainfall scenarios.

2.3 Snow attenuation

The coverage of a communication link in outdoor environments is significantly affected by snowfall referred as 'Snow attenuation'. This attenuation is more prominent at mmWave/sub-terahertz frequencies and becomes highly disruptive as the rate of snowfall increases [15]. Mathematically, Snow attenuation ('Att_{Snow}') is given as [16]:

$$Att_{Snow} = 3.49 \times 10^{-7} \cdot \frac{S^{1.6}}{\lambda^4} + 2.24 \times 10^{-4} \cdot \frac{S}{\lambda} \text{ for } \lambda < 15\,\text{mm} \quad (6)$$

where, 'λ' is the wavelength of the signal in mm and 'S' represents the rate of snowfall in mm/h. The attenuation due to light, moderate and heavy snowfall is illustrated in Figure 5 which shows the disruptive attenuation effects in moderate and heavy snowfall especially when the link is operated beyond 120 GHz frequency.

2.4 Fog attenuation

Fog consists of small water droplets or ice crystals. MmWave/sub-terahertz signals while propagating through the fog get highly scattered or absorbed due to these water droplets or ice crystals [17]. This is referred as "Fog attenuation" and is given by [18]:

$$A_{\text{tt\_fog}} = \frac{0.82 f \rho_l}{\varepsilon_n (1 + \eta^2)} \quad (7)$$

where, 'ρ_l' is the liquid water density in fog (g/m^3). 'ε_n' and 'η' are frequency and temperature dependent coefficients. These coefficients along with the fog attenuation for mmWave/sub-terahertz frequencies is computed and presented in Table 4. The attenuation affects due to medium (ρ_l = 0.05 g/m^3) and thick fog (ρ_l = 0.5 g/m^3) is illustrated in Figure 6 which shows that the performance of the mmWave/sub-terahertz link is severely affected by thick fog conditions.

2.5 Foliage loss

The most significant impairment of mmWave/sub-terahertz communication link is the foliage loss. The primary source of

Table 4: Computed values of ε_n and η along with fog attenuation.

f (GHz)	T = 273 K		$A_{\text{tt\_fog}}$ (dB/Km)	
	ε_n	η	ρ_l = 0.05 g/m^3	ρ_l = 0.5 g/m^3
30	22.43	0.6430	0.0388	0.388
60	12.21	0.7825	0.1249	1.249
90	8.544	0.9973	0.2165	2.165
120	6.729	1.2006	0.2995	2.995
150	5.667	1.3768	0.3747	3.747
180	4.974	1.5258	0.4458	4.458
210	4.484	1.6517	0.5149	5.149
240	4.115	1.7602	0.5834	5.834
270	3.822	1.8563	0.6514	6.514
300	3.580	1.9443	0.7188	7.188

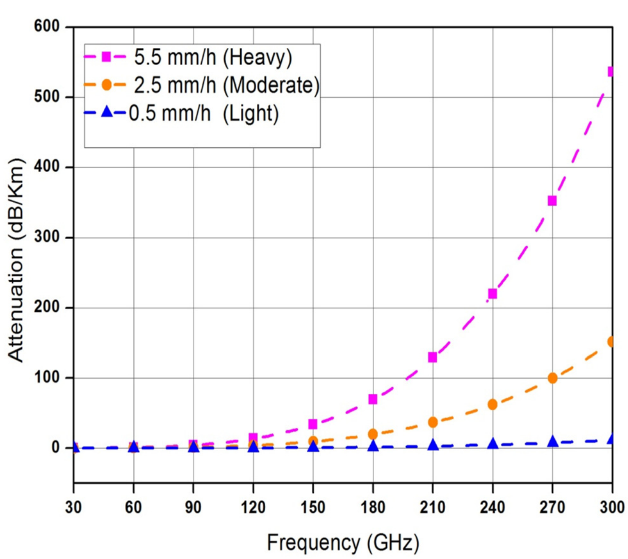

Figure 5: Effect of snowfall on mmWave/sub-terahertz link.

