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5G Coverage Mapping with UWB Indoor Positioning

School of Technology and Innovation
Master's thesis in Technology
Master's Program in Smart Energy

Vaasa 2025

UNIVERSITY OF VAASA
School of Tecnhology and Innovations
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Title of the Thesis: 5G Coverage Mapping with UWB Indoor Positioning :
Degree: Master of Science in Technology
Programme: Smart Enery Master's Thesis
Supervisor: Petri Välisuo,
Instructor: Mohammed Elmusrati
Year: 2025
Number of Pages: 57

ABSTRACT:

This study investigates the use of 5G coverage mapping and signal strength assessment and UWB-based indoor positioning systems. With the widespread use of 5G networks, accurate measurement of signal strength and coverage has become critical for network optimization and improving service quality. In this context, 5G network performance was evaluated using basic signal measurement parameters such as RSSI, RSRP and RSRQ in the study. The data collection process was carried out using Android-based mobile devices and UWB (Ultra Wide Band) positioning technology. The collected signal strength data was processed and visualized via the Node-RED platform. In addition, low bandwidth consumption, energy efficiency and reliable data transfer were achieved by preferring the MQTT protocol. The obtained results show how 5G signal strength is distributed in indoor environments. The study provides data for the optimization of 5G networks and can form a basis for future machine learning-based signal optimization and multi-floor coverage mapping studies.

KEYWORDS: 5G Networks, Mobile Communications, Indoor Positioning, Coverage Map, UWB

Acknowledgements

I would like to express my sincere gratitude to all those who supported me in completing this thesis.

First and foremost, I want to give my heartfelt thanks and love to my beloved soulmate, Burcin, who has always been by my side and provided me with support during this entire process.

I would also like to remember and honor my dear dog, Ece, who I lost while writing this thesis. She was a loyal companion and a source of comfort, and her memory will always remain in my heart.

I extend my sincere thanks to my supervisor Petri Välisuo for his guidance and mentorship throughout both the project and the thesis writing process. His advices were significant in forming my work, and I am grateful for his support. I would also like to extend my respect and gratitude to all the other professors who have helped me during this journey.

Finally, I would like to express my appreciation to Jyri Nieminen for his assistance and friendship. His willingness to help me at every stage of the process made a difference.

Contents

1 Introduction 8
1.1 Purpose of this Thesis 11
1.2 Structure of Paper 12
2 Literature Review 13
2.1 5G in Industry 14
2.2 Internet of Things Applications and 5G 14
2.3 Indoor Positioning Systems 15
2.3.1 Ultra-Wideband (UWB) system 18
2.3.2 Bluetooth Low Energy (BLE) 22
2.3.3 Wi-fi Positioning System (WPS) 23
2.4 Mobile Application Development 24
2.4.1 Mobile Application Development Languages 24
2.5 Communication Methods 25
2.5.1 Hyper Text Transfer Protocol (HTTP) 26
2.5.2 Message Queuing Telemetry Transport (MQTT) 27
2.5.3 Advanced Message Queuing Protocol (AMQP) 29
2.5.4 Constrained Application Protocol (CoAP) 30
3 Methodology 32
3.1 Collecting Signal Data 33
3.1.1 Signal Data 33
3.1.2 Mobile Application 35
3.1.3 Data Logging Server 38
3.1.4 Sending Data via MQTT Protocol 40
3.2 Indoor Position Data 43
3.2.1 Collecting Position Data 44
4 Results 46
4.1 Raw Data 46

4.2 Scatter Plot of the Data 46

4.3 Gaussian Filter 47

4.4 Heat Map 48

5 Conclusion 50

References 52

Figures

Figure 1. The importance of key capabilities in different usage scenarios (ITU, 2015).... 8
Figure 2 (Comparison of Indoor Positioning Systems, Qorvo,..... 16
Figure 3 ToF messaging between Tag and Anchor..... 20
Figure 4 Finding Tag position with ToF 21
Figure 5 Publish subscribe model..... 28
Figure 6 Message Transmissions in Quality of Service Levels (Lee et al, 2013) 29
Figure 7 UDP Protocol..... 31
Figure 9. Nodered Server..... 40
Figure 8. Screenshot of UWB setup from DRTLS manager app..... 45
Figure 10. Scatter Plot of the raw Data on the map of Technobothnia..... 47
Figure 11. Heat Map 49

Tables

Table 1. Comparison 3G 4G and 5G (Ezhilarasan, E., & Dinakaran, M.,2017) 9
Table 2. RF Conditions 35
Table 3. Output Data..... 46

Abbreviations

5G	Fifth Generation Mobile Network
AI	Artificial Intelligence
AMQP	Advanced Message Queuing Protocol
BLE	Bluetooth Low Energy
CQI	Channel Quality Indicator
CoAP	Constrained Application Protocol
dBm	Decibels Milliwatt
D2D	Device-to-Device Communication
DTLS	Datagram Transport Layer Security
ICT	Information and Communication Technology
IoT	Internet of Things
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
QoS	Quality of Service
RSSI	Received Signal Strength Indicator
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSNR	Reference Signal Signal-to-Noise Ratio
SCADA	Supervisory Control and Data Acquisition
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UWB	Ultra-Wideband

1 Introduction

The rapid development and requirements of wireless communication technologies has led to the deployment of fifth-generation (5G) networks. The end-user experience has become almost identical to wired connections since the introduction of 4G wireless network services, which have allowed users to access broadband services using their mobile devices (such as smartphones and tablets) (Yi 2017). However it was not enough to meet the industry demands.

The leap from 4G to 5G networks parallels the transformation from spreadsheets to robotics within industrial factories, incorporating the Internet of Things (IoT), artificial intelligence, and machine learning technologies. 5G technology provides additional features such as ultra-reliable low latency communication and enhanced mobile broadband, paving the way for innovation while enabling smart factories and industry 4.0 applications (Aijaz, 2020).

