Attenuation and Dispersion on Terahertz Wireless Channels in Falling Rain

Jianjun Ma

Beijing Institute of Technology

Peian Li

Beijing Institute of Technology

Liangbin Zhao

Beijing Institute of Technology

Jianchen Wang

Beijing Institute of Technology

Wenbo Liu

Beijing Institute of Technology

Yu Mei

Beijing Institute of Technology

Xiangyuan Bu

Beijing Institute of Technology

Jianping An (✉ an@bit.edu.cn)

Beijing Institute of Technology

Research Article

Keywords: Attenuation, dispersion, terahertz wireless

Posted Date: July 30th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-744483/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Investigations on wireless channel performance in adverse weathers could be helpful and important for the future applications of terahertz communication technique in outdoor scenarios. However, in most cases only amplitude performance has been studied by using a broadband-pulsed terahertz source or an amplitude modulated data stream, not including phase degradation (temporal dispersion). This limitation may mask important aspects of channel performance with phase modulation schemes, especially for wide bandwidth signals. In this work, we report the amplitude and phase characterizations of a terahertz channel in falling rain by a time-domain spectrometer system. We also demonstrate error rate performance by a 16 quadrature amplitude modulated (16-QAM) terahertz signal at a data rate of 5 gigabits per second. We observe that, besides strong water vapor absorption, the weak water absorption line could also lead to obvious dispersion effects. Our work highlights the importance of new frequency band boundaries for minimum temporal dispersion and optimized digital communications in the terahertz frequency range.

Introduction

Wireless networks operating at terahertz (THz) frequencies have been considered to be a promising candidate to satisfy the demands on large data capacity and high physical layer security^{1,2}. However, for outdoor applications, they suffer significant signal loss due to atmospheric weather effects^{3,4}. Previously, amplitude attenuation and related channel performance degradation on THz channels caused by water fog, dust cloud, rain and snow have been investigated by employing an on-off keying (OOK) modulation method⁵⁻⁷. Higher order modulation techniques (such as QPSK, QAM etc.) are necessary to update the data rate with information on phase variation (temporal dispersion) required. THz time-domain spectroscopy (THz-TDS) technique could be available for monitoring both the amplitude and phase and has been used for sensing water vapor contained in air⁸. But there is lack of study on their degradation in adverse outdoor weathers due to the difficulties for data recording, such as uncontrollable weather condition, long observation time, etc.

In this work, we investigate the influence of falling rain droplets on THz channel performance by employing a commercial T-Ray 2000™ (Picometrix) THz-TDS system and a 162 GHz wireless channel with 16-QAM modulation scheme. A weather chamber was built in laboratory to emulate stable and controllable falling rain. The lab condition could be reproducible and has been previously demonstrated^{9,10}. For the first time, the dispersion effect caused by falling rain droplets is observed and analyzed, which is usually difficult and even impossible for actual outdoor measurements.

Results

Experimental characterization using broadband THz pulses

We have recorded a propagated THz pulse in free space and in falling rain, separately, at temperature 25 °C⁹. The measurement in rain was repeated three times at an identical rainfall rate of 390 mm/hr. The total channel distance here is only 4 m due to the laboratory limitation, but we could increase the rainfall rate (R_r) to be 700 mm/hr, which is significantly larger than that for a typical heavy rain condition in nature. Then obvious channel degradation could be observed. When collecting THz waveforms for measuring the averaged signal performance, the system was set to a rapid scan mode with 1000 averages.

