Utilization of THz Signals for Gas Detection

Hadi Mchawrab, Mohamad Lakkis, Mustafa Jouni

AMERICAN UNIVERSITY OF BEIRUT
AMERICAN UNIVERSITY OF BEIRUT MAROUN SEMAAN FACULTY OF ENGINEERING & ARCHITECTURE

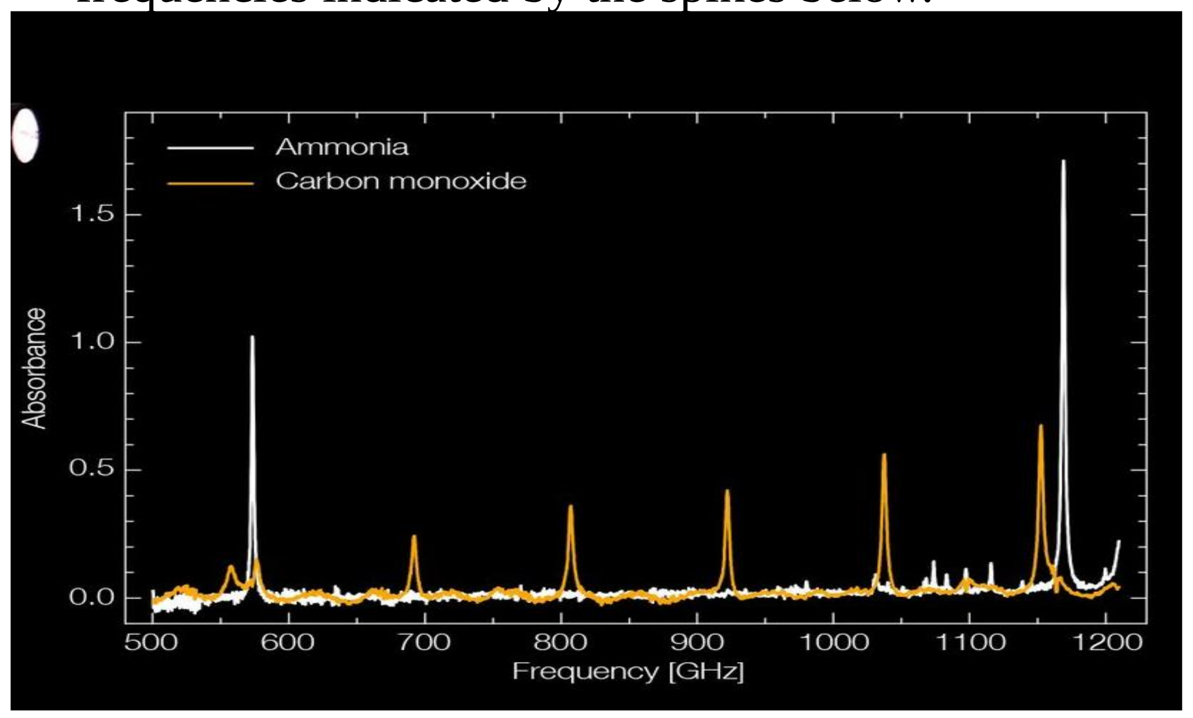
IDEAS 2024

Abstract

Our study focuses particularly on the application of THz band sensing to detect the presence of gases within a medium solely based on signal analysis. Specifically, we propose a novel approach for the identification of inflammable and toxic gases in the environment, enhancing safety and prevention strategies through the advanced capabilities of THz band sensing. To achieve this, we employ a two-pronged methodological approach: initially, generating THz signals within a simulated environment to understand their propagation and interaction with various gases. Utilizing machine learning algorithms, we then classify these signals to accurately predict the presence of specific gases in the medium.

Introduction

- **Frequency Range:** Terahertz radiation spans from 0.1 to 10 THz.
- **Wavelength:** Corresponding wavelengths range from 30 µm to 3 mm.
- **Terahertz Gap:** It is less explored compared to microwave and infrared spectra.
- **Limitations:**
  - Terahertz radiation has difficulty penetrating fog and clouds.
  - It cannot penetrate liquid water or metal.
- **Non-Ionizing:** Terahertz radiation does minimal damage to living tissues.
- **Gas Interaction:** It dynamically interacts with gas molecules, leading to absorption at specific frequencies indicated by the spikes below.