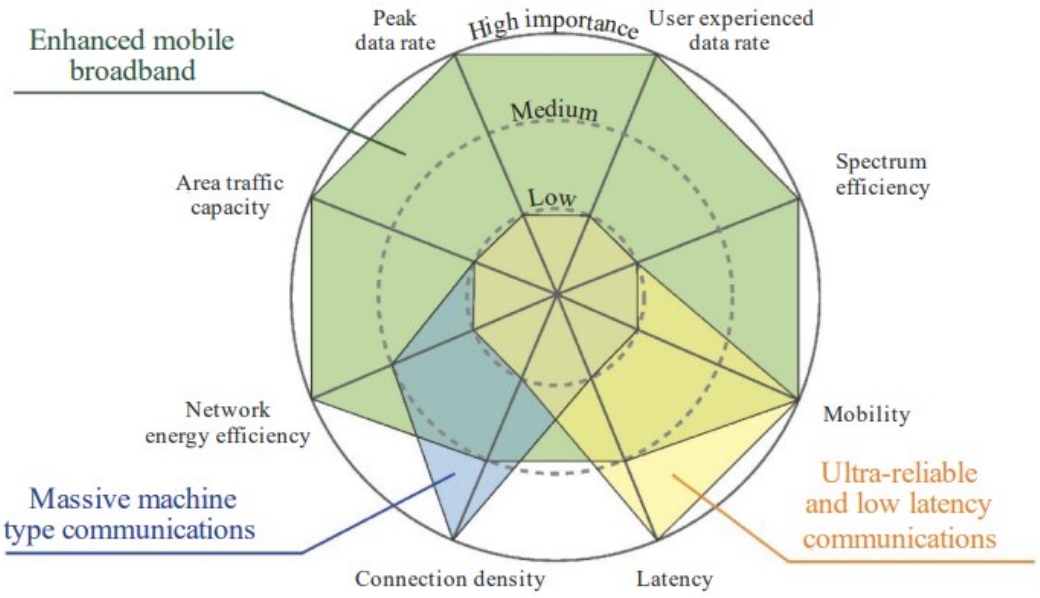

Figure 1. The importance of key capabilities in different usage scenarios (International Telecommunation Union, 2015)

The objective of 5G is to be more widely available at high speeds and with lower latency than 4G. While 4G has a latency rate of over 50 milliseconds, 5G reduces latency to roughly one millisecond. With 5G, transmission speeds will reach 20–30 Gbps, which is 50 times faster than 4G networks (Dahiya, 2017). 5G is poised to considerably change various sectors like telecommunications, health care, transportation and others by its exceptional speed, ultra-low latency and massive connectivity.

Table 1. Comparison 3G 4G and 5G (Ezhilarasan, E., & Dinakaran, M.,2017)

Features	3G	4G	5G
Date	2002	2010	2015
Standards	WCDMA,CD MA2000	OFDMA,MC-CDMA	CDMA,BDMA
Network architecture	IP technology and Broad bandwidth CDMA	combined IP and Combination of broad band standards like LAN,WAN,WLA N,PAN	combined IP and combination of broadband standards like LAN,WAN,PANW LAN and WWWW
Data rate	2 Mbps	2Mbps to 1Gbps	1Gbps & higher
Frequency	1.8 to 2.5 GHZ	2-8 GHZ	3-300GHZ
Core type network	Packet network	All IP network	Flatter IP network & 5G network Interfacing(5G-NI)

However, transitioning to new technologies involves navigating novel functionalities and unexpected obstacles. Therefore, prior to upgrading to 5G networks, a smart understanding of available coverage and requirements is crucial to ensure seamless deployment.

Coverage maps are critical in industrial environments because they provide a visual representation of the network's signal strength and coverage across a facility. In mis-sion-critical operations, ensuring reliable and consistent network connectivity is essential for safety, productivity, and operational efficiency. For instance, SCADA (Su-pervisory Control and Data Acquisition) systems, remote monitoring, and industrial automation

depend on reliable connectivity. A coverage map ensures that all critical areas of a facility, including production lines, warehouses, and control rooms, have sufficient network coverage to support these applications. By identifying weak or dead zones, businesses can take corrective actions (e.g., adding additional access points) to prevent downtime or data loss in areas crucial to operations. Moreover, Industrial Internet of Things (IoT) devices, such as sensors and automated machinery, must be connected at all times to provide real-time data and control. Coverage maps help identify the best locations to place IoT devices and ensure that network resources are optimized across the factory floor.

Traditional signal analysis methods for mapping network coverage generally rely on dedicated hardware and specialized measurement tools that can be prohibitively expensive. These methods typically use spectrum analyzers, network analyzers, or dedicated signal mapping devices (Michal, 2023). These tools are designed to provide precise measurements of signal strength, signal-to-noise ratios, and other performance metrics across different frequencies, however costs are high due to the advanced technology and its precision. In addition, setting up and maintaining these devices require trained personnel, further increasing operational costs.

For large-scale industrial environments, the deployment of such hardware is not only expensive but also resource-intensive, as it requires significant time for installation, calibration, and data processing. Furthermore, these tools are not always practical for continuous monitoring in dynamic environments, where network conditions can fluctuate due to changing layouts or equipment positioning. As a result, smaller organizations or those running pilot projects may find these traditional methods too costly and impractical for their specific needs.

By contrast, the use of low-cost alternatives, such as mobile devices with custom applications, offers a more accessible solution for collecting and mapping 5G signal strength. Modern smartphones are equipped with the necessary hardware (e.g., high-quality antennas and GPS) to measure signal strength and log positional data, making them a

worthwhile alternative for preliminary studies or low-budget projects. This approach democratizes access to network analysis and allows smaller companies to conduct essential network mapping without the financial burden of high-end equipment. Moreover, mobile-based solutions are easier to deploy and more flexible for real-time and continuous monitoring in dynamic environments.