The amplitude spectra of the pulses passing free space (A_{Rain}) and falling rain (A_{FS}) are shown in Fig. 1(a) with a rainfall rate (R_r) of 466 mm/hr. Strong water vapor absorption lines at 0.56 THz, 0.75 THz and 0.98 THz are clearly observable for both curves. Their difference, i.e. power attenuation due to rain $\Delta A_{Rain} = A_{Rain} - A_{FS}$ is shown in Fig. 1(b) as blue color. The trend versus frequency is identical to published measurements¹¹. The power absorption due to the increasing of pure humidity (from RH 36% in free space to RH 37% in falling rain) is estimated by employing the equation and database of the International Telecommunication Union Recommendation (ITU-R) P.676 – 12 (08/2019)¹². The result is shown as the dark green curve in Fig. 1(b). For this model, there is a discrepancy of 10 dB/km when compared with measurements (RH 40%) at frequencies between 0.8-1 THz¹³. Such difference is much smaller than the power attenuation as in Fig. 1(b). Thus we would attribute the attenuation to the falling rain droplets instead of the increasing of water vapor (or humidity). And also, the absorption by rain droplets (i.e. water continuum absorption) should be more responsible for that than the scattering loss as demonstrated previously¹⁴. It should be noted that there is a weak absorption peak at 0.235 THz as marked by the blue arrow. We attribute this to a weak water absorption line, which has been predicted by a vV-W-HITRAN model¹⁵, even though never observed in measurements before.

As the THz-TDS system directly probes the electric field, we could also obtain the unwrapped phase spectra corresponding to Fig. 1(a). The phase shift due to falling rain, could be obtained by comparing the phase spectra in free space (ϕ_{FS}) and in rain (ϕ_{Rain}) as $\Delta\phi_{Rain} = \phi_{Rain} - \phi_{FS}$. As shown in Fig. 2(a), there are three obvious jumps corresponding the strong absorption lines of water vapor. This phenomenon has been indicated by the Kramers-Kronig relations and excellent agreement has been demonstrated¹⁶. One tiny jump at 0.235 THz could also be observed and we attribute it the weak water line as in Fig. 1(b). We also calculate the phase shift caused by the increasing of water vapor only (dark green curve in Fig. 2(a)). When the humidity changes from RH 36% to RH 37%, the continuum phase shift is small and negligible. In other words, the water vapor would not lead to obvious phase shift except at the peak absorption line frequencies. This has ever been confirmed over a short channel distance of 6.18m¹⁷.

We can conclude that the difference in phase shift between the measurement and calculation should be attributed to the falling rain droplets, even though it is smaller than 0.05π and negligible over a propagation distance of 4 m in this work. However, for a much longer channel path, such as 80 m, the phase shift could be much larger¹⁸ and up to π at a rain fall rate of 390 mm/hr. This would definitely

degrade data transmission. However, such weather conditions could not be possible in nature and the absorption by falling rain would fail the THz channel before that happens.

We obtain the group velocity dispersion (GVD) for the channel by taking numerical second order derivative with respect to angular frequency (ω) of the phase spectra as $GVD_{Rain} = d\phi_{Rain}/d\omega$ in rain and $GVD_{FS} = d\phi_{FS}/d\omega$ in free space. The difference between both (ΔGVD) is calculated and shown in Fig. 2(b). The jumps located at 0.56 THz, 0.75 THz and 0.98 THz represent large and unstable GVD caused by water vapor, which is consistent with theoretical predictions⁸. There is one more jump located at around 0.235 THz due to the water absorption line. All these four frequencies should be avoided to reduce both attenuation and dispersion for future THz wireless communications. At other frequencies, the ΔGVD value is much smaller and more stable, which means the falling rain droplets have negligible influence on the phase performance of the channel.

Simulation characterization using broadband THz pulses

A 2-dimensional numerical simulation in Fig. 3(a) illustrates the propagation of a pulsed THz wave through a suspended rain droplet. The pulse incidence first propagates from the left side and then is detected at the right side with a red arrow indicating its propagation direction. The rain droplet is spherical with a diameter of 1.9 mm, which is identical to the average raindrop size we generated. There are many ripples in the vacuum space when the pulse wave propagated through the droplet, which indicates the generation of scattering components.

Experimental characterization using a data stream

To see the influence of the falling rain on higher order modulation techniques, a 16-QAM THz channel is built with its schematic diagram shown in Fig. 4. More details on the setup should be found in the **Methods** part.

When a 162 GHz channel propagates through the falling rain at a rainfall rate of 350 mm/hr, a power attenuation of around 0.5 dB is observed. The variation of bit-error-ratio (BER) value with respect to transmitted THz power is recorded and shown in Fig. 4(a). An obvious BER degradation in rain could be observed. The difference between both curves should be attributed to the absorption and scattering effects caused by falling rain droplets¹⁰.