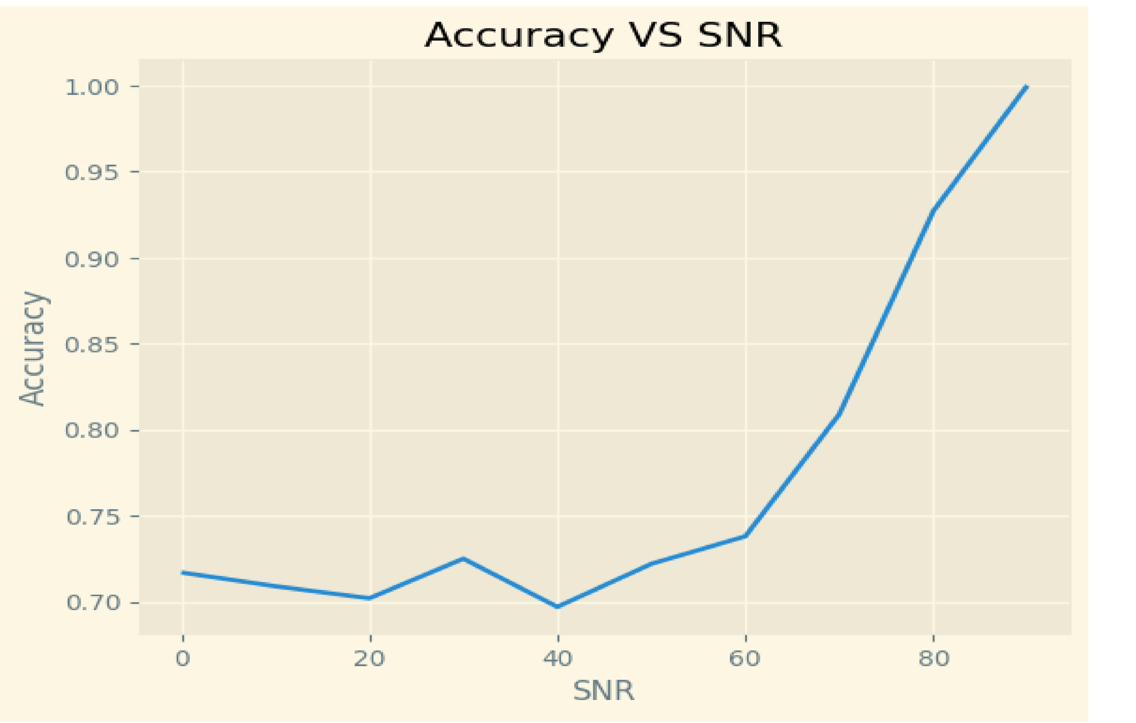
Methodology

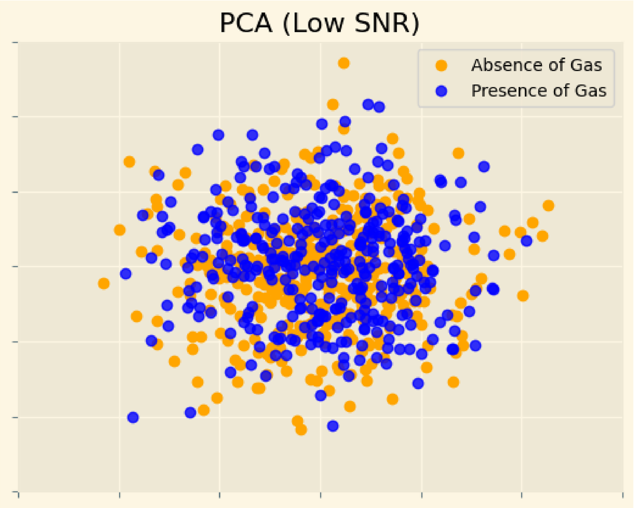
- **Path Loss and Absorption**:
  - THz frequencies experience significant path loss due to high absorption by atmospheric molecules.
  - The equation of path loss below depends on distance and frequency, influenced by absorption coefficients.