The project to map the coverage entailed gathering signal strength through an android telephone which acted as a mobile sensor taking on measurements of signals at different points. This data collection process provides valuable insights into the performance of the network, identifying areas where there might be coverage gaps or places where signal strength may require improvement.

The project was not only concerned with coverage mapping but also involved work towards indoor positioning using Decawave UWB devices. Within building, indoors positioning technologies enhance location-based services due to lack or weakness of GPS signals. Through utilizing UWB technology providing high-precise range and position estimation opportunities this project endeavored to securely determine location of users or objects within building environment by collecting signals' data.

1.1 Purpose of this Thesis

This study investigates the low cost way to identify coverage through Technobotnia collect the 5G signals, which is broadcasted from 5G Lab. 5G signal strength data is obtained by android mobile phone with custom mobile application, position data is obtained with indoor positioning system simultaneously and analyzed with python software.

During this project, it is possible to see the signal changing due to obstacles and how it is affected.

1.2 Structure of Paper

This thesis contains five parts, each of which sequentially explains the topic, starting from its background to the conclusion.

Part 1 – Introduction

The study background is briefly described at the beginning of this chapter, which then goes on to explain the main research objectives. It also contains the definitions of the major research terms, study limitations, and the processes.

Part 2 – Literature Review

This part includes detailed literature reviews of 5G networks, communication methods and indoor positioning systems.

Part 3 – Methodology

This part explains the applications and software used for this specific study to obtain required data for the research process and the reasons why these methods are selected.

Part 4 – Results

This part answers the research questions and explains the results obtained using the methods described in the previous chapter.

Part 5 - Conclusion

This part concludes the study and presents a summary of the findings based on the goals of the research.

2 Literature Review

The journey of mobile communication began with 1G in the 1980s, which introduced analog voice calls. The 1990s saw the rise of 2G, enabling digital voice and basic data services like SMS. The early 2000s 3G, providing higher data speeds and internet access. 3G allows users to browse the web use e-mail services and multimedia messaging (Karjaluoto, 2006). The 2010s were dominated by 4G, which revolutionized mobile internet with high-speed data and seamless streaming.

Future 5G services are expected to evolve in various directions, enabling ultra-fast data transmission, massive device connectivity, and the integration of new small-scale technologies, particularly sensors. This advancement will be driven by innovations such as 360-degree videos, holograms, machine-type communications, and smart transportation. Beyond personal communications, 5G will have widespread applications in areas like wearable technology, autonomous vehicles, robotics, sensors, actuators, and mobile devices. As a result, 5G networks can be seen as a fundamental infrastructure for the growth of the ICT industry and the advancement of technological innovation in society.

5G is not limited with speed and latency connectivity. Network slicing is another feature in 5G networks. Network slicing enables the separation of a physical network infrastructure into multiple virtual network segments (slices) that serve various groups of users or applications. Each slice can be configured and managed according to a specific quality of service (QoS), security level, and other requirements. This makes it possible to provide flexible and efficient network services suitable for different usage scenarios on the same physical network (Foukas et al. 2017). Customized network slices can be created according to the needs of different applications (Zhang, 2019). For example, one slice can provide low latency and high reliability for IoT devices, while another can be optimized for video streams that require high bandwidth.

2.1 5G in Industry

The improvement in 5G technology is important in dynamic telecommunications today since it has a potential to change industries like health care, transport and entertainment. It is one of the main reasons that make it unique among others as it can offer fast connections that are reliable and at the same time significantly lower latency than previous generations (Neumann et al., 2018). This expansion has been particularly beneficial for industrial applications by allowing machine-type communication with high reliability over low latencies in Industrial 4.0 or IoT contexts. This could potentially be easily utilized by connecting various wireless networks bridging Ethernet backhaul for greater RF coverage and higher data rates. When deploying a network, it becomes essential to accurately map indoor coverage to ensure consistent telecom experience for users across all connected devices including smart homes and wearables through heterogeneous wireless networks thus realizing these cutting-edge technologies' fullest potentials.

2.2 Internet of Things Applications and 5G

The Internet of Things (IoT) is a large ecosystem of interconnected and uniquely identified devices. These devices continuously collect data using standard communication protocols, transmit it to central systems, and store, process, and analyze this data. The integration of 5G technology and IoT has increased efficiency in many sectors such as healthcare, transportation, security, agriculture, and infrastructure, and has enabled real-time monitoring, automation, and intelligent decision-making processes.

The application of 5G in the IoT ecosystem offers unique advantages such as high data transmission speeds, ultra-low latency, and the ability to connect a large number of devices simultaneously. These developments have made 5G an ideal infrastructure for applications requiring instant data processing and high network reliability. In addition, advanced techniques such as Device-to-Device (D2D) direct communication and network slicing enable 5G-supported IoT systems to operate more flexibly and efficiently.

However, the integration of 5G into IoT networks also brings with it some technical and operational challenges. In order for the 5G infrastructure to be fully compatible with the IoT, issues such as uninterrupted connection management, data security between devices, and spectrum efficiency need to be addressed. In particular, high data density scenarios, applications requiring low latency, and the need for reliable communication are among the main factors shaping the solutions offered by 5G for the IoT.

In addition, new technologies such as multi-layer network architectures, edge computing integration, and autonomous systems are increasingly being used in 5G-supported IoT systems. These developments are leading to major transformations not only for industrial and corporate applications, but also in large-scale areas such as smart cities, healthcare systems, and energy management. The combination of IoT with 5G will enable connected devices to work smarter, faster, and more efficiently in the future, thus accelerating digital transformation and automation and leading to radical changes in many sectors.

2.3 Indoor Positioning Systems

Indoor Positioning Systems (IPS) consist of technologies developed to determine location in indoor areas where GPS is inadequate or completely disabled. access to accurate and reliable location information in indoor areas has become critical in today's world with demand for connectivity and digitalization. In large and complex indoor areas such as shopping malls, airports, hospitals, industrial facilities, IPS systems enable people, objects, and devices to be effectively monitored and directed.