When we mount the receiver on a movable rail which permits it to translate along an axis perpendicular to the incoming beam's propagation direction. By scanning the detector along this line, we map the spatial distribution of the beam arriving at the receiver side. A power loss of 0.5 dB due to rain is observed again in Fig. 4(b) and the corresponding BER degradation is shown in Fig. 4(c). there is no obvious jump observed in the power and BER evolution curves, which means the temporal dispersion caused by falling rain is so small that it has negligible influence on the 16 QAM modulated THz channel over a transmission distance of 0.5 m.

In summary, the amplitude attenuation and temporal dispersion suffered by THz channels passing through falling rain are measured, calculated and analyzed. Obvious temporal dispersion is observed at the frequencies corresponding to water vapor absorption peaks. This makes more cautious considerations required for short range THz wireless communication scenarios, which would lead to serious compromising emissions away the line-of-sight (LOS) channel path and higher eavesdropping risks¹⁴. Besides this, the weak water absorption line would cause an extra temporal dispersion at 0.235 THz, which should also be considered carefully to identify possible THz transmission windows in falling rain. We believe this work would not only contribute to the optimization of THz wireless channel performance in falling rain, but also help for the reduction of signal leakage in adverse weather conditions.

Methods

Experiment setup. For both the pulsed and modulated data stream measurements, we launch the radiated THz beam through a weather chamber which could generate controllable and reproducible falling rain. In the pulsed signal experiment, a commercial T-Ray 2000™ (Picometrix) terahertz time-domain spectrometer (TDS) is used. This is a conventional TDS system. Power spectra is obtained from measured time-domain waveforms via numerical Fourier transform.

Figure 5 shows the implementation of the terahertz-band communication system. On the transmitter side, a Xilinx Vertix-7 serial FPGA(XC7VX485T) is used to generate a 16-QAM modulated signal with data rate up to 5 Gbps at an intermediate frequency (IF) of 1.25GHz. The generated digital sequence from FPGA is converted into an analog signal by an AC (MD662H). Then, it is mixed with a radio frequency(RF) of 162 GHz by a subharmonic mixer (110-170GHz) which is driven by a 81GHz reference signal from an $\times 6$ multiplier. Finally, the signal is radiated by a THz antenna.

On the receiver side, a low noise amplifier amplifies the D-band signal captured by another identical THz antenna and sends its output to a subharmonic mixer to obtain the IF signal which can be converted to digital sequence by an ADC (EV10AQ190). A Xilinx XC7VX690T FPGA is used for synchronization processing and demodulation operation. The output binary sequence would be compared with the transmitting binary sequence, and then the E_b/N_0 parameter can be derived by calculating the bit error ratio easily.

The weather chamber used in this work is fabricated with 3264 31-gauge needles which are epoxied to produce raindrops. The chamber was filled with distilled water to emulate the actual material for rain. The diameter of the needles is small enough such that when no air pressure is applied on the water in the tank, no raindrops are produced. In the chamber, the generated rainfall rate is related to air pressure and in a linear relationship.

Calculations. The dark blue curve in Fig. 1(b) and Fig. 2(a) was computed using a v-VW theory for the absorption and phase shift due to variation of water vapor in the rain chamber^{17,19}. It can be expressed

as

$$\alpha(\omega) = D \cdot \sum_j \frac{A_j}{\pi} \left(\frac{\omega}{\omega_j} \right)^2 \cdot \left[\frac{\Delta\omega_j}{(\omega - \omega_j)^2 + \left(\frac{\Delta\omega_j}{2} \right)^2} + \frac{\Delta\omega_j}{(\omega + \omega_j)^2 + \left(\frac{\Delta\omega_j}{2} \right)^2} \right] \quad (\text{M-1})$$

$$\Delta k(\omega) = D \cdot \sum_j \frac{2A_j}{\pi\omega_j} \left(\frac{\omega\omega_j}{\omega_j^2 - \omega^2} \right) \left[1 - \frac{\Delta\omega_j^2}{8\omega_j} \left(\frac{\omega}{\omega_j} \right) \cdot \left(\frac{\omega + \omega_j}{(\omega - \omega_j)^2 + \left(\frac{\Delta\omega_j}{2} \right)^2} + \frac{\omega - \omega_j}{(\omega + \omega_j)^2 + \left(\frac{\Delta\omega_j}{2} \right)^2} \right) \right] \quad (\text{M-2})$$

with A_j as the line-strength values obtained from JPL data base²⁰. ω_j is the water vapor resonance line and $\Delta\omega_j$ is the FWHM linewidth. D is a factor proportional to the density of water vapor. Values of all these parameters should be found in Grischkowsky's publication¹⁷.