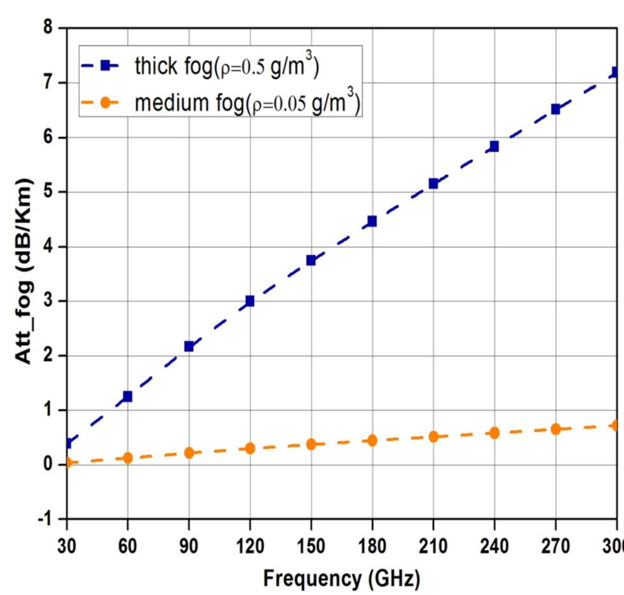

Figure 6: Effect of fog on mmWave/sub-terahertz communication link.

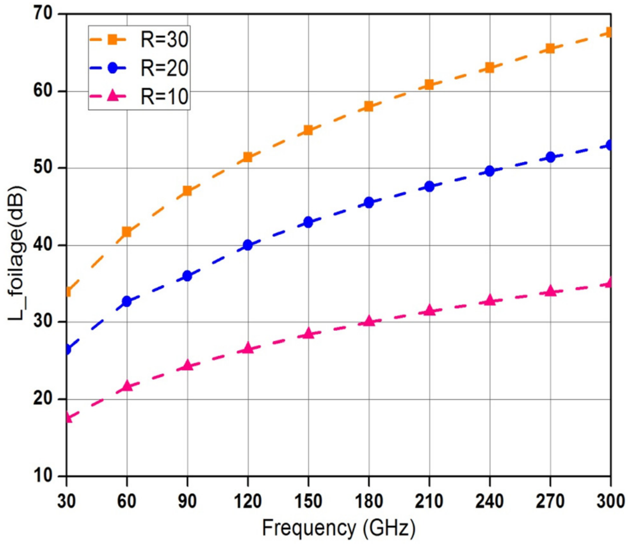

Figure 7: Effect of foliage on mmWave/sub-terahertz link.

the foliage is randomly distributed leaves, tree branches, twigs and trunks. MmWave/sub m terahertz signals while travelling through the foliated environment experience significant power loss [19, 20]. This loss depends on the frequency of the signal and depth of foliage. Mathematically, "Foliage loss (L_{foilage})" is given by the ITU-R model as [21]:

$$L_{\text{foilage}}, \text{dB} = \frac{1}{5}\left(f \times 10^3\right)^{0.3} R^{0.6} \tag{8}$$

where, 'f' is frequency in GHz and 'R' represents the foliage depth in meters. The effect of foliage attenuation on the mmWave/sub-terahertz link at different foliage depths is illustrated in Figure 7. The figure shows that even for smaller foliage depths and lower end frequencies of mmWave/sub-terahertz band spectrum, the foliage induced attenuation effects are very severe and can result in the non-availability of the communication link.

3 Mathematical analysis

Consider a mmWave/sub-terahertz band communication scenario as shown in Figure 8.

If the transmitter and receiver are separated by a distance "d", "f" is the frequency of operation, then the signal power at the receiver given by Friis free space model is as [22]:

$$\frac{P_R}{P_T} = \left(\frac{c}{4\pi f d}\right)^n \cdot G_T \cdot G_R \cdot \varepsilon_p \tag{9}$$

where, "G_T" and "G_R" represent the gain of antenna at transmitter and receiver respectively, "ε_p" is the polarization factor, "n" is the path loss exponent. For various Line of Sight ("LoS") and Non-Line of Sight ("$NLoS$") communication scenarios in 5G and B5G applications, the path loss exponent "n" varies as [23, 24]:

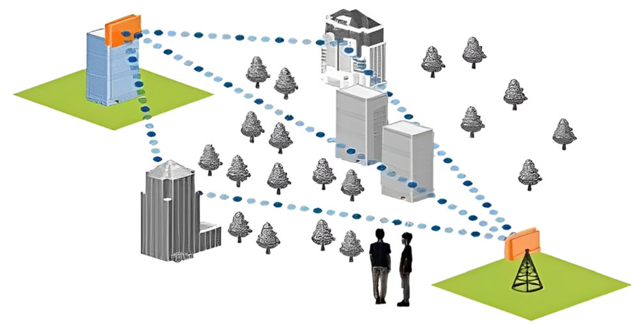

Figure 8: mmWave/sub-terahertz communication scenario.