Indoor positioning technologies include methods such as radio frequency, Bluetooth, Wi-Fi, infrared sensors and computer vision (Magda & Nel, 2009). Modern IPS technologies can measure with centimeter precision. These systems make it possible to track the current locations of active devices and users in real time, especially in large and complex

structures. This is extremely useful for routing and security purposes in areas such as large shopping malls, airports, and hospitals (Klaithem & Hesham 2011).

Hata! Başvuru kaynağı bulunamadı.2 compares the performance of indoor positioning technologies across various criteria. The technologies include UWB (Ultra-Wideband), Bluetooth, Wi-Fi, RFID, and GPS, and each is evaluated for its area of use, accuracy, reliability, range, data communication, security, latency, scalability, power consumption, and cost.

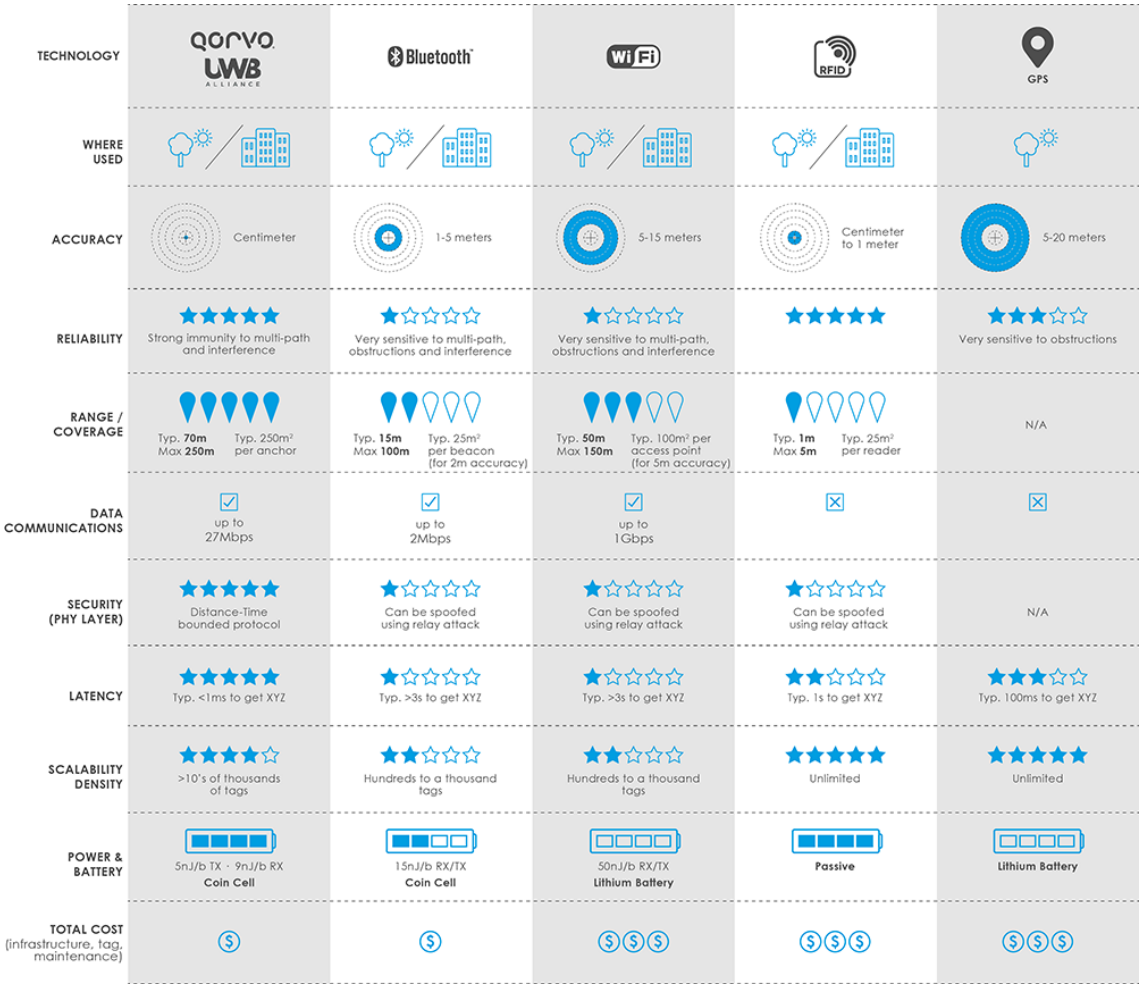

Figure 2 (Comparison of Indoor Positioning Systems, Qorvo, https://www.qorvo.com/innovation/ultra-wideband/technology, 2025**)**

UWB and Wi-Fi are the most used technologies, especially in indoor applications. Bluetooth offers a low-cost and easy-to-implement alternative in indoor areas, while RFID is generally preferred in small areas such as object tracking. GPS is more commonly used in outdoor areas due to its reduced accuracy and signal strength in indoor areas.

In terms of accuracy, UWB and RFID demonstrate the best performance by achieving centimeter-level precision. Bluetooth and Wi-Fi can provide accuracy within 1 to 15 meters, which may be sufficient for certain applications. GPS offers accuracy between 5 to 20 meters in open areas.

Regarding reliability, UWB is highly resilient to obstacles such as multipath propagation and does not experience signal loss. Multipath propagation happens when a signal travels from a source to a receiver along multiple paths due to reflection, and scattering caused by obstacles. In contrast, Bluetooth and Wi-Fi are more susceptible to issues like signal reflections and interference. The reliability of RFID is generally more consistent in short-range usage.

When evaluated in terms of range, UWB stands out with a broad coverage area ranging up to 250 meters. Bluetooth offers effective performance at shorter ranges (max 100 meters). Wi-Fi typically has a coverage area up to 150 meters. While RFID offers a limited range of only a few meters, GPS provides a wider range in open areas, but its usage is limited indoors.