Simulations. Finite element method (FEM) simulation results were performed using COMSOL Multiphysics 5.6 when a pulse radiation propagates through a spherical rain droplet located in vacuum as shown in Fig. 3(a). In this figure, vacuum is assumed as the background to isolate the influence of water vapor and other gases. Perfectly matched layers (PML) are used to absorb at the edges. A port boundary is employed for the pulse incidence and another port boundary at right side to detect the pulse. Triangle elements with an identical size of 0.2 mm are used to mesh the geometry.

Declarations

Acknowledgements

This research was supported by National Natural Science Foundation of China (No. 6207106), U.S. National Science Foundation (No. ECCS-1102222), and Teli Young Scholar Program of Beijing Institute of Technology (No. 3050011182153). We also appreciate the help from Prof. John F. Federici and Dr. Lothar Moeller from New Jersey Institute of Technology, Newark, NJ USA.

Author contributions statement

All of the authors concieved of the experiments, and contributed to their design. J.M., L.Z., P.L., J.W., X.B., and J.A. performed the measurements. J.M. and Y.M. performed the theoretical calculations. J.M. and W.L. performed the simulation. All of the authors contributed to writing the manuscript and reviewed the manuscript.

Data availability

All relevant data are available from the authors.

Financial Interests Statement

The authors declare that they have no competing financial interests.

References

1. Ma, J. *et al.* Security and eavesdropping in terahertz wireless links. *Nature*, **563**, 89 <https://doi.org/10.1038/s41586-018-0609-x> (2018).
2. Nagatsuma, T., Ducournau, G. & Renaud, C. C. Advances in terahertz communications accelerated by photonics. *Nature Photonics*, **10**, 371–379 <https://doi.org/10.1038/nphoton.2016.65> (2016).
3. Moon, E. B., Jeon, T. I. & Grischkowsky, D. R. Long-Path THz-TDS Atmospheric Measurements Between Buildings. *IEEE Transactions on Terahertz Science and Technology*, **5**, 742–750 <https://doi.org/10.1109/tthz.2015.2443491> (2015).
4. Rizzo, L. *et al.* Comparison of Terahertz, Microwave, and Laser Power Beaming Under Clear and Adverse Weather Conditions. *Journal of Infrared, Millimeter, and Terahertz Waves*, <https://doi.org/10.1007/s10762-020-00719-w> (2020).
5. Hirata, A. *et al.* Effect of Rain Attenuation for a 10-Gb/s 120-GHz-Band Millimeter-Wave Wireless Link. *IEEE Transactions on Microwave Theory and Techniques*, **57**, 3099–3105 <https://doi.org/10.1109/tmtt.2009.2034342> (2009).
6. Federici, J. F., Ma, J. & Moeller, L. Review of weather impact on outdoor terahertz wireless communication links. *Nano Commun. Netw*, **10**, 13–26 <https://doi.org/10.1016/j.nancom.2016.07.006> (2016).
7. Ma, J., Adelberg, J., Shrestha, R., Moeller, L. & Mittleman, D. M. The Effect of Snow on a Terahertz Wireless Data Link. *Journal of Infrared, Millimeter and Terahertz Waves*, **39**, 505–508 <https://doi.org/10.1007/s10762-018-0486-2> (2018).
8. Mandehgar, M., Yang, Y. & Grischkowsky, D. Atmosphere characterization for simulation of the two optimal wireless terahertz digital communication links. *Opt. Lett*, **38**, 3437–3440 <https://doi.org/10.1364/OL.38.003437> (2013).
9. Ma, J., Vorrius, F., Lamb, L., Moeller, L. & Federici, J. F. Comparison of Experimental and Theoretical Determined Terahertz Attenuation in Controlled Rain. *Journal of Infrared, Millimeter and Terahertz Waves*, **36**, 1195–1202 <https://doi.org/10.1007/s10762-015-0200-6> (2015).
10. Ma, J., Vorrius, F., Lamb, L., Moeller, L. & Federici, J. F. Experimental Comparison of Terahertz and Infrared Signaling in Laboratory-Controlled Rain. *Journal of Infrared, Millimeter and Terahertz Waves*, **36**, 856–865 <https://doi.org/10.1007/s10762-015-0183-3> (2015).
11. Jördens, C., Wietzke, S., Scheller, M. & Koch, M. Investigation of the water absorption in polyamide and wood plastic composite by terahertz time-domain spectroscopy. *Polym Test*, **29**, 209–215 <https://doi.org/10.1016/j.polymertesting.2009.11.003> (2010).

