

Modeling Line-of-Sight Terahertz Channels Using Convex Lenses

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Abstract—The terahertz band (0.1 – 10 THz) has a great deal of unused spectrum that could satisfy the ever-increasing demand for wireless communications. However, as a first step in realizing this goal, we need to understand how terahertz signals behave in indoor environments. In this study, we present broadband channel measurements of the 0.1 to 2 THz band using convex lenses at the transmitter and collimating lenses at the receiver. The convex lens provides coverage over an indoor region while a collimating lens at the receiver maximizes signal strength. The measurements are based on Line-Of-Sight (LOS) since reflected signals in this frequency band are absent. Applying geometric analysis, we propose a path loss model which matches our measurements well.

Index Terms—Terahertz, channel model, propagation

I. INTRODUCTION

The unprecedented growth in both data traffic and number of new applications in wireless networks is accompanied by a need for more bandwidth. The THz frequency band (0.1 – 10.0 THz) contains unused bandwidth that can support high data rate communication systems [1], [2]. Unfortunately, the THz frequency band suffers from severe propagation loss compared with the lower frequency bands [3], [4] and molecular absorption by water causes even more severe loss [5]. However, some frequency windows exist that have lower absorption loss and can thus be used for communications [6].

Given these impairments, in order to provide a high data rate channel, it is necessary to use highly directional links. Adaptive antenna arrays are a typical solution for such links. However, given the very large bandwidth and high frequency, such arrays are likely to be very expensive. In this paper, we explore an alternative approach that uses inexpensive lenses. In previous work [7] we showed that collimating lenses¹ are very effective in producing point-to-point links. However, this method cannot be used in typical indoor wireless networks where an AP (Access Point) serves many users because it is very difficult to dynamically create a point-to-point link using collimating lenses at both the transmitter and receiver. We propose using a convex lens at the transmitter to cover a given region and use collimating lenses at the receiver to maximize signal strength, see Fig. 1. In this architecture, only

¹These are lenses that produce a parallel beam at the transmitter and which focus this beam at a point at the receiver, thus maximizing gain.

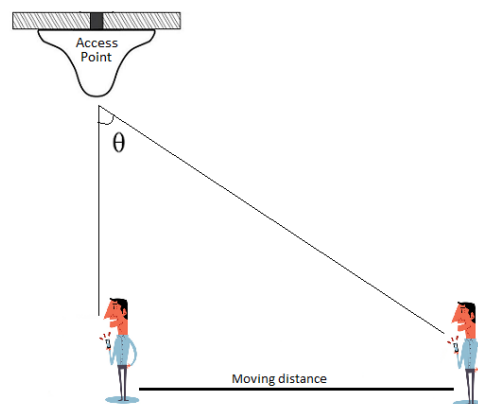


Fig. 1. Receiving signal at two different points

the receiver needs to align its lens to maximize signal strength. In order to design such THz networks, we need a channel model to analyze protocols and coverage problems.

Unfortunately, existing narrowband channel models intended for carrier frequencies of up to 5 GHz with bandwidths not exceeding 40 MHz cannot be used for broadband THz channels [8], [9]. Indeed, exploiting THz frequency windows requires new models for the propagation channel and the models need to take into consideration the coverage problem for the THz band. As shown in Fig. 1, a THz Access Point (AP) is serving a mobile user. Here, unlike 801.22 networks, the received power at the user depends on the angle θ . Fig. 2 shows the magnitude of the received signal at two different points with the same distance between the transmitter and the receiver when the transmitter has a 1-inch convex lens and the receiver uses a collimating lens. In one case the receiver is on the same axis as the transmitter while in the second scenario, the receiver is off at an angle of 36.86 degrees. As Fig. 2 shows, at the frequency of 300 GHz (one of the usable frequency windows), the magnitude drops from 8.7dB to $-32dB$. As the angle increases, the magnitude over the whole frequency domain drops rapidly. Therefore, in order to study how to provide indoor wireless coverage utilizing terahertz, we need to understand the angular dependence on signal strength when using convex lenses.

