Localization of Mobile Devices in Future Wireless Networks

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***Abstract*— High-precision localization is essential for fully realizing the potential of future mobile networks (6G). A critical factor in achieving such localization accuracy is the incorporation of Terahertz (THz) bands into an efficient localization technique. In this context, we propose an approach for localizing mobile devices in 6G mobile networks. Such an approach is based on the Angle of Departure (AoD) localization technique in order to provide high localization accuracy. Using NYUSIM 4.0 for implementing it, we perform simulations for two different scenarios: the first one emulates a 5G mobile network in the mmWave bands, whereas the second one emulates a 6G mobile network in the THz frequency bands. Results show that 6G mobile networks outperform 5G mobile networks in terms of localization accuracy. This improvement is attributed to finer channel estimation facilitated by THz frequencies, which results in enhanced positioning accuracy.**

***Keywords*— 6G; accuracy; Angle of Departure (AoD); future mobile networks; localization technique.**

I. Introduction

Future wireless technology will offer intelligent and ubiquitous connectivity with Terabits-per-second (Tbps) data rates and sub-millisecond (sub-ms) latency over three-Dimensional (3D) network coverage [1]. In order to achieve such goals, accurate localization information of mobile devices will be essential [2]. In fact, determining the position of mobile devices with high degree of precision is not only crucial for navigation and location-based services, but also for enabling a plethora of emerging applications, such as intelligent telesurgery, holographic teleportation, connected robotics, Augmented Reality (AR) and more [3].

Moreover, higher positioning accuracy is in high demand in many vertical and industrial applications, particularly in indoor environments where satellite-based positioning systems are ineffective. In this context, the introduction of 6G mobile networks will improve high precision positioning within a home or an office. According to [4], with the application of THz bands, such networks are expected to achieve a 3D localization precision of 1 cm. Figure 1 provides a visual representation of how localization will be used in 6G mobile networks.

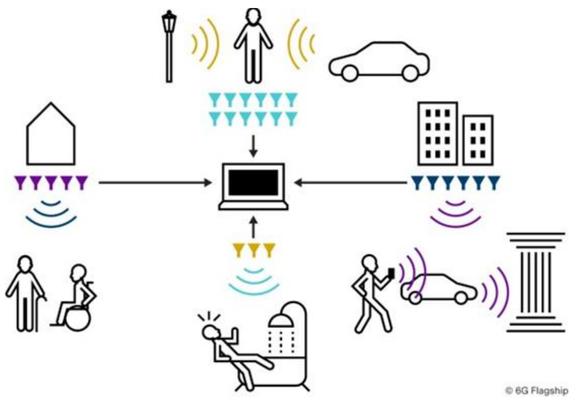

Figure 1. Localization illustration in future wireless networks [5].

The importance of accurate localization gained more attention after the U.S. Federal Communications Commission implemented the enhanced 911 (FCC-E911) rules [6]. Additionally, with the advent of the Global Positioning System (GPS) and the standardization of cellular communication systems, it is now possible to achieve an accuracy of 10 cm in rural areas and 1 m in outdoor urban environments approximately [7]. However, accurately determining localization in indoor environments using cellular networks and GPS can be challenging, as signals are reflected and dispersed by various objects [8]. To overcome such challenging, WiFi-based and Bluetooth-based localization methods have been developed [6]. In complex indoor environments, multi-path signal components and signal blockage can negatively impact localization accuracy, but the use of ultra-wide bandwidth (such as terahertz bands) can make multi-path signals resolvable and improve performance [8].

A number of papers on 6G localization have recently been published [2][9]-[14]. More specifically, the works from [2][13], and [14] were primarily concerned with the vision and technology requirements of 6G localization. Meanwhile, Chen et al. [6] summarize the most recent literature findings related to the use of THz wireless systems for accurate localization. Although this significant work reveals key concepts about THz communication systems and localization, it does not propose transformative solutions required to effectively deploy realistic THz localization systems.

Furthermore, while some of these works [11][12] acknowledge the importance of THz localization capability, they fail to highlight the challenges and prospective techniques required to deploy THz systems capable of performing accurate localization in a real-world scenario.

In this paper, we propose an approach for localization of mobile devices in future wireless networks. It is organized as follows. Section II analyses various localization techniques. Section III provides an overview of localization systems and services that are currently in use. Section IV provides an overview of 6G-compatible simulation tools. Section V presents the basic principles of the proposed approach for localizing mobile devices in future mobile networks. Section VI explains the simulation environment, as well as the parameters needed to perform the simulations, and presents simulation results, whereas Section VII presents concluding remarks.

II. LOCALIZATION TECHNIQUES

Localization techniques are employed to estimate locations of mobile devices using readings from reference points. This section provides an overview of well-known positioning techniques.

