Sensing in Terahertz Communications for the Sixth-Generation Mobile Technology

Mmohaankumar S/O Muthukkumaran
Faculty of Engineering
Multimedia University
Cyberjaya, Selangor
1191101435@student.mmu.edu.my

Mohamad Yusoff bin Alias
Faculty of Engineering
Multimedia University
Cyberjaya, Selangor
yusoff@mmu.edu.my

Suhandi Bujang
Center of Excellent for Intelligent Network
TM R&D Sdn Bhd
Cyberjaya, Malaysia
suhandi@tmrnd.com.my

Azah Syafiah Mohd Marzuki
Center of Excellent for Intelligent Network
TM R&D Sdn Bhd
Cyberjaya, Malaysia
azah@tmrnd.com.my

***Abstract* — This paper investigates the use of compressed sensing methods in waveform design to enhance transmission efficiency while minimizing free-space path loss (FSPL). It introduces a classification framework tailored for communication and sensing services, considering critical parameters such as data rates, operational frequencies, and latency requirements. Additionally, the research evaluates the potential of integrating Terahertz (THz) sensing into sixth generation (6G) networks, utilizing the distinctive attributes of THz waves for applications like imaging, spectroscopy, and environmental sensing. The project demonstrated that waveforms developed with compressed sensing techniques improved both data acquisition and reconstruction. Simulation results reveal substantial challenges in THz communication for 6G networks, including significant path losses, atmospheric absorption, and scattering at higher frequencies and over longer distances. Addressing these challenges necessitates advanced technologies—such as high-gain antennas, power amplifiers, and robust error-correcting codes—to ensure reliable communication. These findings are essential for the design and optimization of 6G networks, providing guidance for the development of technologies and infrastructure that can meet the unique demands of THz communication, thereby supporting the ultra-high-speed, low-latency applications envisioned for future networks.**

Keywords— Terahertz Communications, Sensing Technology, 6G.

I. Introduction

The sixth generation (6G) mobile technology represents the next evolution in wireless communication, building upon the advancements introduced by the fifth generation (5G) networks. While 5G has brought significant improvements in speed, latency, and connectivity, 6G aims to push these boundaries further, achieving ultra-high data rates, near-instantaneous latency, and ubiquitous connectivity. It is envisioned to support a wide range of applications, from enhanced mobile broadband to massive machine-type communications and ultra-reliable low-latency communications.

One of the key innovations of 6G is the utilization of the terahertz (THz) frequency band, ranging from 0.1 to 10 THz. This band offers vast amounts of unused spectrum, enabling extremely high data rates in the order of terabits per second (Tbps). In addition to THz communication, 6G technology integrates various advanced features, including artificial intelligence (AI) and machine learning (ML), network slicing, virtualization, holographic, extended reality (XR), quantum communication and computing, while focusing on environmental and energy efficiency.

6G will advance the concept of network slicing, enabling the creation of multiple virtual networks within a single physical infrastructure. Each slice can be customized to meet the specific requirements of various applications, such as industrial automation, low-latency gaming, high-bandwidth streaming, and ultra-reliable communication. This adaptability allows diverse use cases to coexist and perform optimally on the same network.

A key focus of 6G development is energy efficiency and sustainability. Innovations in green technology, energy harvesting, and network design aim to reduce the environmental impact of 6G infrastructure. Energy-efficient devices and communication protocols will contribute to creating sustainable digital ecosystems and eco-friendly smart cities.

One of the major challenges facing current 5G technology is the overcrowding of frequency bands due to the rapid growth of mobile devices, Internet of Things (IoT) devices, and other wireless applications. The frequency bands below 6 Gigahertz (GHz), traditionally used for wireless communication, are becoming increasingly congested. Even the millimetre-wave (mmWave) bands, which extend up to 100 GHz and are used in 5G for high-speed data transfer, are facing congestion. This leads to interference, reduced data rates, and a decline in service quality.

Another complex challenge in 6G is designing a waveform that efficiently balances the trade-offs between sensing and communication needs. Since waveform design directly impacts a system's ability to transmit data reliably and efficiently, it becomes more complex in 6G, where sensing and communication functionalities are expected to coexist and complement each other.