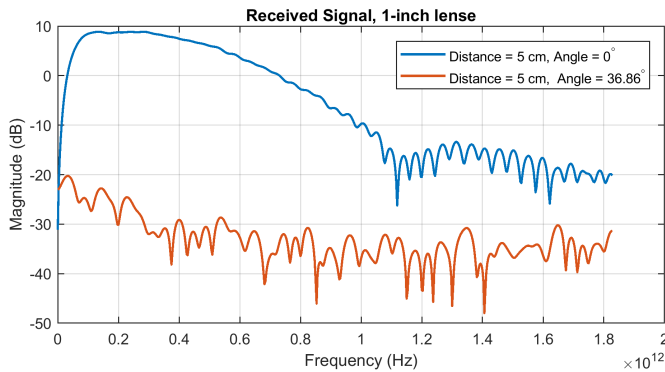


Fig. 2. Received signal at two different points

In this paper, we develop a channel model for 0.1 – 2 THz where the transmitter utilizes a convex lens and the receiver has a collimating lens. The model takes into consideration the *offset* θ of the receiver with respect to the transmitter lens axis. Finally, the channel model incorporates the effect of atmospheric absorption by various molecules. We conducted extensive measurements of signal propagation and show that our channel model fits the experimental data very well.

A. Organization

The rest of the paper is organized as follow. Section II gives a review on the related works in THz communication. Section III explains our modeling approach and presents our basic path loss model. Section IV explains our measurement setup and the system we have used for collecting data. The experimental results and the evaluation of our model also is presented in this section. Finally, section V gives the conclusion.

II. RELATED WORK

Although channel modeling in the frequency regions of below and above the Terahertz Band, 0.1 to 10.0 THz, has been received a great deal of attention, the Terahertz band is still largely unexplored. Recently, however, the Terahertz band has begun receiving some attention in the literature. Jornet et al. [5] propose a propagation model for the entire Terahertz band (0.1 - 10 THz). They have developed a Line-of-sight (LOS) and Non-line-of-sight (NLOS) propagation model by utilizing the information in the HITRAN database [10]. They analyze the impact of molecular absorption on the path loss. However, their pathloss model, which is a function of frequency and distance, doesn't consider the effect of angle. Authors in [11] developed a stochastic propagation model for an indoor radio channels from 275 to 325 GHz. However, this model is based on a specific environment and they do not provide an analysis for the proposed channel. The study in [12] utilizes Kirchhoff scattering theory and ray tracing approach, and introduces a deterministic channel model for the THz radio channel. By using an updated HITRAN database they improved the LOS model of [5]. In [13], the authors focus on the scattering of the THz wave on particles suspended in the

air. These solid or liquid particles, called aerosols [14], cause scattering and make additional losses on the LOS component of the channel [13]; they provide frequency analysis and the impulse responses regarding the aerosols scattering effect. Han et al. [15] introduce a channel model for the entire THz band (0.06 - 10 THz) based on ray tracing techniques. They divide the entire THz band into sub-bands and consider each sub-band as a stationary channel. However, the sub-THz bands are observed as non-stationary, since the users are mobile [16]. Therefore, the assumption of channel stationarity is not valid for THz band communication. Furthermore, their unified multi-ray channel model is formed by the summation of the line-of-sight (LOS) model, reflected model, scattered and diffracted model. They provide a thorough analysis of the channel for the entire band. However, their evaluation for their unified model is limited to the 0.06 to 1 THz band. A 3-D time-varying channel model is developed in [16] where the time-varying THz channel response in time domain and frequency domain are investigated. The study in [17] investigates the effect of phase component on causality of the channel. They show that linear phase component causes a response at the receiver before the arrival of the main peak. Therefore, they propose minimum phase in the channel response to maintain the causality rule in their channel model. However, in their NLOS model they only consider the reflected paths, and it does not take into consideration the effect of scattered and diffracted paths.

Authors in [18] and [19] provide a channel model for a LOS scenario based on their own measurements using a time-domain THz system. They utilize the absorption model in [5] for their channel model. Furthermore, they propose two different channel models for directional channels and omnidirectional channels. Moshir et al. [18], [19] use these channel models for their simulation and evaluation of their modulation and rate adaptation algorithms. They achieve the datarates of terabit/sec in their work.