A. Received Signal Strength Indicator (RSSI)

The Received Signal Strength (RSS)-based approach is a simple and widely used method for indoor localization [15]. It relies on the measurement of RSS, which represents the power of the signal received by the receiver in decibel-milliwatts (dBm) or milliwatts (mW). By analyzing the RSS, the distance between a Transmitter (TX) and a Receiver (RX) can be estimated, where a higher RSS value corresponds to a shorter distance between TX and RX. The absolute distance can be determined using various signal propagation models, provided that the transmission power is known. RSSI, which is a relative measurement of the RSS with arbitrary units, can be expressed as follows [16]:

$$RSSI = -10n\log_{10}(d) + A \quad (1)$$

where *d* is the distance between TX and RX, *n* the path loss exponent of the signal attenuation and *A* represents the RSSI value at a reference distance from RX.

From (1) and a simple path-loss propagation model, the separation distance *d* between TX and RX can be expressed as follows:

$$d = 10^{\frac{(A-RSSI)}{10n}} \quad (2)$$

where *n* is the path loss, and *A* the RSSI value at a predefined distance from RX. Figure 2 illustrates a network topology consisting of three Root Nodes (RN_1, RN_2, RN_3) which are commonly referred to as base stations. The primary objective of this configuration is to demonstrate the process of localizing a mobile device within the network, using RSSI and applying the triangulation technique. Each of the three base stations serves as a reference point with known geographical coordinates.

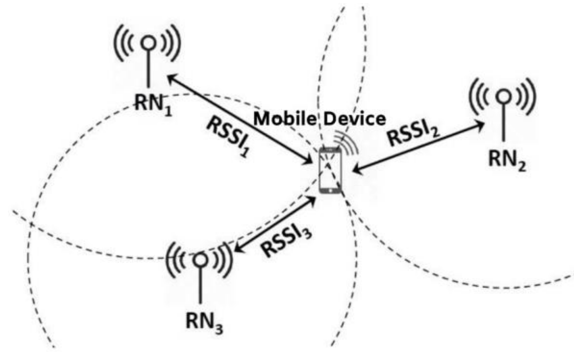

Figure 2. Localization based on RSSI [16].

The mobile device location is to be determined based on the signal strength measurements received from these base stations ($RSSI_1$, $RSSI_2$, $RSSI_3$). The RSSI values from each base station provide an indication of the signal's attenuation due to distance and obstacles. By analyzing the RSSI values received at the mobile device, the network can estimate the relative distances between the mobile device and each base station.

Triangulation is then employed to calculate the mobile device position. This technique involves drawing circles centered at each base station, with the radius of each circle determined by the estimated distance to the mobile device. The intersection points of these circles represent the potential mobile device locations, as the technique uses the known positions of the base stations (RN_1, RN_2, RN_3) and the estimated distances from each base station to refine the mobile device location.

B. Fingerprinting

Fingerprinting, also known as scene analysis-based localization techniques, is used to determine the location of a mobile device by comparing received signal characteristics, known as fingerprints, to a pre-existing database of fingerprints associated with known locations [17]. This method relies on the fact that signal propagation and behavior vary in different physical environments, creating unique patterns or fingerprints for each location.

To create a fingerprint database, measurements of signal characteristics are collected from various points within the environment. For each location where measurements are taken, a fingerprint is generated. This fingerprint represents a unique signature of the wireless signal behavior in that specific location. The fingerprint includes a set of signal parameter values that can be used to identify that particular location. The collected fingerprints, along with their corresponding known locations, are stored in a database. When a user needs to be localized, it measures the same signal characteristics (RSSI) at its current location. These measurements are compared with the fingerprints stored in the database. The system identifies the stored fingerprint that closely matches the measured values. Once a matching fingerprint is found, the associated known location from the

 ISBN: 978-1-68558-174-9

database is used to estimate the device position. This can be done through probabilistic methods, artificial neural networks, k-Nearest Neighbor, and Support Vector Machine [16].

The accuracy of fingerprinting depends on the grid size defined during a training period, with a tradeoff between accuracy and complexity. Finer grids offer higher accuracy, but require longer training periods [18]. Fingerprinting localization can provide high accuracy in scenarios with well-defined and stable environments. While fingerprinting has been traditionally associated with Wi-Fi due to the widespread availability of signals in typical indoor environments [19], it has also been utilized in 4G [20] and 5G [21] mobile networks. In the future, the increased densification of base stations in 6G networks will enhance the resolution of fingerprinting-based localization [22].

Despite its advantages in terms of accuracy and low infrastructure investment, fingerprinting has some disadvantages. It is sensitive to environmental changes [23]. A major limitation is the requirement for complex training procedures, which limits its applicability in scenarios where prior exploration is not possible or when covering large areas [22].