In terms of data communication, Wi-Fi and UWB excel in high-speed data transfer, making them prominent in advanced applications. Bluetooth can provide data transfer up to 2 Mbps, making it adequate for mid-level applications. RFID does not facilitate data transfer and is used solely as a passive tracking solution.

IPS facilitates navigation, especially in complex interiors, by providing position information that can be used to show how users should be guided in each space by creating

navigation maps. It can also help security teams quickly locate people and equipment during emergencies, helping to create an effective evacuation plan in the event of a fire, earthquake, or other emergencies.

In interior spaces, efficiency can be increased in processes such as transportation, inventory management, and personnel tracking. In warehouses and logistics areas, employees and materials can be located more quickly and accurately, increasing operational efficiency. In addition, IPS allows users to be provided with personalized recommendations or offers based on their location. For example, special discounts can be shown to users near a store in shopping malls.

Location data can also be used to save energy. Smart lighting and air conditioning systems can reduce the energy consumption of buildings by automatically dimming empty rooms in interior spaces or optimizing temperature control. IPS can also facilitate the tracking of patients, staff and equipment in healthcare institutions, helping to locate medical equipment in the right place and monitor the condition of patients.

Finally, indoor location data is also important for space management. By analyzing the use of spaces such as office spaces, meeting rooms or warehouses, more efficient space planning can be achieved. In addition, understanding which areas are used more intensively or which paths are preferred allows for better optimization of space.

2.3.1 Ultra-Wideband (UWB) system

UWB (Ultra-wideband) is a high-bandwidth radio frequency technology. It is used in short-range and high-accuracy positioning systems, especially indoors. UWB offers significantly higher accuracy than traditional RF-based systems, with the ability to make precise distance measurements in milliseconds. Therefore, UWB technology has significant application potential, especially in areas such as industrial automation, healthcare, smart buildings and logistics.

UWB technology covers a wide frequency band (between 3.1 GHz and 10.6 GHz) and operates at very low energy levels. This allows the system to provide high data rates and precise distance measurements while maintaining low power consumption. UWB signals spread over a much wider spectrum than traditional narrow-band systems. UWB (Ultra-Wideband) systems transmit data over a wide frequency band with short-duration pulses. This technical structure allows interference from multipath effects generally becomes insignificant in UWB systems (Sandeep et al., 2005). UWB signals provide a clearer temporal separation of incoming signals due to their very short duration. The wide-band structure reduces interference by distributing the effects of phase shifts caused by different path lengths. UWB receivers can detect very precise timing differences in signals. The receiver can analyze signals coming from different paths separately and select only the strongest signal.

In UWB (Ultra-Wideband) technology, ToF (Time of Flight) and TDoA (Time Difference of Arrival) are the two basic methods used for determining distance and location.

ToF calculates distance by measuring the time it takes for a signal to travel from a source (for example, a transmitter) to a receiver. The transmitter sends out a UWB signal. The receiver detects the signal and records how long it took.

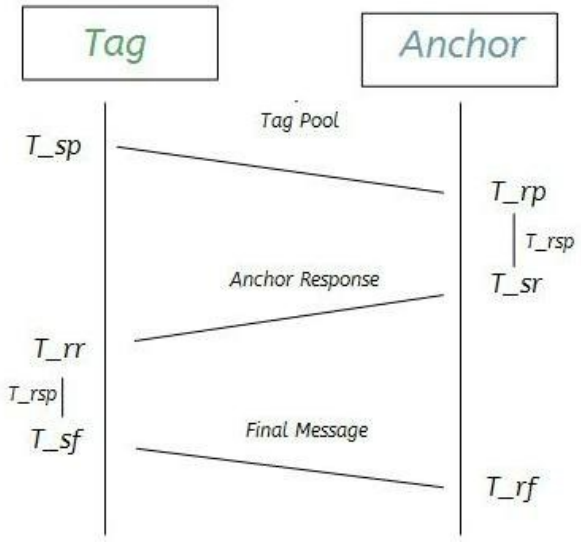

Figure 3 ToF messaging between Tag and Anchor

A tag initiates communication by sending a poll packet and recording the timestamp as Tsp (Time Start Poll). Upon receiving this packet, the anchor logs the event with Trp (Time Receive Poll). The anchor then processes the signal and prepares a response packet, with this process being marked by Trsp. Once ready, the anchor transmits the response, recording Tsr (Time Start Response).

The tag receives the response packet and timestamps it as Trr (Time Receive Response). After processing the signal and preparing a final message, the tag logs this process with Trsp and sends the final message, noting the transmission time as Tsf (Time Start Final). Finally, the anchor receives the final message and records the timestamp as Trf (Time Receive Final). Tof can be calculated with these known values with the formula 4.

$$ToF = [(TRR - TSP) - (TSR - TRP) + (TRF - TSR) - (TSF - TRR)]/4$$

Distance between tag and anchor can be found by where signal speed is equal to speed of light.

$$Distance = Signal\ speed \times ToF \qquad (5)$$

After calculating the distance between the anchor and the tag, the possible tag positions are determined for different anchors. The intersection point is then considered as the position of the tag as indicated in Figure 4

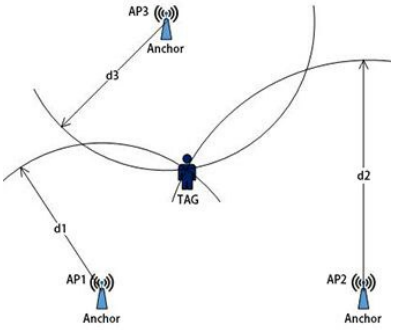

Figure 4 Finding Tag position with ToF

TDoA uses the time difference between when a signal reaches different receivers to determine the location of the signal source. This method usually requires multiple receivers. The UWB signal is sent from a source to all receivers simultaneously. Since the distance from the tag to the receivers is different, the signal will reach them at different times. The time differences measured by each receiver are used to determine the location of the signal source. TDoA typically uses the time difference between two receivers (Equation 2)

$$\Delta T = T2 - T1 \qquad (2)$$

Here, T1 andT2 are the time it takes for the signal to reach receiver 1 and receiver 2. This difference is used to calculate the relative distance of the source to the receivers. In this system, no clock synchronization is required between receivers, but multiple receivers are required.