In terms of coverage, Soorki et al. [20], [21] consider the problem for coverage in the mmWave spectrum. They investigate the problem of having stochastic user orientation and deployment of the access points (APs) in an indoor environment. In a THz network, Moldovan et al. [22] investigate a scenario in an indoor environment for the THz network. They suggest a single frequency network where APs simultaneously send signals in the same frequency band to the users. They propose a frequency division scheduling resource allocation scheme in their work.

To the best of our knowledge, enhancing the coverage in a directional THz channel has not been addressed in the literature so far.

III. MODELING

As we noted earlier, in order to provide coverage using terahertz APs, we utilize a convex lens attached to the front of the transmitter to spread the beam in a selected area. If the signal source is located between the focal point and the lens, the beam diverges (with a virtual image formed on the

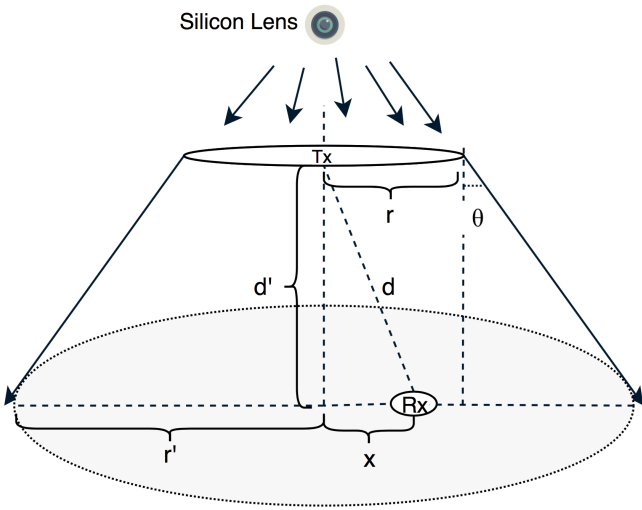


Fig. 3. Model for signal propagation.

same side of the lens), as shown in Fig. 3. In the figure, we assume that the transmitter lens is d' away from the plane where the receiver is located (e.g., the height of an AP in a room measured from a user device). We also assume the radius of the transmitter lens is r (our experimental testbed uses a lenses with one inch diameter) and focal length is F (we used 1-inch and 3-inch focal lengths in our measurements). x is the *offset* distance of the receiver with respect to the lens axis of the transmitter. Finally, let us assume that the divergence angle of the beam is θ and the resultant radius of the covered area is r' . Note that θ depends on the focal length F of the beam as well as the distance between the signal source and the lens.

We derive the formula for path-loss in two steps. First, we derive the formula for the case when $x = 0$. In other words, the receiver is aligned with the transmitter lens axis. Subsequently, we generalize the formula to take into consideration the offset distance x of the receiver relative to the optical axis.

A. Basic Path Loss Model

In wireless communications the received signal power decreases with distance, and Friis transmission equation [23] models this behavior well. However, since the transmitter and the receiver are using focussing and collimating lenses in our measurements, we need to incorporate this aspect into the channel model. Using Fig. 3 as a guide, we can approximate the fraction of power hitting the receiver lens as, $P_t \times \frac{\pi r_{Rx}^2}{\pi r'^2}$, where P_t is the signal power at the transmitter, r_{Rx} is the radius of the receiver's lens, and r' is the radius of the covered area². From the Fig. 3 we have

$$r' = r + d' \tan \theta \quad (1)$$

²An important assumption we are making in this equation is that power is distributed uniformly over the covered area. This is obviously not the case in practice and we take that fact into consideration in the next section where we refine our basic model.

An important clarification we need to make here is that the transmitter lens is fully illuminated by the transmitter and all rays hitting the lens propagate through the lens.