C. Time of Arrival (ToA)

Time of Arrival (ToA) or *Time of Flight* (ToF) is a localization technique that uses signal propagation time to calculate the distance between a transmitter TX and a receiver RX [24]. Figure 3 illustrates the application of ToA technique for determining the position of a mobile device within a mobile network. The depicted scenario involves three root nodes, also referred to as base stations (BS), labeled as RN_1, RN_2 and RN_3. As the signal reaches each base station, it is received at slightly different times due to the varying distances between the mobile device and the base stations. Figure 3 indicates these arrival times as t_1, t_2, and t_3 for RN_1, RN_2, and RN_3 respectively. The distances between the mobile device and each base station are labeled as d_1, d_2, and d_3.

To illustrate the calculation of distances using ToA, consider a transmitter TX_i and a receiver RX_j. Suppose TX_i sends a message at time t_i, which is received by RX_j at time t_j. The time taken for the signal to travel from TX_i to RX_j is denoted as t_p, where $t_j = t_i + t_p$.

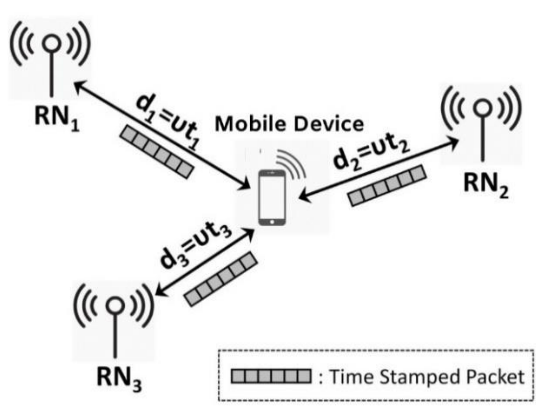

Figure 3. Localization based on ToA [16].

Therefore, the distance between TX_i and RX_j can be calculated as follows:

$$D_{ij} = (t_j - t_i) * v \quad (3)$$

where v represents the signal velocity.

D. Return Time of Arrival (RToA)

Return Time of Arrival (RToA), also known as *Return Time of Flight* (RToF), uses the time taken for a signal to propagate from TX to RX, and back to TX, to estimate the distance [24]. Similar to ToA, RToA involves a two-way signal exchange where the receiver responds to the transmitter's signal, allowing the calculation of the total round-trip time. One advantage of RToA is that it requires relatively moderate clock synchronization between TX and RX compared to ToA [16]. However, the accuracy of RToA estimation is influenced by the same factors as ToA, such as sampling rate and signal bandwidth, which can have a more significant impact since the signal is transmitted and received twice [16].

One challenge with RToA-based systems is the response delay at the receiver, which is dependent on the receiver electronics and protocol overhead. Although this delay can be disregarded in long-range systems where the propagation time outweighs the response time, it becomes significant in short-range applications, like indoor localization.

E. Angle of Arrival (AoA)

Angle of Arrival (*AoA*)-based methods use antenna arrays to estimate the angle at which the transmitted signal arrives at the receiver [6][16]. This is achieved by calculating the time difference of arrival at individual elements of the antenna array [25]. The primary advantage of AoA is its ability to estimate the location of a mobile device with only two monitors in a 2D environment or three monitors in a 3D environment [16]. Figure 4 illustrates how AoA can be used to estimate a mobile device location based on the angles at which signals are received by the antenna array. Transmitter TX emits a signal that propagates through the air towards receiver RX, equipped with an antenna array. From Figure 4, we can determine d, which represents the separation distance between TX and RX. Such a distance plays a critical role in determining the AoA at which the signal arrives at RX. This angle is denoted as θ.

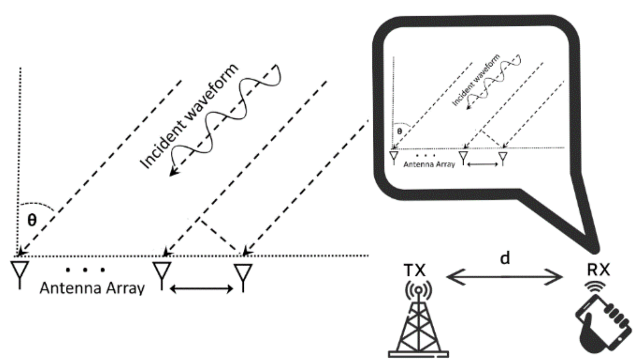

Figure 4. Localization based on AoA [16].

F. Phase of Arrival (PoA)

Phase of Arrival (PoA) based approaches estimate distance using the phase of the carrier signal [24]. They can be combined with other techniques for better localization accuracy [16]. However, they rely on line-of-sight, which is often unavailable indoors [16]. Figure 5 demonstrates the application of PoA technique in estimating the user location by analyzing the phase difference of signals received by an antenna array. It shows that when incident signals reach different antennas in an antenna array, they exhibit a phase difference. This phase difference can be used to derive the user location.