Al-Okby et al. (2024) studied the accuracy and performance of UWB systems in real-time indoor monitoring applications. Their study compared TDOA and TOF methods, indicating that TDOA offers higher accuracy in larger areas, due to its ability to minimize cumulative errors caused by signal delays.

2.3.2 Bluetooth Low Energy (BLE)

Bluetooth Low Energy (BLE) is a wireless communication technology frequently used in indoor positioning systems with its low power consumption and cost-effective advantages. Beacon devices, which are an important component in BLE-based systems, allow devices to be positioned by emitting low-power Bluetooth signals at certain intervals.

Beacons are small-sized and portable devices. Their working principle is based on continuously emitting low-power signals. These signals are usually used to determine the location of a device (e.g. smartphone). Beacons only emit signals; analysis of the signal and location calculation are usually performed by the receiving device or a central system (Ponte et al., 2024).

The BLE method stands out with its advantages such as energy efficiency, cost effectiveness and easy installation in indoor positioning systems. Long battery life is a remarkable feature of these devices in terms of energy saving. In addition, the fact that it can be applied without the need for high-cost infrastructures makes BLE technology a suitable option for many businesses and organizations. Thanks to its small size, beacon devices can be easily installed in any indoor environment and offer a wide range of applications. This technology, which is frequently preferred in sectors such as retail, healthcare, logistics and education, offers solutions to many needs with its flexible use opportunities. However, it also has some disadvantages. For example, metal surfaces, walls and other environmental factors can negatively affect signal quality (Ponte et al., 2024). The limited coverage area of each beacon may require the use of more devices in large areas. In addition, accuracy problems may arise in location estimates due to signal reflection (multipath effect) in the RSSI method (Kaushal et al., 2025). In addition, battery replacement

and management can be a time-consuming challenge in projects where many beacons are used.

2.3.3 Wi-fi Positioning System (WPS)

Wi-Fi positioning systems (WPS) are a technology that detects the locations of devices using wireless networks. It offers decimeter level solutions, especially in indoor environments where GPS is insufficient. WPS determines the locations of users via smartphones or other wireless devices using the existing infrastructure of Wi-Fi access points.

WPS works with several methods. Various methods used in Wi-Fi positioning systems offer different approaches to accurately determine the locations of devices. The RSSI (Received Signal Strength Indicator) method estimates the distance between the device and the access point based on the Wi-Fi signal strength. In this method, the location of the device is determined by triangulation using multiple access points (Zhong et al., 2025).

Fingerprinting involves extracting Wi-Fi signal profiles of a specific area and storing these profiles in a database. Then, real-time measurements are compared with these profiles to determine a precise location (Hou et al., 2025). Another method, Time of Arrival (ToA) and Time Difference of Arrival (TDoA), determine the distance by calculating the time it takes for the signals to reach the access points, and thus the location is estimated (Saveliev et al., 2025). Finally, the Angle of Arrival (AoA) method provides high accuracy by analyzing the angle of arrival of the signal. However, this method is generally used in more specialized applications due to the requirement of additional hardware (Dang et al., 2025).

Wi-Fi-based positioning systems provide cost savings by using existing infrastructure. Using already installed Wi-Fi access points eliminates the need for additional hardware, making this technology more accessible (Zhong et al., 2025). In addition, thanks to its wide device compatibility, it is quite easy for users to use these systems since most

smartphones and devices support Wi-Fi signals today. Wi-Fi networks generally cover large areas, making them an ideal solution for large indoor spaces (Hou et al., 2025). However, these systems also have some challenges. For example, Wi-Fi signals can be weakened by walls, furniture, and other physical obstacles, causing signal noise. Constantly running devices increase energy consumption, while factors such as signal reflection (multipath effect) can lead to positioning errors and cause inaccurate estimates (Dang et al., 2025).

2.4 Mobile Application Development

These types of projects usually include applications designed specifically for individuals or institutions with specific needs that cannot be met with standard solutions. Mobile applications used in special projects offer unique functionality in areas such as field work, scientific research, healthcare services, security applications and internal operational processes.

While commercial applications are designed to appeal to a wide range of users, applications developed for special projects have completely customized features in line with project goals. This ensures that user needs are fully met, while also offering higher security, flexibility and integration capabilities.

Custom mobile application development processes are usually carried out with one of the native or cross-platform development approaches. While native approaches provide high performance and full hardware access, cross-platform solutions offer advantages in terms of cost and development time.

2.4.1 Mobile Application Development Languages

The programming languages and technologies used in mobile application development processes can vary greatly depending on the requirements of the project, the target platform, and performance needs. Each language and development technology offers

certain advantages and disadvantages, affecting developers' preferences. Today, there are various languages that stand out for native and cross-platform solutions in mobile application development.

Kotlin and Java stand out as the most popular languages in the field of Android application development. Java has been main language of Android for many years but Kotlin was announced as the official language for Android by Google in 2017 and quickly became popular. Kotlin can offer the same functionality with 40% less code compared to Java. On the other hand, Java is still preferred in many projects with its rich library support and platform-independent structure. However, its complex code structure is among the disadvantages of Java.

Flutter and React Native stand out in cross-platform solutions. Flutter is developed by Google. Flutter works with the Dart programming language and offers the opportunity to develop applications with a single code base on both Android and iOS devices. Flutter, which provides a fast development process thanks to its rich widget library, optimizes the user experience by offering native-like performance. However, the disadvantages of this technology include the fact that the Dart language is not as popular as others and that performance problems can occur in large projects.

React Native is another cross-platform solution developed by Meta. Based on JavaScript and Typescript, React Native offers wide community support and integration with native components. However, it has disadvantages such as performance problems in large-scale projects and difficulties in accessing some hardware features.