Sensing and communication applications have varying needs, requiring different operational frequencies, latency requirements, and data rates. The framework for 6G technology addresses these varying demands:

- ***Latency Requirements:*** Critical for applications like autonomous vehicles or real-time control systems, where ultra-low latency is necessary for accurate and timely responses. Conversely, applications like environmental monitoring, which require continuous data collection over extended periods, can tolerate higher latency.

- ***Data Rates:*** Essential for applications requiring fast and reliable data transfer, such as virtual reality or high-definition video streaming. In contrast, sensors in IoT or industrial automation may require lower data rates but prioritize consistency and energy efficiency.
- ***Operating Frequency***: This includes microwave, millimetre-wave, and terahertz frequencies, each suited to different applications and environments, contributing to the overall versatility and robustness of 6G networks.

This paper employs a simulation model to examine free space path loss and scattering effects on THz signals, analyzing their impact on signal integrity and overall system performance. The research focuses on assessing the accuracy of the path loss model in predicting the behavior of THz signals in indoor environments. These insights are essential for the design and optimization of 6G networks, providing a foundation for developing technologies and infrastructure tailored to the unique requirements of THz communication. This, in turn, supports the realization of ultra-high-speed, low-latency applications envisioned for the future.

The paper is organized as follows. The paper starts with this introduction section. This is followed by Section II that will investigate some recent works related to terahertz and sensing technology in 6G. Then, Section III will lay out the methodology. Section IV will be looking into the results and discussion. Finally, the conclusion will be presented in Section V.

II. Related Works

Sensing is a pivotal component of 6G technology, enhancing the network's ability to perceive and interact with its environment. This capability extends beyond traditional communication, enabling precise environmental monitoring, object detection, and localization. By integrating sensing into the network infrastructure, 6G supports applications such as autonomous driving, where vehicles must detect obstacles and navigate safely, and smart cities, where real-time environmental data optimizes energy use, traffic flow, and public safety. Additionally, advanced health monitoring systems can track vital signs non-invasively, providing critical data for remote healthcare services. The combination of sensing and communication in 6G allows for more efficient spectrum and infrastructure utilization, reducing costs and enhancing overall system performance. This integration transforms 6G networks into intelligent systems capable of proactive and adaptive operations, driving innovation across various industries [1].

Several types of sensing already implemented in 5G technology are being tested for 6G. Passive sensing, for instance, identifies and analyzes natural signals emitted or reflected by objects in the environment without the sensor needing to actively send out signals [2]. By utilizing ambient signals already present, passive sensing can monitor and collect data efficiently without generating additional electromagnetic emissions. Radiofrequency (RF) sensing, a popular form of passive sensing, uses pre-existing RF signals such as Wi-Fi, Bluetooth, or cellular networks to detect environmental changes or anomalies. These variations, caused by movement, signal strength changes, or interference patterns, reveal critical details about the surroundings.

RF sensing works by continuously observing the frequency, phase, and strength of surrounding signals. When an object passes through the monitored area, it disrupts or reflects these RF signals [3]. By analyzing these disruptions, one can infer details about the object's presence, motion, and size. This method is particularly effective for indoor localization, where it can track people or assets within a building without additional infrastructure or active signal emission. Similarly, it can be employed in security systems to detect anomalous behavior or unauthorized access by monitoring changes in the radio frequency environment.

Environmental monitoring is another application of passive sensing, where sensors detect natural elements such as humidity, temperature, light levels, and air quality. These sensors rely on the inherent fluctuations in the environment to gather data rather than emitting any signals. For example, humidity sensors monitor moisture levels in the air, while temperature sensors measure thermal energy emitted by objects and the atmosphere [4]. Air quality sensors provide essential information for health and safety applications by measuring the concentration of various gases and particles in the atmosphere.