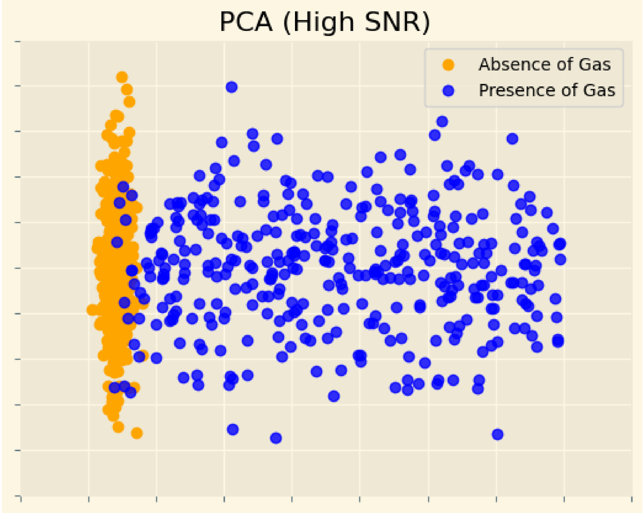
$$\alpha^{\mathrm{LoS}}_{m_r n_r, m_t n_t} = \frac{c}{4\pi f d_{m_r n_r, m_t n_t}} \times e^{-\frac{1}{2}\mathcal{K}(f) d_{m_r n_r, m_t n_t}} e^{-j\frac{2\pi f}{c} d_{m_r n_r, m_t n_t}}$$

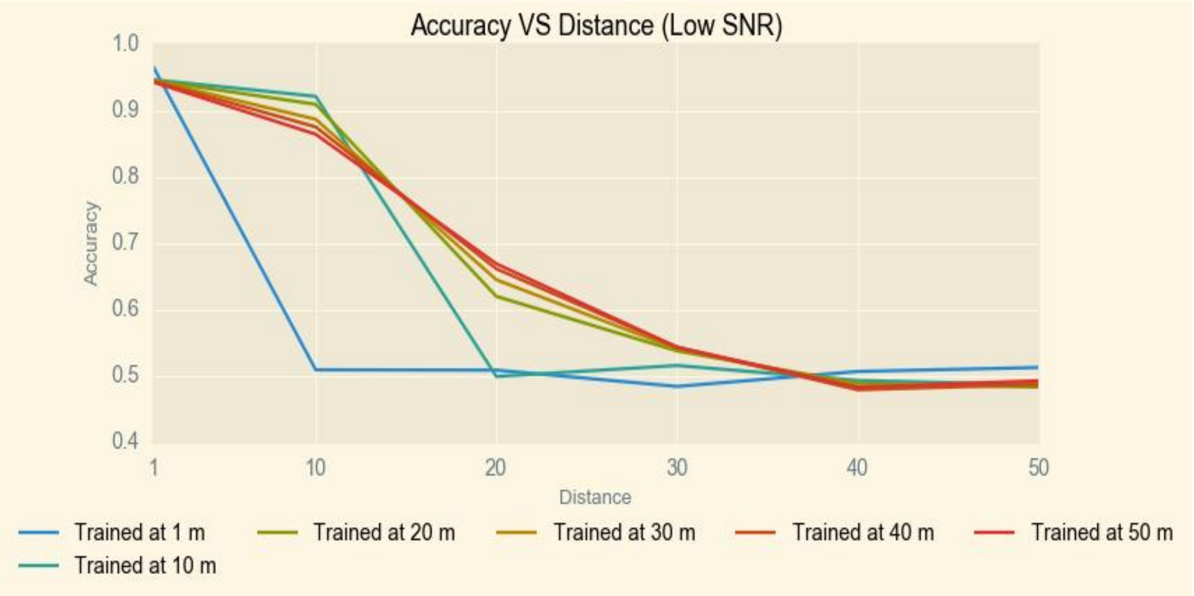
- **SNR vs. Accuracy**:
  - As SNR increases (clearer channel), accuracy improves.
  - Analyzing multiple frequencies requires dimensionality reduction techniques like PCA for visualization and analysis which reduces dimensionality while preserving the most variance in the data.
- **SNR and Class Separation**:
  - Low SNR values make class differentiation challenging.
  - Increasing SNR reveals separability between classes.
- **Effect of Distances on Accuracy**:
  - Accuracy depends on training data, SNR and distance.
  - Up to a certain threshold, training at lower distances significantly impacts accuracy positively.
  - Beyond this threshold, additional training points yield minimal accuracy improvement.
- **SNR and Max Distance**:
  - Lower SNR shifts the accuracy-distance curve leftward (Reduces the maximum distance achievable).
  - Reduced max achievable distance compromises gas detection (i.e.less molecules to sample from).
  - Thus, as we lower the SNR value the max distance that we can achieve will become less and the system's ability to detect gases like CO becomes significantly compromised, emphasizing the critical role of SNR and robust training in the design of THz sensing systems.

