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The Effect of Snow on a Terahertz Wireless Data Link

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The importance of the effects of weather on the transmission of high frequency signals has been recognized for some time [1]. As carrier frequencies increase from RF to millimeter-wave to terahertz, the impact of adverse weather conditions on wireless data links is expected to become substantially more pronounced. At lower frequencies, these effects are typically dominated by attenuation due to molecular absorption [2]. However, at higher frequencies, as the wavelength approaches the size of dust, rain, or snow particles, the effects of Mie scattering are expected to become more significant, representing an important contribution to link budget calculations. Yet, few experimental studies have been reported in the terahertz range, particularly for the case of outdoor tests in adverse weather conditions which may pose a threat to sensitive measurement equipment. Ma and Federici have described controlled weather chamber measurements for modulated data links for a few simulated situations such as rain, fog, dust, and turbulence [3–7], but snow conditions are difficult to simulate indoors. Jeon and Grischkowsky reported a broadband characterization of long-range (~ 180 m) outdoor transmission, comparing clear weather results to recordings in rain and snow [8]. These data indicated a relatively small change in the received power, a somewhat surprising result for a situation where the scattering particles (individual snowflakes) are comparable in size to the wavelength of the radiation.

Here, we report the first characterization of a terahertz data link outdoors during a snow fall. On 13 March 2018, a significant snow storm was forecast for New England [9]. Anticipating this event, we assembled an 11-m outdoor line-of-sight data link, using the same equipment described in ref. [10]. The transmitter was placed under an overhanging roof, such that the first 3 m of the beam path was protected from the falling snow. For the remaining 8 m, the beam propagated through the snowfall to the receiver (see Fig. 1a). The carrier wave at 200 GHz was modulated using amplitude shift keying (ASK), with a data

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rate of 1 Gb/s. We measured the received power and the bit error rate (BER) as a function of transmitted power, before the snow began falling (i.e., clear conditions) and again during the snowstorm. We observe that the snowfall decreases the received power by approximately 2 dB. The measured BER curves, shown in Fig. 2, indicate that a higher received power is required to achieve a given error rate.

An interesting feature of this result is that the two data curves in Fig. 2 have different slopes. In other words, the apparent power penalty on the BER is not independent of the received power level. We can understand this phenomenon by computing the expected effect of the snow on the measured signal. First, we use our measured values for the snowfall rate ($d_s = 3.5$ mm/h) and snow density ($\rho_s = 0.52$ g/cm^3), along with a rough estimate for the radius (1.5 mm) and terminal velocity (1.5 m/s) of a snowflake, to compute the number of snowflakes that pass through the beam during the integration time of the BER tester. The half-power beam width increases with distance from the transmitter (see Fig. 1a), but we use an effective beam diameter of 5 cm, constant from transmitter to receiver, since this is the aperture of the collection lens in front of the receiver horn antenna. From these values, we compute that about 27 snowflakes pass through the beam per second, each requiring about 32 ms to traverse the full diameter of the beam. Now, wet snow is a combination of ice, water, and air. From Debye's mixture theory [11, 12], we can obtain the effective dielectric constant of the snow (ε_s):

$$\frac{\varepsilon_s-1}{\varepsilon_s+U} = W\frac{\varepsilon_w-1}{\varepsilon_w+U} + \frac{\sqrt{W}-W}{0.92}\,\frac{\varepsilon_i-1}{\varepsilon_i+U} \tag{1}$$

Here, W is snow wetness factor, set to 25% in our calculation. U is a form number depending on the shape of snow particles [13], which we set to 10^9, while ε_w and ε_i are dielectric constants of water and ice, taken from literature [14]. Using Mie scattering theory [15], we can calculate the signal loss due to absorption and to scattering for the worst-case scenario, when all of the 27 snow particles are inside the beam path simultaneously. This result is shown in Fig. 1b. We find that the effects of absorption and scattering are quite comparable throughout the entire spectral range of interest for millimeter-wave and terahertz communication systems. At 200 GHz, the predicted worst-case attenuation (absorption plus scattering) is close to 3 dB.

Next, we calculate the degradation of the received power and the BER due to snow. We use the black data points from Fig. 2 (no snow) as a reference to compute the change in the BER due to power loss. We assume that $\Delta t = 0.032$ s is required for all 27 snowflakes to pass through the beam simultaneously, while the beam remains clear for the remainder of the

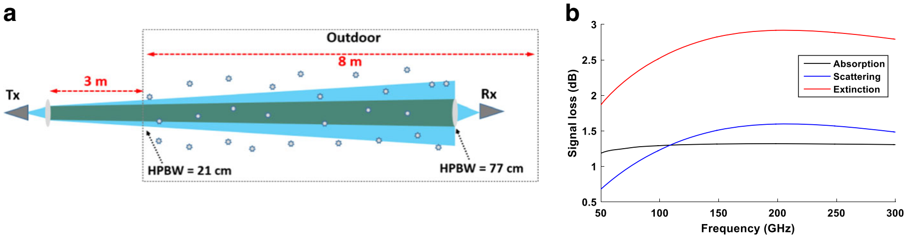

Fig. 1 **a** Schematic diagram of terahertz wireless link measurement setup. HPBW half-power beam width. **b** Computed signal loss due to snow, as described in the text. The effects of absorption and scattering are of comparable magnitude throughout the frequency range 100–300 GHz