Unlike passive sensing, active sensing involves the deliberate emission of signals by the sensing equipment, followed by analysis of the signals absorbed, scattered, or reflected by surrounding objects [5]. This approach allows for more controlled and precise measurements, as the emitted signals can be adjusted in frequency, power, and modulation to meet specific sensing requirements. The sensor initiates the process by sending out a signal, such as a radio wave, laser beam, or sound wave, which interacts with objects in its path. The reflections or scatterings from these objects are then captured and analyzed to obtain crucial data regarding their properties, locations, and movements.

When THz waves encounter an object, three processes can occur: absorption, scattering, and reflection. Reflection occurs when waves strike an object and return in the same direction or at an angle, a phenomenon common with materials that have smooth surfaces and specific electromagnetic properties, such as metals [6]. Scattering happens when waves hit an uneven surface or a medium with irregularities, causing the waves to disperse in different directions, revealing details about the object's structure and texture. Absorption occurs when a material absorbs all or part of the THz energy, providing insights into the object's thickness and composition. A sensor or receiver capable of accurately capturing these high-frequency waves then receives the reflected and scattered THz signals. These incoming signals are processed using advanced signal processing techniques and algorithms to analyze time delay, frequency shift, and signal strength, yielding detailed information about the object's size, shape, internal structure, and distance from the sensor.

Radio Detection and Ranging (Radar) is a widely used form of active sensing. It works by emitting radio waves and timing the return of the echoes from objects. The distance to the objects can be calculated from this time delay, given the known speed of radio waves. Radar technology is crucial in many fields, including aviation, marine navigation, weather monitoring, and vehicle safety systems. It can detect objects at great distances, providing precise information about their direction and speed, and it operates effectively in various weather and lighting conditions [7]. While using different types of waves, both ultrasonic sensing and light detection and ranging (lidar) are active sensing systems based on similar principles. Lidar devices emit laser pulses and measure the time it takes for light to reflect off objects. Given that light travels faster and has a shorter wavelength than radio waves, lidar is ideally suited for applications such as environmental monitoring, topographic mapping, and autonomous vehicle navigation [8]. This technology enables precise three-dimensional mapping of environments, identifying the size, shape, and distance of objects.

III. Methodology

In this paper, MATLAB is utilized to generate and modulate sensing data using advanced techniques such as Orthogonal Frequency-Division Multiplexing (OFDM) and Quadrature Amplitude Modulation (QAM). The simulation models the free space path loss and scattering effects on THz signals, analysing their impact on signal integrity and system performance. Detailed plots and graphs are then used to visualize the results.

In the context of THz communication and sensing for 6G technology, MATLAB is employed to simulate and analyse the performance of communication systems. This includes the processes of signal modulation, demodulation, and the evaluation of channel effects such as FSPL and scattering. The simulation code aims to model and examine the behaviour of THz communication and sensing within a 6G network environment, with a particular focus on how THz signals propagate, interact with objects, and are received over varying distances and carrier frequencies. By simulating these scenarios, the code provides insights into the impact of physical and environmental factors on the reliability and accuracy of THz-based communication and sensing systems [9][10].

The code implements a communication system using OFDM with 64-QAM modulation. The system transmits a modulated signal over a THz channel and analyses the effects of distance and frequency on the quality of the received signal. The simulation is divided into four major steps [11][12]:

1. **Modulation**: Binary data is converted into QAM symbols, and OFDM modulation is applied.
2. **Propagation Losses**: The simulation evaluates the propagation losses that THz signals endure, considering various forms of attenuation. These include free space path loss, scattering due to atmospheric molecules, and absorption by oxygen and water vapor. The transmitter-receiver distances at which these losses occur are computed, and the effective received power is calculated at different frequencies and distances.
3. **Energy Detection**: The code includes an energy-detection technique to examine the received signals. This technique determines whether the transmitted signal was successfully received and distinguished from background noise. The algorithm evaluates the probability of accurately identifying the transmitted data by measuring the energy of the received signal relative to a predetermined threshold. Energy detection is especially useful when signal properties are unknown, or the signal-to-noise ratio (SNR) is low. The energy of the received signal is calculated by integrating the square of the signal amplitude over the observation interval. Mathematically, the energy, *E,* over a time interval, *T*, is given by:

$$E = \int_0^T |r(t)|^2 \, dt \qquad (1)$$

where *r(t)* represents the received signal.