Thus, the receiver receives $P_t \times \frac{\pi r_{Rx}^2}{\pi (r + d' \tan \theta)^2}$ portion of the transmitted power. In addition, based on Friis transmission equation [23], the received signal power P_r is proportional to the product of the transmitted signal power P_t , transmitter gain G_t , receiver gain G_r , and the wavelength λ :

$$P_r \propto P_t G_t G_r \lambda^2 \quad (2)$$

Thus, the received signal power for a specific frequency band at the distance d from the transmitter is calculated as:

$$P_r = \left(\frac{r_{Rx}}{r + d' \tan \theta} \right)^\beta \times P_t G_t G_r \lambda^2 \quad (3)$$

where β is the path loss exponent that we derive using measurements. Therefore, we have the path loss model, P_L , of the channel as,

$$P_L = \left(\frac{r + d' \tan \theta}{r_{Rx}} \right)^\beta \times \frac{1}{G_t G_r \lambda^2} \quad (4)$$

B. Incorporating Atmospheric Effects

Terahertz signals are severely attenuated by the atmosphere, though the degree of attenuation is frequency dependent. According to the Beer-Lambert law, transmittance of the signal decreases exponentially with the transmitter-receiver distance [24]. If τ is the time in seconds required for the signal to travel through distance d , and $K(f)$ is the atmospheric attenuation from [19], the channel transfer function can be written as,

$$H(f) \propto e^{-(j2\pi f \tau + dK(f))} \quad (5)$$

Therefore, we refine equation 3 to,

$$P_r = \left(\frac{r_{Rx}}{r + d' \tan \theta} \right)^\beta \times P_t G_t G_r \lambda^2 \times e^{-dK(f)} \quad (6)$$

C. Incorporating Receiver Offset x

In Fig. 3 we see that if the receiver is offset by distance x from the lens axis, the distance between the receiver and transmitter increases from d' to $d = \sqrt{d'^2 + x^2}$. In addition, we have observed that the signal intensity is not uniform over the covered surface. If we denote the signal intensity as a function $f(x)$ (note that if the lens is circularly symmetric, it suffices to use a one-dimensional formulation for signal intensity), then the final expression for received power becomes,

$$P_r = \left(\frac{r_{Rx}}{r + d' \tan \theta} \right)^\beta \times f(x) \times P_t G_t G_r \lambda^2 \times e^{-dK(f)} \quad (7)$$

IV. MEASUREMENT AND EVALUATION

We use the commercially available time-domain Picometrix T-Ray 4000 system from Advanced Photonix, Inc (API) [25] in our measurements. The transmitter is equipped with a convex lens in which no rays are internally reflected, and the emitted radiation emerges with a divergence angle. The receiver is equipped with a collimating-lens in which it converges the rays on the receiver's silicon lens that is located behind it. The transmitter sends pulses and receiver captures and saves the

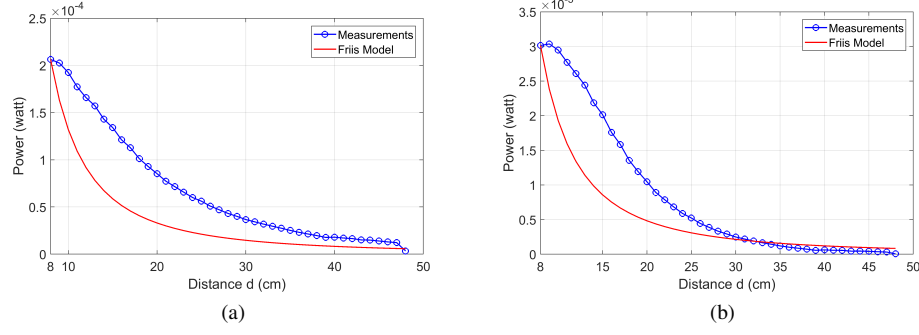


Fig. 4. Received power of our measurements and Friis model at $x = 0$, for frequency bands of (a) 0-2 THz and (b) 300-370GHz.



Fig. 5. Picometrix T-Ray 4000 system.

average of 10000 pulses for each of the measurements. Each generated pulse covers the frequency range of 0 to 2 THz. Fig. 5 shows the Picometrix system and our measurements setup for this study.

A. Evaluation of the $x = 0$ Offset Model

We conduct initial experiments with a convex lens having a 3 inch or 7.62 cm focal length, where the offset angle was 0° and the distance between the transmitter and receiver was 8 cm. In other words, the distance x in Fig. 3 is equal to zero. Fig. 4 plots the received power as a function of distance d in a LOS scenario, $x = 0$, for the whole frequency band of 0 - 2 THz and the band of 330 - 370 GHz. As we can see, the received power degrades rapidly with distance and Friis's equation does not model the behavior particularly well. Similar behavior is observed at other bands as well.