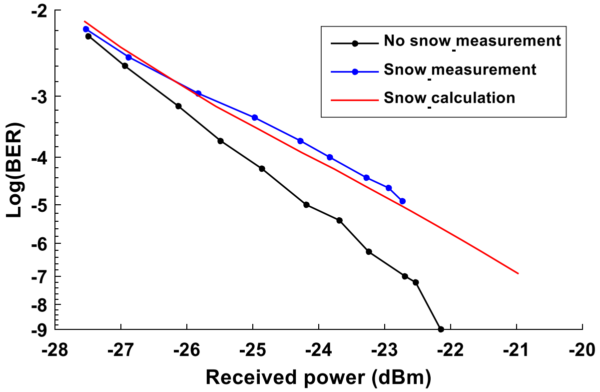

Fig. 2 Measurement with (blue) and without (black) snow, and the calculated result (red)

integration time of the BER tester (1 s) or the power meter (40 ms). Then, the average values for the measured power and BER are given by:

$$\overline{\text{Power}} = \frac{\text{power}_{\text{NS}}\cdot(0.040-\Delta t) + \text{power}_{\text{S}}\cdot\Delta t}{0.040\ \text{s}} \tag{2}$$

$$\overline{\text{BER}} = \frac{\text{BER}_{\text{NS}}\cdot(1-\Delta t) + \text{BER}_{\text{S}}\cdot\Delta t}{1\ \text{s}} \tag{3}$$

Here, Power_{NS} is the received power when no snow particle is in the beam and Power_{S} is the received power when all 27 particles are passing the beam. For the bit error rate, BER_{S} is calculated from the reference data (black line in Fig. 2) based on a signal loss of 2.95 dB (extracted from Fig. 1b). Using Eq. (2), we predict an average attenuation of 2.2 dB, which is in agreement with the measured value of 1.8 ± 0.5 dB. The predicted BER result from Eq. (3), shown as the red curve in Fig. 2, matches closely to the experimental result.

In conclusion, we have characterized the power attenuation and degradation of the BER due to snow by direct measurement of an outdoor wireless data link, during a snow storm. We find a fairly significant attenuation of about 2 dB in 8 m of propagation distance in moderate snowfall, at a carrier frequency of 200 GHz. We attribute this to both absorption and scattering in roughly equal proportions. Though our transmission range is relatively short, these results will have important implications in link budget calculations for outdoor THz wireless systems in adverse weather conditions.

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References

1. Liebe, H. J. & Hufford, G. A. Millimeter-wave attenuation and delay rates due to fog/cloud conditions. *IEEE Trans. Antennas Propag.* **37**, 1617–1623 (1989).
2. Yang, Y., Mandehgar, M. & Grischkowsky, D. Determination of the water vapor continuum absorption by THz-TDS and molecular response theory. *Opt. Express* **22**, 4388–4403 (2014).
3. Su, K., Moeller, L., Barat, R. B. & Federici, J. F. Experimental comparison of performance degradation from terahertz and infrared wireless links in fog. *J. Opt. Soc. Am. A* **29**, 179–184 (2012).

4. Su, K., Moeller, L., Barat, R. B. & Federici, J. F. Experimental comparison of terahertz and infrared data signal attenuation in dust clouds. *J. Opt. Soc. Am. A* **29**, 2360–2366 (2012).
5. Ma, J., Moeller, L. & Federici, J. F. Experimental comparison of terahertz and infrared signaling in controlled atmospheric turbulence. *J. Infrared Millimeter THz Waves* **36**, 130–143 (2015).
6. Ma, J., Vorrius, F., Lamb, L., Moeller, L. & Federici, J. F. Comparison of experimental and theoretical determined terahertz attenuation in controlled rain. *J. Infrared Millimeter THz Waves* **36**, 1195–1202 (2015).
7. Yang, Y., Mandehgar, M. & Grischkowsky, D. Broadband THz signals propagate through dense fog. *IEEE Photon. Technol. Lett.* **27**, 383–386 (2015).
8. Moon, E.-B., Jeon, T.-I. & Grischkowsky, D. R. Long-path THz-TDS atmospheric measurements between buildings. *IEEE Trans. THz Sci. Technol.* **5**, 742–750 (2015).
9. https://www.cnn.com/2018/03/13/weather/northeast-winter-storm/index.html Accessed 19 March 2018.
10. Ma, J., Shrestha, R., Moeller, L. & Mittleman, D. M. Channel performance of indoor and outdoor terahertz wireless links. *APL Photon.* **3**, 051601 (2018).
11. Jiusto, J. E. & Weickmann, H. K. Types of snowfall. *Bull. Amer. Meterolog. Soc.* **54**, 1148–1162 (1973).
12. Fares, M. A., Fares, S. C. & Ventrice, C. A. The effect of precipitation rate on the phase shift of the electromagnetic wave due to various types of snow. in *IEEE Proc. Southeastcon.* (2012). DOI: https://doi.org/10.1109/SECon.2012.6196998
13. Oguchi, T. Electromagnetic wave propagation and scattering in rain and other hydrometeors. *Proc. IEEE* **71**, 1029–1078 (1983).
14. Jiang, J. H. & Wu, D. L. Ice and water permittivities for millimeter and sub-millimeter remote sensing applications. *Atmos. Sci. Lett.* **5**, 146–151 (2004).
15. Ulaby, F. T. & Long, D. G. *Microwave Radar and Radiometric Remote Sensing*. (University of Michigan Press, 2013).