In discrete-time scenarios, the energy of a signal can be computed by summing the squared samples over a sequence of time or frequency bins.

A detection threshold, γ, is set based on the expected noise level or the desired probability of false alarm (P_{fa}), which represents the likelihood of mistakenly detecting a signal when none is present. This threshold γ is typically chosen to minimize the probability of false alarms while ensuring reliable detection of signals above a certain SNR. Once the energy *E* of the received signal is computed, two outcomes are possible based on the threshold comparison. If $E > \gamma$, a decision is made that a signal is present. Conversely, if $E \leq \gamma$, the decision is that no signal is present.

If a signal is detected, the received OFDM signal is demodulated back into the original message bits after further processing to reduce noise and enhance signal quality. The simulation's focus on the material reflection characteristics of glass, particularly in the context of THz sensing, is noteworthy. The code computes the reflection coefficient for glass to evaluate how effectively THz signals reflect off glass surfaces, which is crucial for sensing applications where environmental information is gathered by analysing signal reflections.

The code also utilizes a compressed sensing technique to efficiently acquire and reconstruct signals from a smaller dataset. This approach is particularly beneficial when direct sampling at the Nyquist rate—twice the highest frequency component—is impractical or too costly. By exploiting the sparsity or compressibility of signals within a specific domain, compressed sensing can reconstruct the original signal from significantly fewer samples than those required by the Nyquist-Shannon sampling theorem. The code aims to reconstruct a sensing signal that has been modified and transmitted across a communication channel, potentially for sensing applications. First, a random Gaussian sensing matrix *A* is generated, typically of dimension $m \times N$, where *N* is the length of the signal of interest and *m* is significantly smaller than *N*. The matrix *A* is crucial because it defines how the signal measurements are obtained and ensures a sparse representation of the signal, as each component of *A* is randomly drawn from a standard normal distribution.

IV. Results and Discussion

The study prioritizes evaluating the effectiveness of the path loss model in accurately predicting the behaviour of THz signals in indoor environments. The provided code generates various plots to visualize the performance of a 6G THz communication system, including SNR, path loss, and scattering attenuation as functions of distance for different carrier frequencies. Additionally, it compares the transmitted and received signals.

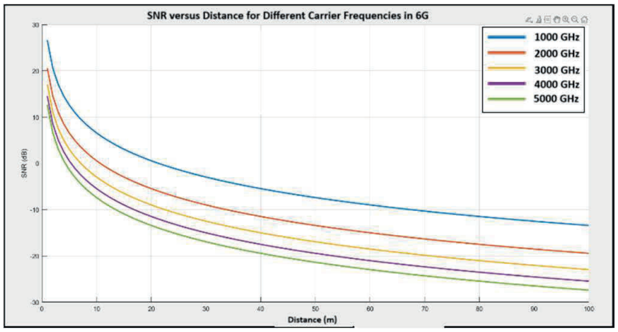

Fig. 1: Signal-to-Noise Ratio versus distance

The graph illustrates the signal-to-noise ratio (SNR) as a function of distance for carrier frequencies ranging from 1 THz to 5 THz. Like Fig. 1, the graph includes five curves, each representing a distinct carrier frequency: 1 THz in blue, 2 THz in orange, 3 THz in yellow, 4 THz in purple, and 5 THz in green. As the carrier frequency increases, the SNR decreases more rapidly with distance. All the curves exhibit a declining trend, signifying that SNR diminishes as distance increases. This behaviour is expected due to the greater path loss and scattering attenuation as the signal travels farther. Additionally, for a given distance, higher frequencies exhibit lower SNRs compared to lower frequencies. This is attributed to the increased path loss and scattering effects at higher frequencies.