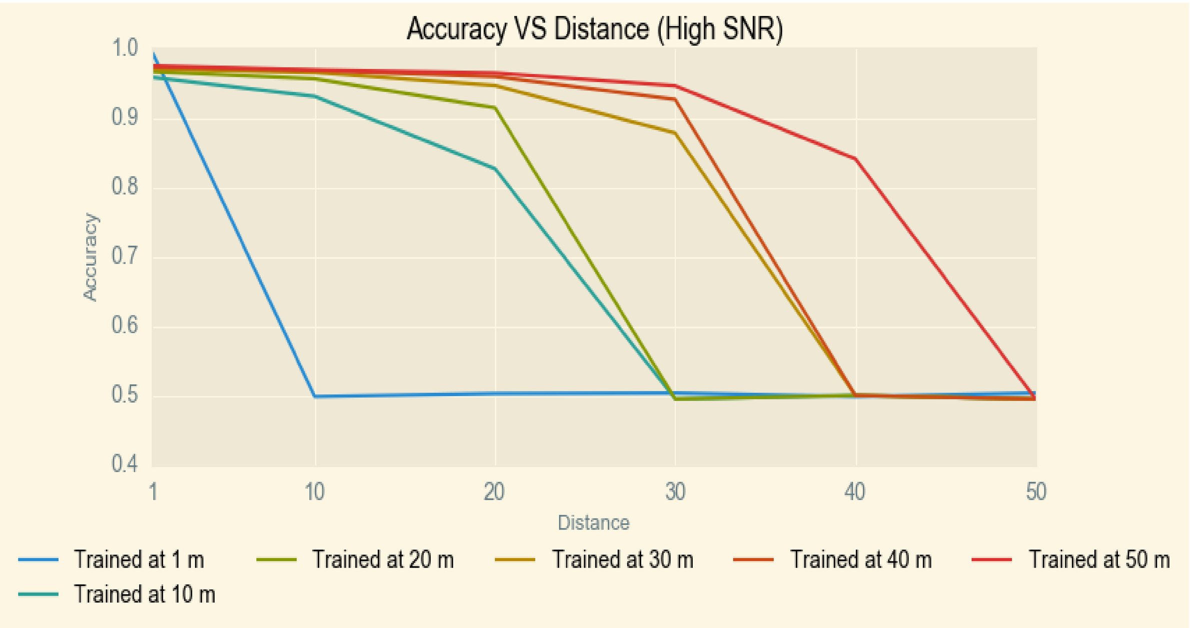
Note: Simulated signals were used due to limited real THz data.