Signals emitted by the transmitters propagate through the mobile network medium and reach the mobile device. Due to the varying distances between the transmitters and the mobile device, the signals experience different phase shifts. The receiver measures the phase difference between the received signals from different transmitters. This phase difference reflects the relative time delay that the signals experienced due to their different propagation distances. As the phase difference increases or decreases, the corresponding distance between the transmitter and the mobile device changes. By comparing the measured phase differences with a reference phase, the system can estimate the distances between the mobile device and each transmitter (TX). Using the estimated distances from multiple transmitters, the user position can be determined through multilateration techniques.

G. Angle of Departure (AoD)

The Angle of Departure (AoD) localization technique is a method used to estimate the position of a mobile device by analyzing the angles at which signals are transmitted from the mobile device [26]. AoD is particularly relevant in scenarios where a mobile device is equipped with an array of antennas capable of transmitting signals in different directions [6].

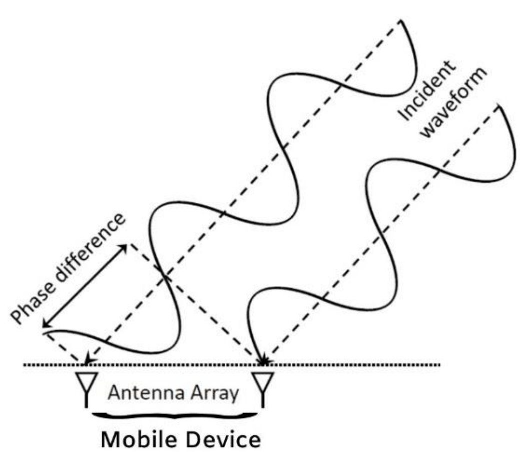

Figure 5. Localization based on PoA [16].

The fundamental principle behind AoD localization is based on the concept that the angle at which a signal departs from the mobile device transmitting antenna provides valuable information about its spatial location relative to the base stations. This information is then utilized to triangulate the position of the mobile device [6]. This involves calculating the intersection point of lines originating from the base stations at the estimated angles. The intersection point obtained through triangulation represents the estimated position of the mobile device. This position is typically provided in terms of coordinates within the coverage area [26].

AoD localization offers several advantages, including its suitability for scenarios where Line-of-Sight (LOS) conditions are prevalent, such as open outdoor environments. Additionally, it can provide high accuracy positioning in both outdoor and indoor settings. However, it may also be sensitive to obstacles and multipath propagation that can alter the angle estimation accuracy [27]. In the context of future mobile networks (*e.g.*, 6G), the AoD technique holds significant potential for improving localization accuracy [26].

H. Angle Difference of Departure (ADoD)

The *Angle-Difference-of-Departure (ADoD)* localization technique is a method used to determine the position of a mobile device based on the angles at which the signals from the mobile device are transmitted from multiple antennas. ADoD-based localization utilizes an array of antennas at the receiver side to measure the angles at which the signals arrive. By comparing the angle differences of arrival at these antennas, the system can triangulate the position of the mobile device [6]. ADoD-based localization can offer improved accuracy compared to single angle localization techniques. However, AoD information can be used to assist ADoD-based localization and estimate orientation alongside estimated positions [6].

III. CURRENT LOCALIZATION SYSTEMS AND SERVICES

In modern telecommunications, localization systems and services play a crucial role in enabling a wide array of applications that rely on precise positioning information. This section provides an overview of localization systems and services that are currently in use.

A. Ultra Wideband (UWB)

UWB technology has gained significant attention for indoor localization due to its immunity to interference from other signals [16]. Currently, this technology is primarily employed in short-range communication systems, such as PC peripherals, and various indoor applications [16]. It operates by transmitting ultra-short pulses with a duration of less than 1 nanosecond (ns) over a broad frequency range of 3.1 to 10.6 GHz. It utilizes a low duty cycle, resulting in reduced power consumption [16].

UWB signals have the ability to penetrate various materials, including walls, although metals and liquids can potentially interfere with them [16]. Additionally, the short duration of UWB pulses minimizes the impact of multipath effects, enabling the identification of the primary signal path and providing accurate Time of Flight estimation. Research has demonstrated that UWB localization can achieve accuracy levels as precise as 10 cm [28]. However, the development of UWB standards has progressed slowly, particularly in terms of its adoption as a standard in consumer products and portable devices [16].

B. Visible light positioning systems (400-790 THz)

Visible Light Positioning (VLP) systems leverage *Visible Light Communication* (VLC) technology to estimate the location of receivers by utilizing Light-Emitting Diode (LED) transmitters with known positions [6]. In indoor environments, VLP systems, coupled with the capabilities of LED technology, enable precise and reliable localization, making them an affordable solution for applications that demand compact and efficient positioning systems [29]. The potential benefits of VLP in terms of precise localization make it an attractive option for specific applications and environments where high accuracy is crucial [29]. Unlike traditional wireless systems that rely on congested, limited, and costly RF spectrum, VLP systems make use of the visible light portion of the electromagnetic spectrum, which is free from licensing and regulations [30]. This visible light spectrum enables high-speed data transmission and reduces operational costs for operators [29].