At distances up to around 10 meters, the Signal-to-Noise Ratio (SNR) remains relatively high across all frequencies but begins to decline rapidly beyond that range. After 20 meters, the SNR drops sharply, especially at higher frequencies like 4 THz and 5 THz, which experience a much steeper decline. This reduction in SNR is largely due to frequency-dependent path loss—higher carrier frequencies face greater path loss and scattering, leading to lower SNR compared to lower frequencies over the same distance. As a result, lower THz frequencies may be more suitable for longer-range communication to maintain better SNR.

SNR diminishes with distance primarily because of path loss, which refers to the signal weakening as it travels through the medium (air, in this case). Both distance and frequency influence path loss, with higher frequencies (like 4000 GHz and 5000 GHz) experiencing more substantial losses compared to lower frequencies (such as 1000 GHz and 2000 GHz). This is why the higher frequency bands, represented by the green and purple lines, exhibit a more dramatic drop in SNR as distance increases.

The decrease in SNR with distance is driven by two main factors. First, free-space path loss, which is proportional to the square of both distance and frequency, affects higher frequencies more severely. Second, higher frequencies are more prone to absorption by atmospheric gases and environmental factors, further accelerating the reduction in SNR.

The system's performance concerning scattering attenuation can be evaluated by examining the increase in attenuation with distance and frequency. Fig. 2 depicts the scattering attenuation plotted against distance for each carrier frequency.

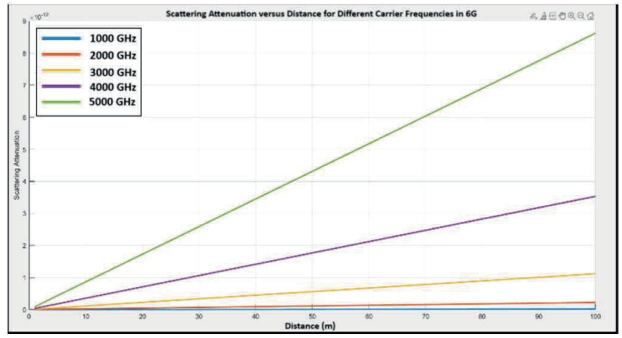

Fig. 2: The graph of scattering attenuation versus the distance for different carrier frequency

The scattering attenuation for multiple THz carrier frequencies, including 1000 GHz (1 THz), 2000 GHz (2 THz), 3000 GHz (3 THz), 4000 GHz (4 THz), and 5000 GHz (5 THz), is plotted as a function of distance. The plot reveals a clear trend: scattering attenuation increases with distance for all carrier frequencies. This is expected, as the signal interacts with more scattering particles as it travels, leading to greater attenuation. Additionally, the plot shows that higher frequencies experience more significant scattering attenuation, with the signal at 5000 GHz (5 THz) exhibiting the greatest attenuation, followed by 4000 GHz (4 THz), and so on. This occurs because the shorter wavelengths of higher-frequency signals are more easily scattered by small particles in the medium. This result aligns with theoretical wave propagation principles, which state that higher frequencies interact more with particles of comparable size to the wavelength, making them more prone to scattering.

Fig. 3 below shows the path loss calculated for each carrier frequency compared to the FSPL under 6G technology conditions.

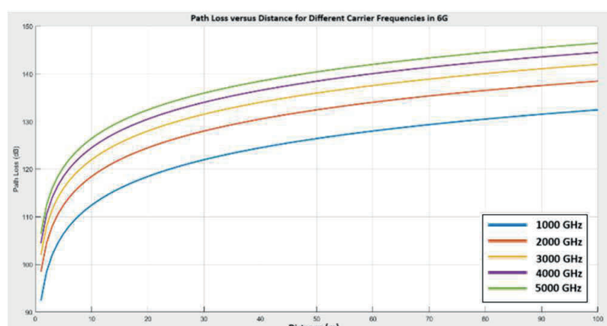

Fig. 3: Path loss vs distance for different carrier frequencies in 6G technology.

Fig. 3 illustrates a clear pattern: path loss increases with both frequency and distance. This relationship is crucial for understanding signal propagation in wireless communication systems, particularly as 6G technology advances into higher frequency bands. The graph shows that, across all carrier frequencies, path loss consistently rises with distance. This is typical of free-space propagation, where electromagnetic waves weaken as they travel over longer distances. This behavior aligns with the inverse square law, which states that a wave's power density decreases in proportion to the square of its distance from the source. Consequently, as the distance between the transmitter and receiver increases, signal power diminishes, leading to higher path loss. The graph effectively visualizes this phenomenon, with all frequency curves trending upward as distance increases.