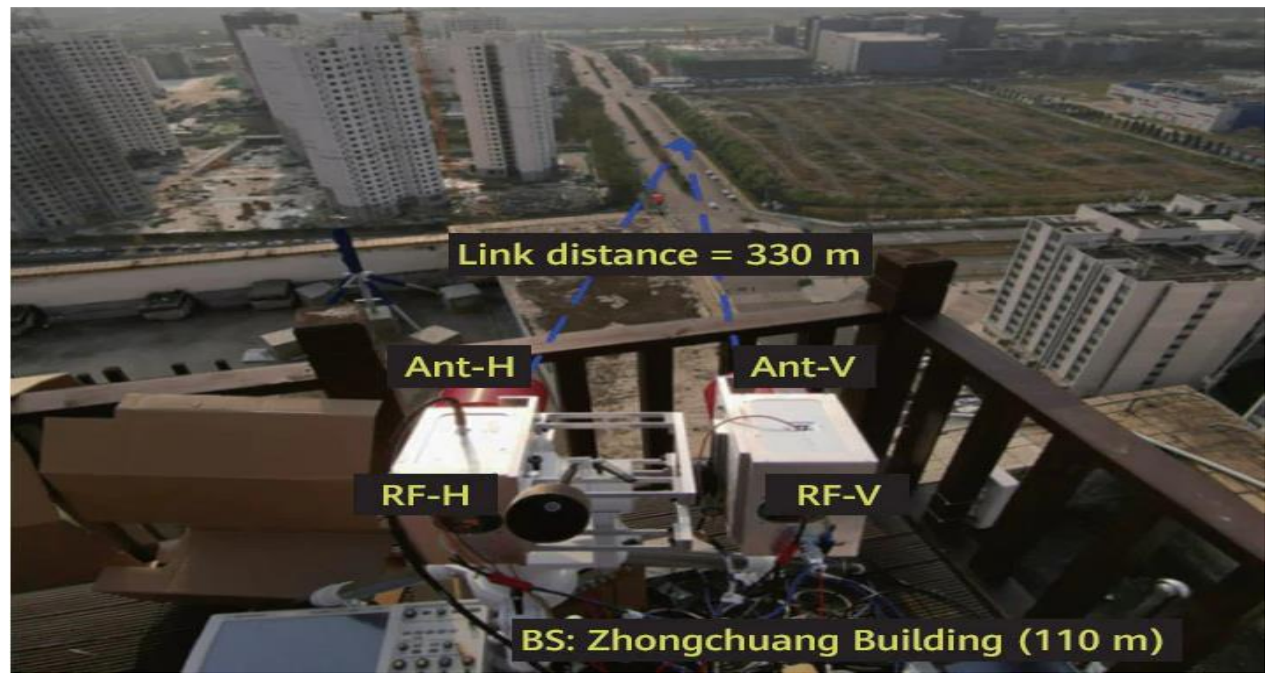


Findings

After training our model across various distances with a significantly high Signal-to-Noise Ratio (SNR), we achieved an impressive detection rate that surpassed expectations up to a specific threshold. However, as distances increased beyond this critical point, maintaining such high accuracy required an even higher SNR, resulting in a substantial demand for additional power resources. This underscores the crucial role of SNR in determining achievable accuracy levels, particularly at extended distances. Strategic resource allocation and optimization are essential to ensure consistent performance across varying operational ranges.

Aspirations

The need for a huge power budget to get the needed value of SNR presents a significant financial challenge, as connecting multiple antennas requires substantial capital investment. Fortunately, similar antennas have been successfully deployed worldwide, demonstrating the capability to transmit signals over distances of up to 330 meters. Leveraging these advancements, our future efforts will focus on utilizing datasets from established stations to detect specific gases. This approach not only capitalizes on existing infrastructure but also streamlines the deployment of gas detection systems, leading to efficient and cost-effective monitoring solutions. By collaborating with global initiatives, we aim to accelerate progress in gas detection technology, enhancing environmental safety and industrial efficiency on a global scale.



1. S. Helal, H. Sarieddeen, H. Dahrouj, T. Y. Al-Naffouri and M. -S. Alouini, "Signal Processing and Machine Learning Techniques for Terahertz Sensing: An overview," in IEEE Signal Processing Magazine, vol. 39, no. 5, pp. 42-62, Sept. 2022, doi: 10.1109/MSP.2022.3183808.
2. Wang, G., Gu, H., Li, X., Yu, Z., Li, O., Liu, Q., Zeng, K., He, J., Chen, Y., Lu, J., Tong, W., & Wessel, D. (2022b, December 13). Terahertz Sensing And Communication Towards Future Intelligence Connected Networks. Huawei. https://www.huawei.com/en/HUAWEItech/future-technologies/terahertz-sensing-communication
3. Yang, L., Guo, T., Zhang, X., Cao, S., & Ding, X. (2018, September 1). Toxic chemical compound detection by Terahertz Spectroscopy: A Review. De Gruyter.
4. BMBF project "HORATIO"