While VLP systems offer the advantage of high accuracy localization, one of their main limitations is to design a system, which like GPS, can combine the functions of data receiver and position estimation in order to provide accurate position information without accessing external databases [31]. This means that implementing VLP systems may involve significant upfront investments, including the installation of LED-transmitters and receivers, as well as the development of compatible communication protocols and algorithms.

C. mmWave Systems

With the increasing demand for higher data rates and the growing number of connected devices requiring high-precision localization, traditional frequency bands have become crowded and limited in capacity [3]. This has led to the exploration of Millimeter waves (mmWaves) as a solution to meet the ever-increasing demands. Millimeter waves are electromagnetic waves with frequencies ranging from 30 to 100 GHz [6]. These waves have wavelengths ranging from 1 to 10 millimeters [32], hence the name "millimeter waves". They use a relatively high-frequency band compared to traditional radio waves (below 30 GHz) used in wireless communications.

mmWave frequency bands were first introduced in 5G mobile networks [33]. This integration played a crucial role in achieving higher data rates, reduced latency, and improved localization accuracy [6]. It enabled a localization precision of 10 cm [1], and with the inclusion of antenna arrays at the mobile device, it becomes possible to estimate the orientation of the mobile device [34]. Moreover, by using the NLOS paths and reconfigurable intelligent surfaces (RIS), localization tasks can be accomplished using a single base station [35]. These advantages make mmWave systems highly attractive in communication networks [6].

While mmWave systems offer sufficient localization precision for many applications supported by current communication systems, they fall short in meeting the requirements of applications, such as telesurgery, extended reality, holography, connected vehicles [2]. These applications demand a higher level of location accuracy, typically within the range of 1 cm [3]. To fully realize the potential of these applications and pave the way for new ones to emerge, the utilization of higher frequency bands becomes necessary.

D. THz Localization

With the advancement of highly precise positioning capabilities, there is a belief that THz frequency bands (0.1-10 THz) are gaining attention for high-speed transmissions and high accuracy positioning [3]. The integration of these bands has the potential to fulfill the demands of applications that require both high data rates and high localization accuracy, surpassing the capabilities of current communication systems. The IEEE 802.15.3d standard has already proposed the use of sub-THz frequencies, pushing the signal frequency from 73 GHz to 300 GHz, and the bandwidth from 2 GHz to 69 GHz [6].

While THz systems offer advantages, such as higher frequencies, larger bandwidths, and improved localization performance, they also present challenges in hardware design, coverage, overheads, and computational complexity. As compared to 5G mmWave, 6G THz systems are expected to deliver enhanced localization performance.

IV. 6G-Compatible Simulation Tools

This section provides an overview of the following 6G-compatible simulators: *Aff3ct* [36], *CloudRT* [37], *Matlab* [38], Terasim [39], *NYUSIM* [40][41]. We will highlight their strengths and limitations in the context of 6G localization. Based on this evaluation, we will select the most suitable simulator for the upcoming results.

A. Aff3ct

AFF3CT is a free open-source toolbox for Forward Error Correction (FEC) that includes a simulator and a library written in C++ [36]. The toolbox can effectively emulate physical layer behavior for simulation purposes. However, we have observed that AFF3CT does not simulate the entire THz system. Specifically, AFF3CT is more focused on the physical layer, only implementing digital channels without any waveform generation. Therefore, the ability to analyze signal and waveform-related effects on data transmission is limited.

Additionally, AFF3CT fails to consider a range of propagation effects, such as the ground nature, weather, polarization, human blockage, barometric pressure, humidity, and foliage attenuation. Although AFF3CT provides high throughput simulations with multi-node, multi-threaded, and vectorization paradigms, the results obtained are limited since the simulator does not consider the complete communication system scenario.

B. CloudRT

CloudRT is an open-source Ray Tracer simulator that can be accessed via the platform (www.raytracer.cloud). This platform has three main libraries: the Environment library, Material library, and Antenna library [37]. The Environment library contains 3D models of environments for Ray Tracing simulation, and users can upload and manage their models through the platform's web user interface. The Material library stores different material parameters required for different propagation models, including dielectric parameters, transmission loss, scattering coefficients, and equivalent roughness. The Antenna library provides information on various types of antennas, and users can create and upload their antenna radiation patterns to the library.

However, CloudRT has some limitations. It does not consider essential parameters, such as human blockages, polarization, rain rate, and barometric pressure, which could affect the simulation results. Therefore, the provided scenario may be insufficient for localization simulation.