2.5 Communication Methods

To analyze the collected data, it should be transmit to a server or computer to make further analyze. This data includes signal data and position information in this case. Many communication protocols have been developed to perform such data transmission

processes efficiently and reliably. These protocols include Hyper Text Transfer Protocol (HTTP), Message Queuing Telemetry Transport (MQTT), Advanced Message Queuing Protocol (AMQP), Constrained Application Protocol (CoAP). (Al-Masri et al, 2020). Each protocol offers optimized features for different application needs and is preferred according to important factors such as data transmission security, packet size, energy efficiency and low latency.

2.5.1 Hyper Text Transfer Protocol (HTTP)

HTTP (Hypertext Transfer Protocol) is the basic protocol that enables data exchange on the internet. It regulates communication between web browsers and servers, enabling web pages to be loaded and users to interact with content.

The main purpose of HTTP is to transport hypertext documents (HTML, CSS, JavaScript, images, videos, etc.) between the client (browser) and the server. It was originally designed as the cornerstone of the World Wide Web (WWW). Today, HTTP plays a critical role not only for websites, but also in many areas such as mobile applications, IoT devices, and web services.

HTTP/1 and HTTP/2 are protocols that work on TCP (Transmission Control Protocol). Google developed the QUIC (Quick UDP Internet Connections) protocol as a UDP-based alternative to TCP. In 2018, IETF (Internet Engineering Task Force) started working on the next-generation HTTP protocol based on QUIC and this protocol was named HTTP/3. It was officially accepted as the RFC 9114 standard in June 2022.

HTTP/3 was developed to address the shortcomings of HTTP/2 and make the Internet faster, more secure, and more efficient. HTTP/2 can send multiple requests over the same connection (multiplexing), but because of the use of TCP, if a packet is lost, all streams must wait until that packet is resent. HTTP/3 made each stream independent by using the UDP-based QUIC protocol instead of TCP. HTTP/2 must reestablish the

connection when the IP address changes. HTTP/3 can maintain the connection even if the IP changes by using QUIC's Connection ID mechanism.

2.5.2 Message Queuing Telemetry Transport (MQTT)

MQTT (Message Queuing Telemetry Transport) is a lightweight messaging protocol developed for IoT (Internet of Things) devices. MQTT is based on the Publish-Subscribe model and provides low data usage, fast communication and energy efficiency while transmitting data between devices.

MQTT works over TCP/IP (Transmission Control Protocol). TCP/IP is a connection-based protocol and provides important features such as security, error-free and ordering during data transmission. Data transmission does not start without establishing a connection. In addition, TCP/IP provides a secure connection between both devices and performs error checking during data transmission to ensure that the data is transmitted completely. If data is lost, TCP/IP retransmits the lost data and provides secure communication.

To understand how MQTT works, it needs to look at the concepts of MQTT Client, MQTT Broker, Publish-Subscribe mode, Topic and QoS.

MQTT Client is the device which publishes or receives the data contain the topic and data. If the client sends the data, it is called publisher, and fit receives the data, it is called receiver. The client determines the data format such as text, binary, XML, or JSON files.

MQTT Broker is the backend system which coordinates messages between the different clients. Brokers can take on various roles including identifying clients, manipulating data, filtering, sending messages.

Topic refers to the keywords used by the MQTT broker to filter messages for the MQTT clients. Topics are structured hierarchically, much like a file or folder directory.

The publish-subscribe model differs from the client-server model by separating the client that sends messages (publisher) from the client that receives them (subscriber). Publishers and subscribers do not need a direct connection, as the MQTT Broker handles the routing and distribution of all messages can be seen in Figure 5.

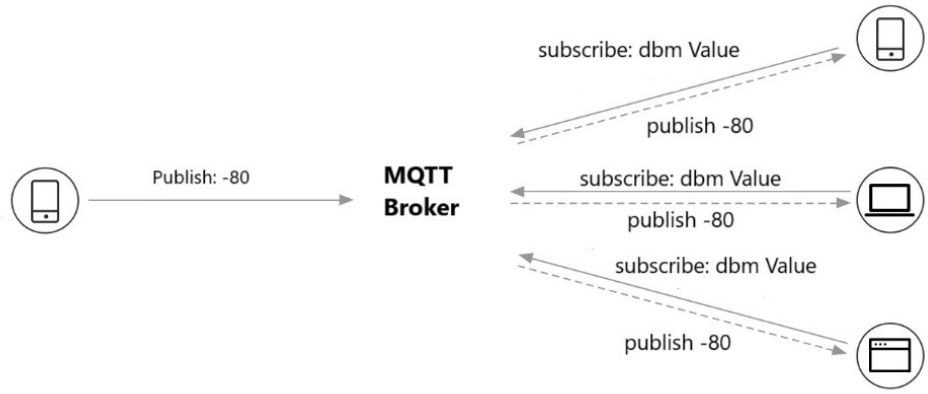

Figure 5 Publish subscribe model

QoS (Quality of Service) in MQTT consists of three different levels that determine the reliability of message transmission. These levels control the number of times the message will be sent and the security of the transmitted message as shown in the Figure 6.