Fig. 6 shows the received power for the frequency band 0 to 2 THz at different distances and shows Friis model as well as our model from equation (7). For this simulation the divergence angle θ and the path loss exponent β are equal to 3.6° and 3.1, respectively. As we can see our model is in good agreement with the measurements data. We note, however, that for distances greater than 20 cm, we only consider frequencies up to 1.342 THz since, as Figure Fig. 7 shows the signal becomes extremely weak after this frequency,

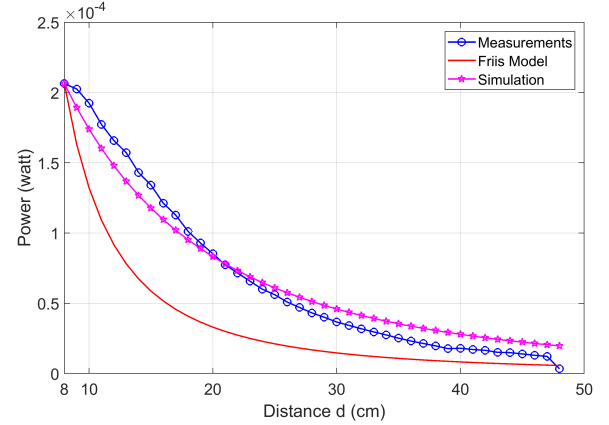


Fig. 6. The experimental and the simulation results of the received power, frequency band: 0-2 THz, $x = 0$, $\theta = 3.6^\circ$, and $\beta = 3.1$.

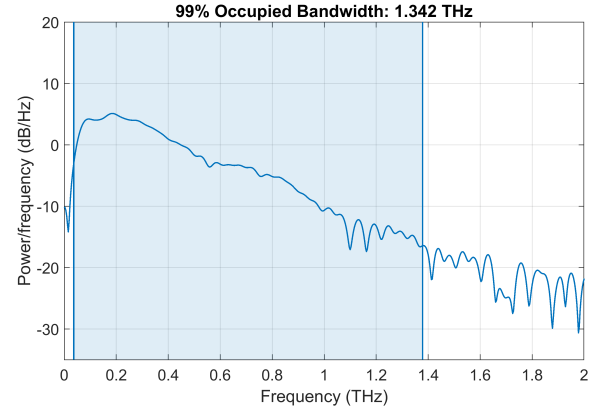


Fig. 7. Power density spectrum at the distance 20 cm

B. Evaluation of the $X \geq 0$ Offset Model

As we discussed in previous sections, our measurements show a rapid drop in received power when the offset distance x increases, Fig. 3. We conducted a set of measurements in which the receiver moves on the x axis while d' is fixed. As the results in Fig. 8 shows, the power profile on the x axis is not uniform. Indeed, a normal distribution fits this profile

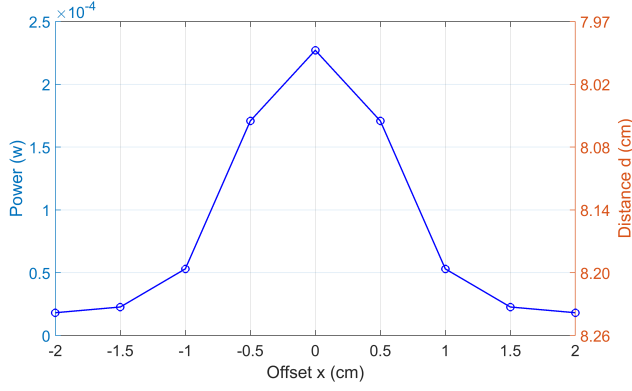


Fig. 8. The experimental results of the received power. 0 - 2 THz. $d' = 8\text{cm}$.