C. Matlab

Matlab is a robust and useful tool that has been widely utilized in communication systems for various simulations due to its communication toolbox. The toolbox offers an extensive range of signal processing functions, including standard-compliant waveform filters, multi-carrier systems, statistic channel models, and antenna systems [38]. However, Matlab has limitations, as it does not fully support THz communication systems. This means that Matlab's 5G toolbox needs to be adapted to 6G mobile networks. Moreover, since Matlab is a closed platform with an extra license requirement, users have limited insight into specific realizations of algorithms and applications.

D. Terasim

Terasim is a system-level simulator that fully supports THz frequencies [39]. It is an extension of NS-3, with data transmission modeled at a packet level, and the successful reception of packets is determined by the received power. While Terasim considers some useful parameters, such as molecular absorption, it neglects essential parameters, such as human blockages, temperature, barometric pressure, humidity, polarization, foliage, among others. Additionally, the realization of signals in Terasim is limited to the consideration of power density spectra, which means that the effects of inter-symbol interference or multipath propagation cannot be examined. As a result, Terasim is inadequate for localization purposes.

E. NYUSIM 4.0

NYUSIM is an open source, system level simulator based on Matlab that supports millimeter and Sub-THz bands ranging from 0.5-150 GHz [40][41]. Unlike other simulators mentioned earlier, NYUSIM is advantageous because it considers a wide range of parameters, including 21 channel parameters, 12 antenna properties, 10 spatial consistency parameters and 6 human blockage parameters. These parameters are critical in demonstrating and clarifying the proposed approach for 6G localization. Also, NYUSIM has been developed based on extensive real-world measurements [40] at multiple mmWave and Sub-THz frequencies, over 2 terabytes of measurement data from 28 to 142 GHz in various environments obtained during 2011 and 2022 [42]. As of 2022, NYUSIM is widely used by industry and academia as an alternative to 3GPP Spatial Channel Model. In this context, we have chosen NYUSIM for our simulations.

V. A 6G-BASED APPROACH

The proposed approach is based on AoD localization technique, and is tailored for real-world scenarios, where signal variations are introduced due to environmental factors, such as reflection, diffraction, and scattering. In this section, we frequently use the term Transmitter (TX), which refers to a Base Station (BS), and the term Receiver (RX), which refers to a mobile device. To determine the localization coordinates of RX, we rely on the concept explained in [26]. To initiate this process, the knowledge of three key parameters is required: the distance d_{ML} between TX and RX at a particular point, the AoD β at the TX side, as well as the x and y location coordinates of TX, represented as x_{TX} and y_{TX} respectively, as illustrated in Figure 6.

Since TX remains stationary and acts as the reference point positioned at coordinates (0, 0), we need the values of d_{ML} and β to obtain coordinates x and y of RX. In this scenario, the following formulas can be used:

$$x_{RX} = d_{ML}cos(\beta) \tag{4}$$

$$y_{RX} = d_{ML}sin(\beta) \tag{5}$$

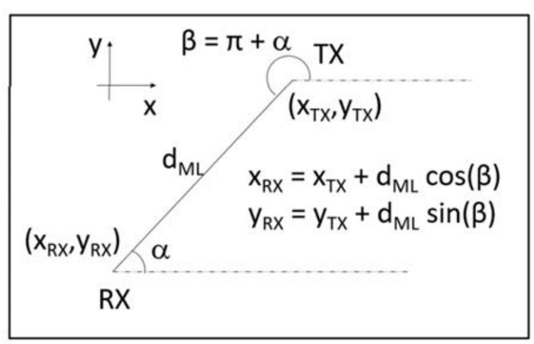

Figure 6. Calculation of mobile device localization coordinates [26].

where x_{RX} is the x localization coordinate of RX, y_{RX} is the y localization coordinate of RX, d_{ML} is the distance between TX and RX at a particular point, β is the AoD at the TX side.

There is an alternative method to calculate x_{RX} and y_{RX} from α, when α is provided. This can be achieved by using the following formulas:

$$x_{RX} = d_{ML}cos(180° + \alpha) \quad (6)$$

$$y_{RX} = d_{ML}sin(180° + \alpha) \quad (7)$$

where α is the AoA at RX and d_{ML} is the distance between TX and RX at a particular point.

Since 6G communication systems will operate at THz frequencies [1], the proposed approach integrates AoD localization technique into *THz localization* in order to achieve high-precision user terminal localization.

VI. Implementation and Results

A. Simulation setup

By using NYUSIM 4.0 [40][41] for setting up the simulation environment, parameters, such as building layouts, street configurations, and environmental conditions, are considered. Also, based on real weather data, parameters, such as rain rate, humidity, and temperature, will be set to accurately model the effects of weather on the localization performance. The placement of BS, mobile device, and other relevant elements is carefully determined to mimic the actual deployment scenarios in Downtown Quebec City. Additionally, the mobility patterns of users, such as walking speed and trajectories, are adjusted to match typical pedestrian movements in the chosen area. This ensures that the simulations accurately reflect real-world scenarios and enable to draw meaningful insights about the performance of 6G localization systems in a location-specific context.