The graph highlights how path loss is influenced by frequency. Higher frequencies experience greater path loss at any given distance compared to lower frequencies. For instance, at 1000GHz (1THz), the path loss is significantly lower than at 5000GHz (5THz) over a distance of 50 meters. This difference is due to several factors that are unique to higher frequencies. Higher frequency waves have shorter wavelengths, making them more susceptible to absorption by air molecules, water vapor, and other particles in the environment. This absorption increases energy loss, thereby amplifying the path loss.

This trend is further demonstrated by the path loss values at various distances. At 10 meters, the path loss for 1000GHz (1THz) is 102dB, increasing to 107dB at 2000GHz (2THz), 111dB at 3000GHz (3THz), 114dB at 4000GHz (4THz), and 117dB at 5000GHz (5THz). As the distance increases to 50 meters, path loss rises accordingly: 117dB at 1000GHz (1THz), 122dB at 2000GHz (2THz), 126dB at 3000GHz (3THz), 129dB at 4000GHz (4THz), and 132dB at 5000GHz (5THz). At 100 meters, these values increase further, with path loss reaching 127dB at 1000GHz (1THz), 132dB at 2000GHz (2THz), 136dB at 3000GHz (3THz), 139dB at 4000GHz (4THz), and 142dB at 5000GHz (5THz). This upward trend in path loss with both increasing frequency and distance aligns with established electromagnetic wave propagation theory and physical principles.

However, minimizing path loss is crucial for practical applications, especially in the context of emerging 6G technology, to ensure reliable and efficient communication. The following simulations illustrate the reflection coefficient for various carrier frequencies as a function of distance.

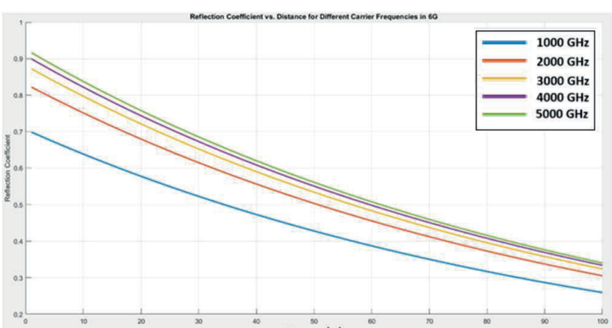

Fig. 4: Reflection coefficient against distance for different carrier frequencies in 6G

Fig. 4 illustrates the reflection coefficient as a function of distance for various carrier frequencies within 6G communication systems. The reflection coefficient, ranging between 0 and 1, indicates the proportion of an incident electromagnetic wave that is reflected by a surface. A lower reflection coefficient suggests more signal transmission through the medium, while a higher value implies increased reflection. This parameter is critical for understanding signal propagation, especially in scenarios where reflections can significantly influence system performance and signal quality.

At a distance of 10 meters, the reflection coefficients for different frequencies are as follows: 0.85 at 1000 GHz (1 THz), 0.88 at 2000 GHz (2 THz), 0.90 at 3000 GHz (3 THz), 0.92 at 4000 GHz (4 THz), and 0.93 at 5000 GHz (5 THz). At 50 meters, these values decrease to 0.60 for 1000 GHz, 0.65 for 2000 GHz, 0.70 for 3000 GHz, 0.75 for 4000 GHz, and 0.80 for 5000 GHz. At 100 meters, the reflection coefficients drop further, reaching 0.35 at 1000 GHz, 0.45 at 2000 GHz, 0.55 at 3000 GHz, 0.65 at 4000 GHz, and 0.75 at 5000 GHz. These results indicate that higher frequencies tend to have larger reflection coefficients at equivalent distances, suggesting that higher-frequency signals are more reflective.