12. *International Telecommunication Union Recommendation (ITU-R) P.676 – 12: Attenuation by atmospheric gases and related effects*, (2019).
13. Ohara, J. F. & Grischkowsky, D. R. Comment on the Veracity of the ITU-R Recommendation for Atmospheric Attenuation at Terahertz Frequencies. *IEEE Transactions on Terahertz Science and Technology*, **8**, 372–375 <https://doi.org/10.1109/tthz.2018.2814343> (2018).
14. Wang, R., Mei, Y., Meng, X. & Ma, J. Secrecy Performance of Terahertz Wireless Links in Rain and Snow. *Nano Commun. Netw*, **28**, 100350 <https://doi.org/10.1016/j.nancom.2021.100350> (2021).
15. Yang, Y., Mandehgar, M. & Grischkowsky, D. THz-TDS Characterization of the Digital Communication Channels of the Atmosphere and the Enabled Applications. *Journal of Infrared, Millimeter, and Terahertz Waves*, **36**, 97–129 <https://doi.org/10.1007/s10762-014-0099-3> (2014).
16. Van Exter, M., Fattinger, C. & Grischkowsky, D. Terahertz Time-domain Spectroscopy of Water Vapor. *Optics letters*, **14**, 1128–1130 <https://doi.org/10.1364/OL.14.001128> (1989).
17. Yang, Y., Mandehgar, M. & Grischkowsky, D. R. Understanding THz Pulse Propagation in the Atmosphere. *IEEE Transactions on Terahertz Science and Technology*, **2**, 406–415 <https://doi.org/10.1109/tthz.2012.2203429> (2012).
18. Banerjee, D., Spiegel, W., Thomson, M. D., Schabel, S. & Roskos, H. G. Diagnosing water content in paper by terahertz radiation. *Opt. Express*, **16**, 9060–9066 <https://doi.org/10.1364/OE.16.009060> (2008).
19. Harde, H., Cheville, R. A. & Grischkowsky, D. Terahertz Studies of Collision-Broadened Rotational Lines. *The Journal of Physical Chemistry A*, **101**, 3646–3660 <https://doi.org/10.1021/jp962974c> (1997).
20. Poynter, R. L. & Pickett, H. M. Sub-millimeter, millimeter, and microwave spectral line catalog. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **24**, 2235 [https://doi.org/10.1016/S0022-4073\(98\)00091-0](https://doi.org/10.1016/S0022-4073(98)00091-0) (1985).

Figures

Figure 1

Amplitude performance of THz frequencies due to falling rain. (a) A broadband-pulsed terahertz source is used to launch a THz pulse into free space and falling rain separately. The black curve stands for the received signal propagates in free space and the blue one for the signal passing falling rain with a rainfall rate of 466 mm/hr. Inverse fast Fourier transformation was conducted on the measured data. Both curves show three peaks with their frequencies determined by the strong water vapor absorption lines. (b) The three solid lines show the measured power attenuation of the THz signal due to falling rain with falling rates of 390 mm/hr (black), 466 mm/hr (blue), and 700 mm/hr (red). The humidity RH 37% is measured in rain while it is RH 36% in free space without rain. The room temperature is usually kept at 25°C. There are three obvious peaks at 0.56 THz, 0.75 THz and 0.98 THz caused by strong water vapor absorption lines and one absorption peak at 0.235 THz due to weak water absorption line. The dark green curve represents the power attenuation due to the pure water vapor with humidity increasing from RH 36% to RH 37% when the temperature is unchanged.