Using NYUSIM 4.0 [40][41], we perform simulations for two different scenarios: Simulation 1 (which implements scenario 1) emulates a 5G mobile network using a frequency of 28 GHz and a bandwidth of 800 MHz, whereas simulation 2 (which implements scenario 2) emulates a 6G mobile network using the frequency of 142 GHz and the bandwidth of 1000 MHz to replicate a 6G mobile network. To ensure that the simulations will produce meaningful and applicable results, we carefully tailor each scenario to match the conditions and characteristics of a specific area in Downtown Quebec city.

As shown in Figure 7, the simulations take place for each scenario along two streets, Cook Street (located in front of the ministry of municipal affairs and housing) and Dauphine Street, each covering a distance of 40 meters. More specifically, the simulations replicate a pedestrian's walk from Cook Street (Point A to B) and then, upon reaching point B, make a left turn onto Dauphine Street (Point B to C).

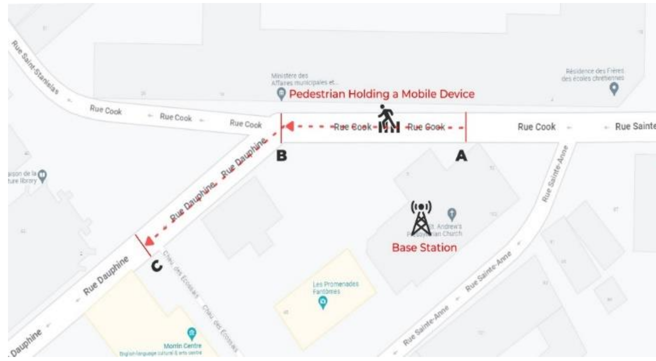

Figure 7. Trajectory of a pedestrian moving from A to C with a mobile device.

The moving distance is set to 80 meters, representing the total distance the user can travel along the path. Throughout the walk, we continuously track and locate the pedestrian, gathering valuable data for analysis. In particular, the corresponding x and y coordinates along this path are recorded.

For each scenario, the stationary BS is located at point (0, 0), serving as the reference point for the measurements. More specifically, it is placed on the rooftop of St. Andrew's Church, with a total height of 35 meters, considering the presence of trees and buildings that create NLOS scenarios. Since the mobile device will be held by a moving pedestrian, we set the mobile device height to 1.5 m from the ground, assuming the pedestrian will use his mobile phone while traveling at a velocity of 1 m/s along the path. Since only one pedestrian is involved in the simulation at a time, the number of RX locations was set to 1. Other environmental factors, such as barometric pressure (1013.25 mbar), humidity (50%), and temperature (20 degrees Celsius), are also set to realistic values. As there is no rainfall in this scenario, the rain rate is set to 0 mm/hr. These carefully selected simulation parameters ensure a realistic representation of the chosen environment and facilitate the collection of relevant localization data for our analysis.

B. AoD Measurement

Since the proposed approach is based on AoD localization technique, it is important to measure this angle in order to get precise localization values. Figures 8 and 9 demonstrate the procedure for extracting the AoD for simulation 1 and simulation 2, respectively. Such a procedure involves using wepik, an online graphic editor, to trace a line between the BS and a specific point to determine the rotation angle of the line. To obtain the AoD, we subtract the rotation angle from 180 degrees. Moreover, when the resulting rotation angle exceeded 180 degrees, we obtained the AoD by subtracting 180 degrees from the obtained rotation angle. This approach improved the accuracy of angle extraction process.

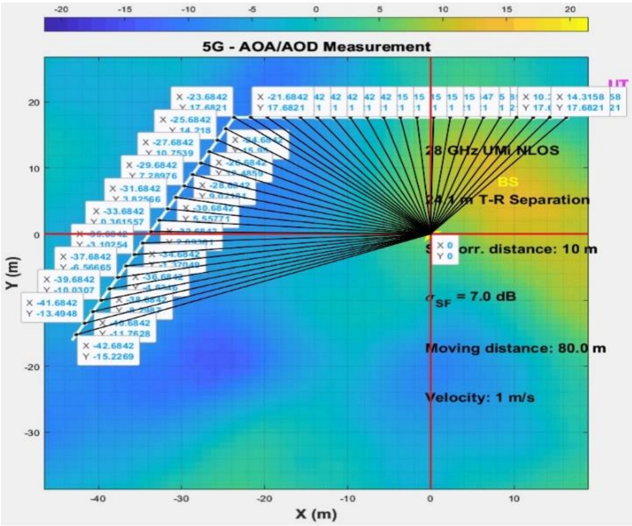

Figure 8. Measurement of AoD for 5G mobile network.