The reflection coefficient plays a pivotal role in the overall performance of sensing and communication systems. High reflection coefficients can lead to multipath propagation, where signals travel along multiple paths before reaching the receiver, potentially causing interference, signal fading, and reduced data rates. In contrast, lower reflection coefficients allow more signal transmission, reducing the impact of multipath effects and improving system reliability and signal quality. Consequently, understanding and optimizing the reflection coefficient is essential for enhancing communication and sensing systems.

V. Conclusion

The simulation results reveal critical challenges in THz communication for 6G networks. Significant path losses, atmospheric absorption, and scattering at higher frequencies and longer distances highlight the necessity for advanced technologies and strategies—such as high-gain antennas, power amplifiers, and sophisticated error-correcting codes—to mitigate these issues and ensure reliable communication. These findings are crucial for designing and optimizing 6G networks, guiding the development of technologies and infrastructure capable of addressing the unique demands of THz communication, thereby enabling the ultra-high-speed, low-latency applications envisioned for the future.

References

[1] I. F. Akyildiz, C. Han, Z. Hu, S. Nie and J. M. Jornet, "Terahertz Band Communication: An Old Problem Revisited and Research Directions for the Next Decade," in IEEE Transactions on Communications, vol. 70, no. 6, pp. 4250-4285, June 2022

[2] Shah, Sabir & Ashraf, Majid & Saeed, Nasir & Jan, Tariqullah & Khalil, Ruhul Amin & Babar, M & Ahmad, Gulzar & Shah, Syed. (2019). Path Loss Model for Future Terahertz (THz) Wireless Communication Systems. Proceedings of the Pakistan Academy of Sciences. 56. 55-65

[3] Sarieddeen, Hadi & Saeed, Nasir & Al-Naffouri, Tareq & Alouini, Mohamed-Slim. (2019). Next Generation Terahertz Communications: A Rendezvous of Sensing, Imaging and Localization

[4] Pant, J. K. (2019). Optimization techniques in BME. In Elsevier eBooks (pp. 112–129). https://doi.org/10.1016/b978-0-12-801238-3.99975-6

[5] Compressive sensing: From theory to applications, a survey. (2013, October 1). KICS Journals & Magazine | IEEE Xplore. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6674179

[6] Lasso Regularization - MATLAB & Simulink. (n.d.). https://www.mathworks.com/help/stats/lasso-regularization.html

[7] Wen, Chao-Kai & Wong, Kai-Kit & Chen, Jung-Chieh & Yuen, Chau. (2014). On Sparse Vector Recovery Performance in Structurally Orthogonal Matrices via LASSO. IEEE Transactions on Signal Processing.

[8] Nasser, Abbass & AL Haj Hassan, Hussein & Mansour, Ali & Yao, Koffi & Nuaymi, Loutfi. (2022). Intelligent Reflecting Surfaces and Spectrum Sensing for Cognitive Radio Networks. IEEE Transactions on Cognitive Communications and Networking.

[9] J. Sanusi, O. Oshiga, S. Thomas, S. Idris, S. Adeshina and A. M. Abba, "A Review on 6G Wireless Communication Systems: Localization and Sensing," 2021 1st International Conference on Multidisciplinary Engineering and Applied Science (ICMEAS), Abuja, Nigeria, 2021, pp. 1-5

[10] T. Gan, S. Dang, X. Li and Z. Zhang, "Integrated Sensing and Communications for 6G: Prospects and Challenges of Using THz Radios," 2024 IEEE Wireless Communications and Networking Conference (WCNC), Dubai, United Arab Emirates, 2024, pp. 1-6,

[11] T. Mao, L. Zhang, Z. Xiao, Z. Han and X. -G. Xia, "Terahertz-Band Near-Space Communications: From a Physical-Layer Perspective," in IEEE Communications Magazine, vol. 62, no. 2, pp. 110-116, February 2024

[12] J. Han, D. He, R. Pan, K. Guan, J. Dou and Z. Zhong, "Terahertz Channel Modeling for Integrated Sensing and Communication," 2023 IEEE 24th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Shanghai, China, 2023, pp. 651-655,