$$n = \begin{Bmatrix} 1.8 & \text{LoS} & \text{Indoor} \\ 2.0 & \text{LoS} & \text{Outdoor} \\ 2.5 & \text{NLoS} & \text{Urban} \\ 3-5 & \text{NLoS} & \text{Suburban} \end{Bmatrix}$$

If the effect of atmospheric conditions like dry air, humidity, fog, rain, snow and foliage is considered then equation (9) modifies as:

$$\frac{P_R}{P_T} = \left(\frac{c}{4\pi f \cdot d \cdot L_{\text{atm}}}\right)^n \cdot G_T \cdot G_R \cdot \varepsilon_p \tag{10}$$

where, 'L_{atm}' represents the attenuation due to atmospheric conditions. Equation (10) depicts that received power decreases with increase in frequency implying that mmWave/sub-terahertz communication links are inherently suited for short range communication applications.

If "B" is the bandwidth of system and "N_o" is the power spectral density of the communication link, then signal to noise ratio ("SNR") at the receiver input is given by [25]:

$$\text{SNR}_{\text{in}} = \frac{P_R}{B N_o} \tag{11}$$

The minimum Signal to Noise ratio ("SNR_{min}") required at the receiver end determines the coverage of the link and corresponds to the received power ("P_{Ro}") given by:

$$\text{SNR}_{\text{min}} = \frac{P_{Ro}}{B N_o} \tag{12}$$

From (10) and (12), Transmission coverage ("d_o") of the communication link can be expressed as:

$$d_0{}^n = \left(\frac{c}{4\pi f \cdot L_{\text{atm}}}\right)^n \cdot \frac{P_T \cdot G_T \cdot G_R \cdot \varepsilon_p}{\text{SNR}_{\text{min}} \cdot B \cdot N_o} \tag{13}$$

Or,

$$d_{\text{o}} = \left(\frac{c}{4\pi f \cdot L_{\text{atm}}}\right) \cdot \left(\frac{P_T \cdot G_T \cdot G_R \cdot \varepsilon_p}{\text{SNR}_{\text{min}} \cdot BN_o}\right)^{\frac{1}{n}} \tag{14}$$

$$\text{Or}, d_0 = \frac{1}{f \cdot L_{\text{atm}}} \cdot \left(\frac{\beta_o}{B}\right)^{\frac{1}{n}}$$

$$\text{where}, \beta_o = \left(\frac{c}{4\pi}\right)^n \left(\frac{P_T \cdot G_T \cdot G_R \cdot \varepsilon_p}{\text{SNR}_{\min} \cdot N_o}\right) \tag{15}$$

Therefore for mmWave and sub-terahertz communication, equations (14) and (15) depict the following:

- mmWave/sub-terahertz transmission coverage will be less than its counterparts at lower frequencies.
- NLOS mmWave/sub-terahertz communication is not practically feasible without using advanced communication techniques like multi-input multi-output (MIMO) technology, Adaptive beamforming, Intelligent Reflecting surfaces (IRS).
- Realistic coverage of the mmWave and sub-terahertz transceiver can be achieved with very high gain antennas.
- Increase in bandwidth leads to the decrease in coverage hence there is a tradeoff between the data rate and the coverage due to the fact that data rate increases with bandwidth.
- The atmospheric losses disrupt the transmission coverage and hence the overall performance of the mmWave/terahertz communication system in outdoor 5G and B5G application scenarios will be deteriorated which needs to be mitigated with appropriate techniques and solutions.

The mmWave/sub-terahertz link in a 5G and B5G mobile network scenario given in Figure 8 is simulated by considering the parameters given in Table 5 [23, 26, 27]. The coverage of the link is investigated under the effect of various atmospheric conditions discussed in Section 2. The simulation results are given in Figures 9 and 10. Figure 9 shows the transmission coverage of the mmWave/sub-terahertz link in outdoor LOS and NLOS scenarios without the consideration of atmospheric conditions. Figure 10 shows the transmission coverage of the same link under the effect of atmospheric conditions like humidity (7.5 g/m^3), rain (25 mm/h), snow (5.5 mm/h) and fog (0.5 g/m^3) in an outdoor LOS scenario. The results show that the transmission

Table 5: Simulation parameters for mmWave/sub-terahertz link.