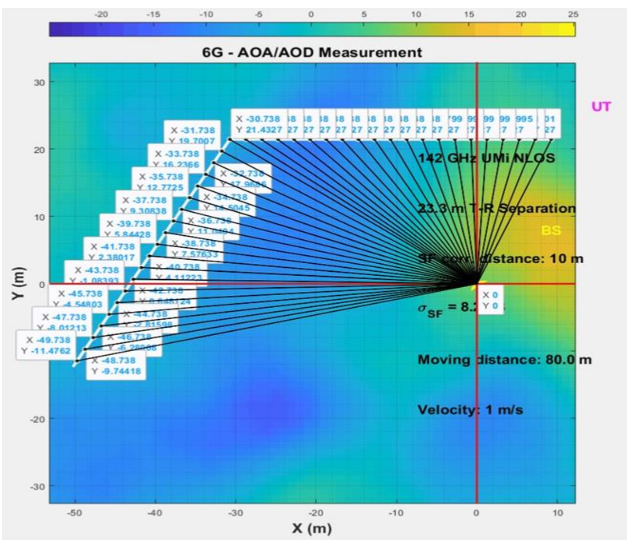

Figure 9. Measurement of AoD for 6G mobile network.

Figures 8 and 9 display various *x* and *y* localization coordinates of the mobile device, generated by NYUSIM during the simulations.

C. Evaluation of localization error

The localization error represents how accurately the NYUSIM localization algorithm can track and estimate the pedestrian position while they walk along the trajectory. It measures the discrepancy between the position obtained from the proposed approach and the position obtained from the simulation tool. As a result, it provides valuable insights into the accuracy and performance of the localization system, and it reflects the level of deviation between the actual path taken by the pedestrian and the path estimated by the simulations. A lower localization error indicates a higher accuracy in positioning, while a higher error suggests a less accurate estimation of the pedestrian location.

To calculate the localization error at a specific point, we take the (x, y) coordinates obtained from the simulation tool, and compare them with localization coordinates (x_{RX}, y_{RX}) obtained from the proposed approach. More specifically, we calculate the localization error, first on the *X*-axis, then on the *Y*-axis. This decision enables to separately examine and analyze the localization error on both *X* and *Y* axes, which helps better understand the factors contributing to the deviation in the *x* and *y* coordinates and gain a more detailed understanding of the localization accuracy.

The localization error x_E on the *X*-axis can be calculated as follows:

$$x_E = x - x_{RX} \tag{8}$$

where *x* is the localization coordinate on the *X*-axis obtained from the NYUSIM simulation tool, and x_{RX} is the localization coordinate on the *X*-axis obtained from the proposed approach. Similarly, the localization error on the Y-axis y_E can be calculated as follows:

$$y_E = y - y_{RX} \tag{9}$$

where *y* is the localization coordinate on the *Y*-axis obtained from the simulation tool, and y_{RX} is the localization coordinate on the *Y*-axis obtained from the proposed approach.

By comparing the localization errors between different simulations (5G vs 6G scenario), we can evaluate the performance and effectiveness of the localization techniques in each scenario, in terms of localization accuracy at different points along the trajectory. We observed that the mean localization error for 6G mobile network is smaller, indicating that the estimated positions from the 6G simulation is closer to actual positions of the pedestrian than the positions estimated in the 5G simulation. More specifically, the mean localization error along the X-axis for the 5G mobile network is 4.71 cm, while 6G mobile network achieves a significantly reduced mean localization error of 0.27 cm. Similarly, along the Y-axis, the 5G mobile network has a mean localization error of 4.57 cm, while the 6G mobile network excels with a small mean localization error of 0.64 cm. Such results are summarized in Table 1 and show that the incorporation of THz frequency bands in 6G mobile networks has the potential to significantly improve localization accuracy, and opens up new possibilities for various applications and services that rely on precise positioning information.

TABLE I. SUMMARY OF THE MEAN LOCALIZATION ERRORS FOR 5G AND 6G MOBILE NETWORKS

Mean localization error	5G mobile network	6G mobile network
X-Axis	4.71 cm	0.27 cm
Y-Axis	4.57 cm	0.64 cm

VII. Conclusion

In this paper, we propose an approach which combines the AoD technique with THz localization for localizing mobile devices in future wireless networks. The simulation environment is set up by using NYUSIM 4.0. Simulation results show that, for a given trajectory, 6G mobile networks outperform 5G mobile networks in terms of mean localization errors. By providing such accurate positioning and navigation capabilities, the proposed approach enables to realize the full potential of future mobile networks while addressing an aspect that may significantly impact various sectors, including healthcare, industrial automation, agriculture, emergency response, public safety, as well as disaster management.

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