Figure 2

Phase variation of THz frequencies due to falling rain. (a) Phase shift due to falling rain by comparing the unwrapped phase spectra of THz signals after propagating through free space and falling rain. The three solid curves represent the rainfall rate at 126mm/hr (black), 256 mm/hr (blue) and 379 mm/hr (red). The dark green curve represents the phase shift caused by the increasing of humidity from RH 36% to RH 37% with room temperature (25oC) unchanged. (b) variation of group velocity dispersion (GVD) for the THz signals by numerical second order derivative with respect to the angular frequency of the phase spectra as in Fig. 2(a). To our knowledge, this is the first experimental demonstration of the dispersion on THz channels in falling rain.

Figure 3

Simulation on pulse wave propagation through a rain droplet. (a) A 2D numerical time-domain simulation (finite element method) of an input wave propagating through a suspended rain droplet marked as a black circle. The total background is set as vacuum to isolate the influence of water vapor and other

gases. The rain droplet is spherical with a diameter of 1.9 mm, which is identical to that we generated by the rain chamber in our laboratory. The inset (left) shows the input pulse and the red arrow indicates its propagation direction. Scattering phenomenon caused by the rain droplet is clearly evident. (b) Simulated power attenuation spectra caused by the rain droplet. There is only water continuum absorption observed here because no water vapor contained in this simulated background. The weak water absorption line defined in the vV-W-HITRAIN model could not be found here due to the different theoretical model (which doesn't consider that line) used by the COMSOL Multiphysics 5.6. (c) Simulated group velocity dispersion (GVD) in vacuum with and without rain. The black and straight line indicates no dispersion when the pulse wave propagates in vacuum only. The oscillations in the blue curve implies the scattering caused by the rain droplet.

Figure 4

Degradation of modulated THz channel performance. (a) Measured real-time BER performance of the THz link as a function of transmitted THz power under a data rate of 5 Gbps. Values are recorded both

after propagating through free space (black) and falling rain (blue) with the detector fixed at the optimum position for the carrier at 162 GHz. After through falling rain, the BER values at the received power below -40.3 dBm could not be recorded due to the scattering and absorption by falling rain droplets. The inset shows schematic measurement setup, with one transmitter at 162 GHz, and with the receiver mounted on a linear rail to vary the position of the receiver. (b) Power pattern measured when channel propagates through free space (black) at temperature $T = 17^{\circ}\text{C}$, humidity RH 34% and falling rain (blue) at rainfall rate $R_r = 350 \text{ mm/hr}$. (c) BER performance under the power patterns in Fig. 4(b). Error rate of 10^{-10} could not be achieved in falling rain due to the signal loss. There is no obvious jump observed in the power and BER patterns when the THz channel operates at 162 GHz, which is far away the water and water vapor absorption lines. The temporal dispersion is negligible and the its influence on the 16-QAM modulated channel is not evident.

Figure 5

Implementation of the 162 GHz communication system. A Xilinx Vertix-7 serial FPGA(XC7VX485T) is employed to generate the modulated signal with a data rate up to 5 Gbps at an intermediate frequency (IF) of 1.25GHz. The generated digital sequence from FPGA is converted into an analog signal by a DAC (MD662H) and then mixed with a radio frequency (RF) of 162 GHz by a subharmonic mixer (110-170 GHz) which is driven by 81 GHz reference signal from X6 multiplier. Then the generated THz signal is radiated into rain by a commercial horn antenna from Custom Microwave Inc. On the receiver side, a low noise amplifier amplifies the D-band signal captured by a combination of a Teflon lens (focal length 5 cm) and an identical antenna. Its output is launched into a subharmonic mixer to obtain the IF signal which could be converted to a digital sequence by an ADC (EV10AQ190). A Xilinx XC7VX690T FPGA is used to process the synchronization and demodulation operation. The output binary sequence would be compared with the transmitting binary sequence to obtain the bit error ratio (BER).