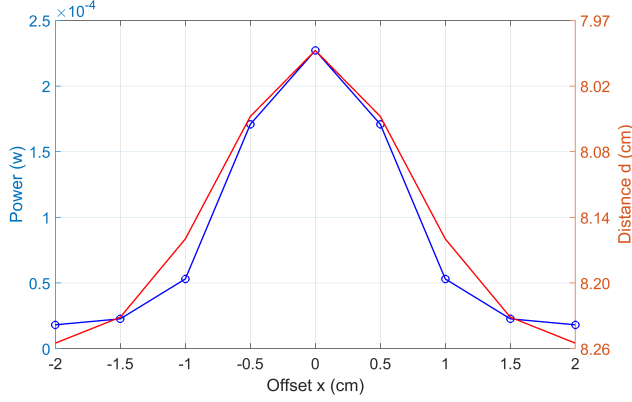


Fig. 9. The experimental results vs. simulation of the received power. 0 - 2 THz. $d' = 8\text{cm}$, $\theta = 3.6^\circ$, and $\beta = 3.1$.

well. We substitute $f(x)$ by e^{-x^2} in equation (7) to obtain,

$$P_r = \left(\frac{r_{Rx}}{r + d' \tan \theta} \right)^\beta \times e^{-x^2} \times P_t G_t G_r \lambda^2 \times e^{-dK(f)} \quad (8)$$

We simulated our collected data using (8) for the whole frequency band 0 – 2 THz as well as for the subband of 300 – 370 GHz.

Fig. 9 shows that our model (8) matches the measurements well over the entire 0 – 2THz band. As we expected, the received power is in maximum when Tx and Rx are aligned. We also applied our model on the subband of 300 – 370GHz. A comparison between the simulation results and the measurements is shown in Fig. 10. Again, our model is a good match for the experimental data.

V. CONCLUSION

THz communication is a very promising technology to meet future wireless data demands. In this study, we have presented channel characterization for the 0 to 2 THz band using measurements conducted on the Picometrix T-Ray 4000 system. We enhanced the coverage in a directional THz channel by using a convex lens on the transmitter. Our measurements show that the conventional path loss models does not work on the THz band. Therefore, by geometric analysis, we proposed

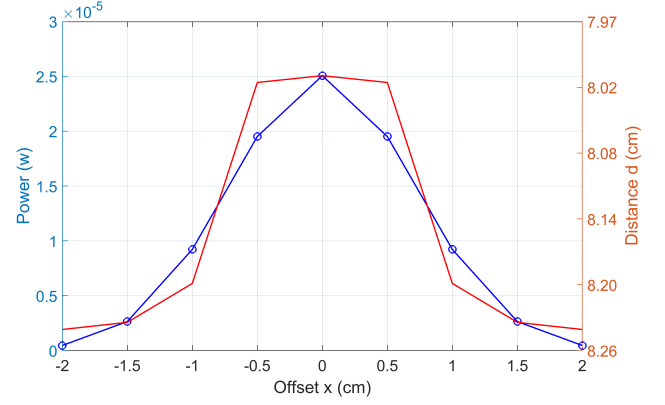


Fig. 10. The experimental results vs. simulation of the received power. 300-370 GHz. $d' = 8\text{cm}$, $\theta = 3.6^\circ$, and $\beta = 3.1$.

a model for the path loss. We also showed that the power is not distributed uniformly on the covered area. We improved our model by adding the gaussian aspect to the power profile. The simulation results show that our model is in good match with the collected data.