Parameter	Value	Parameter	Value
P_T (dBm)	30	Polarization factor (ε_p)	1
G_T (dBi)	16	n (LOS_Outdoor)	2
G_R (dBi)	16	n (NLOS_Urban)	2.5
B (GHz)	2	Shadowing_LOS (dB)	1
$\text{SNR}_{\min}$ (dB)	15	Shadowing_NLOS (dB)	5

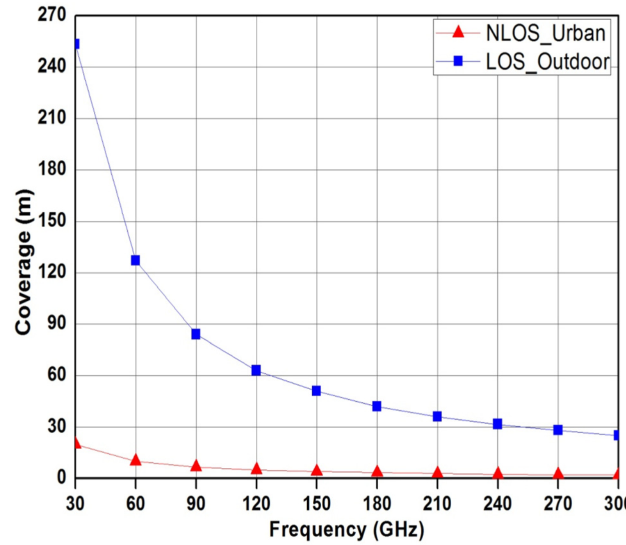

Figure 9: Coverage of mmWave/Sub-terahertz link without consideration of atmospheric conditions.

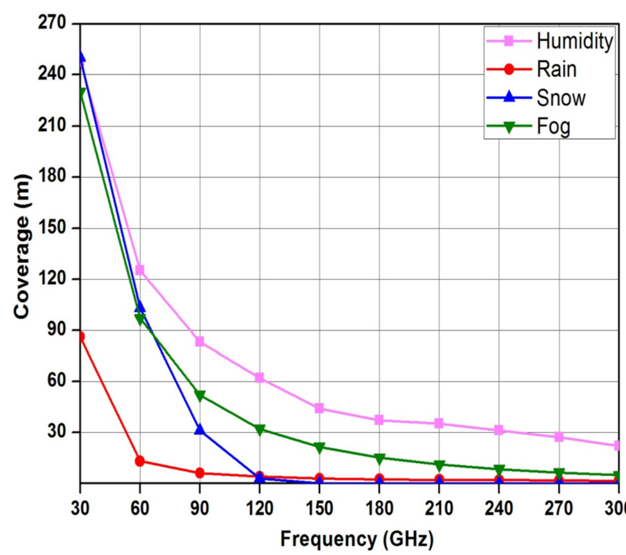

Figure 10: Coverage of mmWave/sub-terahertz link in 5G and B5G network in different atmospheric conditions.

coverage gets highly disrupted by the atmospheric conditions when the link is operated beyond 120 GHz. It can be seen that the mmWave/sub-terahertz link availability almost disappears beyond 120 GHz frequency in the presence of heavy snow or rain in LOS outdoor scenarios. The situation is much worse for NLOS scenarios even in absence of such atmospheric conditions. Therefore for successful implementation of mmWave/sub-terahertz communication in 5G and B5G networks, transmission coverage of the mmWave/sub-terahertz link needs to be improved by various coverage improvement techniques.

4 Conclusions

MmWave/sub-terahertz communication is a key candidate for 5G and B5G mobile networks in order to achieve ultra-high data rate of the order of Gbps and Tbps. However the atmospheric medium for mmWave/sub-terahertz regime is not same as that of its lower frequency counterparts due to fundamentally smaller wavelengths in this spectrum. mmWave/sub-terahertz communication experiences huge losses which in turn affects the transmission coverage and hence the overall performance of the mmWave/sub-terahertz system especially in 5G and B5G application scenarios. This work investigated the effect of atmospheric/environmental factors like dry air, humidity, rain, snow, fog and foliage on the performance of mmWave/sub-terahertz link. This work also presented the mathematical analysis of the coverage of mmWave/sub-terahertz link and investigated the effect of various parameters like frequency, bandwidth, transceiver antenna gain, path loss coefficient (LOS, NLOS case) and system noise on its performance. The results reveal that the attenuation caused by the atmospheric factors in outdoor scenarios is highly prominent and disrupts the performance of the mmWave/sub-terahertz link for 5G and B5G application scenarios. As such attempts should be made in order to improve the coverage of the mmWave/sub-terahertz link and hence the overall performance of the communication system.

In future, this work can be extended by investigating various coverage improvement techniques like MIMO antenna systems, beamforming, intelligent reflecting surfaces and adaptive power efficient network densification techniques.

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