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REFERENCES

- [1] T. Kleine-Ostmann and T. Nagatsuma, "A review on terahertz communications research," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 32, no. 2, pp. 143–171, 2011.
- [2] I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz band: Next frontier for wireless communications," *Physical Communication*, vol. 12, pp. 16–32, 2014.
- [3] J. Federici and L. Moeller, "Review of terahertz and subterahertz wireless communications," *Journal of Applied Physics*, vol. 107, no. 11, p. 6, 2010.
- [4] H.-J. Song and T. Nagatsuma, "Present and future of terahertz communications," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 256–263, 2011.
- [5] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3211–3221, 2011.
- [6] X.-W. Yao, C.-C. Wang, W.-L. Wang, and C. Han, "Stochastic geometry analysis of interference and coverage in terahertz networks," *Nano Communication Networks*, vol. 13, pp. 9–19, 2017.
- [7] F. Moshirfatemi, "Communicating at terahertz frequencies," Ph.D. dissertation, Portland State University, 2017.
- [8] C.-C. Chong, C.-M. Tan, D. I. Laurenson, S. McLaughlin, M. A. Beach, and A. R. Nix, "A new statistical wideband spatio-temporal channel model for 5-ghz band wlan systems," *IEEE Journal on selected areas in Communications*, vol. 21, no. 2, pp. 139–150, 2003.
- [9] S. Priebe, C. Jastrow, M. Jacob, T. Kleine-Ostmann, T. Schrader, and T. Kurner, "Channel and propagation measurements at 300 ghz," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 5, pp. 1688–1698, 2011.
- [10] L. S. Rothman, I. E. Gordon, A. Barbe, D. C. Benner, P. F. Bernath, M. Birk, V. Boudon, L. R. Brown, A. Campargue, J.-P. Champion *et al.*, "The hitran 2008 molecular spectroscopic database," *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 110, no. 9-10, pp. 533–572, 2009.
- [11] S. Priebe and T. Kurner, "Stochastic modeling of thz indoor radio channels," *IEEE Transactions on Wireless Communications*, vol. 12, no. 9, pp. 4445–4455, 2013.

- [12] A. Moldovan, M. A. Ruder, I. F. Akyildiz, and W. H. Gerstacker, "Loss and nlos channel modeling for terahertz wireless communication with scattered rays," in *Globecom Workshops (GC Wkshps)*, 2014. IEEE, 2014, pp. 388–392.
- [13] J. Kokkonen, J. Lehtomäki, K. Umebayashi, and M. Juntti, "Frequency and time domain channel models for nanonetworks in terahertz band," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 2, pp. 678–691, 2015.
- [14] W. C. Hinds, *Aerosol technology: properties, behavior, and measurement of airborne particles*. John Wiley & Sons, 2012.
- [15] C. Han, A. O. Bicen, and I. F. Akyildiz, "Multi-ray channel modeling and wideband characterization for wireless communications in the terahertz band," *IEEE Transactions on Wireless Communications*, vol. 14, no. 5, pp. 2402–2412, 2015.
- [16] S. Nie and I. F. Akyildiz, "Three-dimensional dynamic channel modeling and tracking for terahertz band indoor communications," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2017 IEEE 28th Annual International Symposium on*. IEEE, 2017, pp. 1–5.
- [17] K. Tsujimura, K. Umebayashi, J. Kokkonen, J. Lehtomäki, and Y. Suzuki, "A causal channel model for the terahertz band," *IEEE Transactions on Terahertz Science and Technology*, vol. 8, no. 1, pp. 52–62, 2018.
- [18] F. Moshir and S. Singh, "Ultrafast pulsed thz communication," in *Personal, Indoor, and Mobile Radio Communication (PIMRC), 2014 IEEE 25th Annual International Symposium on*. IEEE, 2014, pp. 348–353.
- [19] —, "Modulation and rate adaptation algorithms for terahertz channels," *Nano Communication Networks*, vol. 10, pp. 38–50, 2016.
- [20] M. N. Soorki, M. J. Abdel-Rahman, A. MacKenzie, and W. Saad, "Joint access point deployment and assignment in mmwave networks with stochastic user orientation," in *Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), 2017 15th International Symposium on*. IEEE, 2017, pp. 1–6.
- [21] M. N. Soorki, A. B. MacKenzie, and W. Saad, "Millimeter wave network coverage with stochastic user orientation," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2017 IEEE 28th Annual International Symposium on*. IEEE, 2017, pp. 1–6.
- [22] A. Moldovan, P. Karunakaran, I. F. Akyildiz, and W. H. Gerstacker, "Coverage and achievable rate analysis for indoor terahertz wireless networks," in *Communications (ICC), 2017 IEEE International Conference on*. IEEE, 2017, pp. 1–7.
- [23] H. T. Friis, "A note on a simple transmission formula," *Proceedings of the IRE*, vol. 34, no. 5, pp. 254–256, 1946.
- [24] D. Swinehart, "The beer-lambert law," *Journal of chemical education*, vol. 39, no. 7, p. 333, 1962.
- [25] [Online]. Available: <http://advancedphotonix.com/>