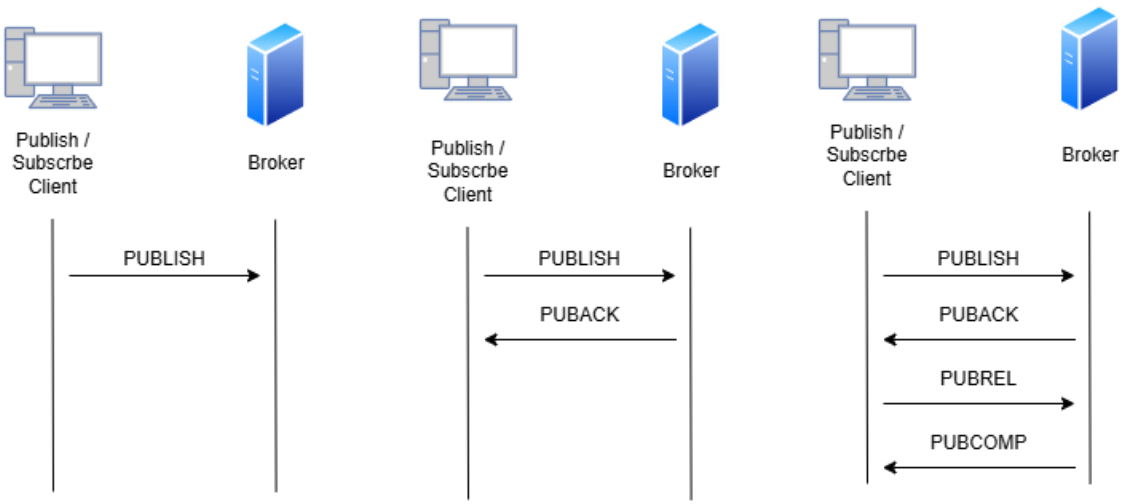

Figure 6 Message Transmissions in Quality of Service Levels (Lee et al, 2013)

- QoS 0: The message is sent once, and no acknowledgement is received from the recipient. This level provides fast but unreliable transmission.

- QoS 1: The message is sent at least once, and the recipient is acknowledged. If the message is lost, it is sent again, but it is possible to send it multiple times.

- QoS 2: The message is sent exactly once and ensures that it reaches the receiver completely. This is the most reliable transmission level and guarantees that the message will not be lost. It includes multiple verification processes between both the sender and the recipient.

2.5.3 Advanced Message Queuing Protocol (AMQP)

AMQP (Advanced Message Queuing Protocol) is an open-source, platform-independent, and language-agnostic messaging protocol. It was designed to provide a secure, reliable, and flexible messaging solution for different applications and systems. AMQP facilitates data transmission via message queues, ensuring efficient communication in environments that require high performance, security, and flexibility.

Message Queues: AMQP allows messages to be sent to a queue and processed by receivers. The queues are organized to ensure timely delivery of messages. AMQP guarantees that messages are not lost. Once a message is sent by the sender, it remains in the queue until it is securely delivered to the receiver. It supports high-volume message transmission and optimizes data transfer between systems.

AMQP provides advanced features such as message routing, prioritization, filtering, and subscription management. It also includes security, authentication, and authorization processes for transmitted messages. It is commonly used in industries like finance, e-commerce, enterprise applications, and IoT, as it emphasizes security, reliability, and speed in data transmission.

2.5.4 Constrained Application Protocol (CoAP)

Constrained Application Protocol (CoAP) is a UDP (User Datagram Protocol) based, lightweight application protocol specifically designed for resource-constrained devices and networks. It was designed to meet the low bandwidth, low power consumption, and limited processing power requirements of IoT (Internet of Things). Although CoAP works similarly to HTTP, it is specifically optimized to meet the needs of IoT devices more efficiently (Manveer and Bikram, 2015). CoAP is an energy saving protocol because it does not require acknowledgments for each message, in contrast to TCP-based protocols.

User Datagram Protocol (UDP) is used for time-sensitive tasks including , gaming, and video playback. UDP does not establish a strong connection with the destination before sending the data, so communication is faster (Figure 7). Eliminating this step speeds up data delivery because connection establishment takes time. But as data packets sent to the destination, UDP might potentially result in their loss.

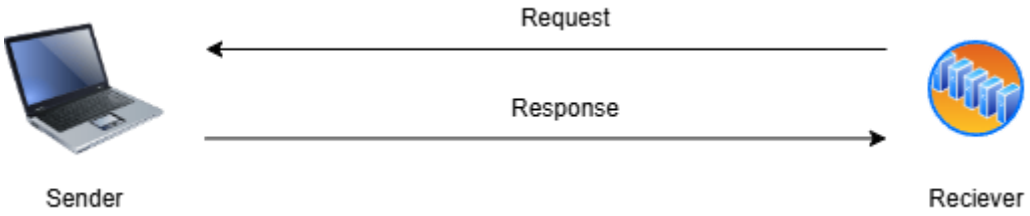

Figure 7 UDP Protocol

CoAP works with client – server model. Client requests the service needed and server response to client's request. It uses similar methods with HTTP, for instance GET, POST, DELETE and PUT methods. The communication is asynchronous because it uses user diagram protocol.

3 Methodology

In this study, an innovative data collection approach is adopted to evaluate 5G coverage in indoor areas. Data is collected by using two different devices. Signal data is gathered by using Google Pixel android phone. Real time position data is provided by Decawave Ultra-Wide Band (owned by Qorvo) devices.

First, signal strength measurements were made using Android phone. Android phone is preferred because it has the necessary hardware and are accessible to a wide range of users. In addition, these devices make large-scale data collection processes more efficient because they are low-cost. A custom mobile application is developed to collect and send data to the server for further data processes.

Second UWB devices used to receive position data. UWB devices provide centimeter-level accuracy. Mobile sensors are placed around the indoor environment for ease of location as well as collecting measurements. Anchors serve as reference points with known positions calculated by laser meter. Tags are attached to mobile devices and use anchor signals to calculate position accurately. This technology makes applications available such as asset tracking, indoor navigation, and context-aware services which go a long way towards improving end-user experience in buildings.

For example, the project aimed at combining the data from these two sources (signal strength measurements done on Android phone and Decawave UWB devices' Indoor Positioning) to produce detailed 5G coverage maps indicating areas with poor performance inside structures. These insights will provide guidance on how best network operators and service providers can optimize their infrastructure for seamless connectivity across various environments resulting in better user experiences.

3.1 Collecting Signal Data

To create a comprehensive 5G coverage map, the project involved collecting accurate signal strength data using an Android phone as a mobile sensor. The process consisted of receiving dBm (decibel-milliwatts) data from the device and sending it to Node-RED for further analysis.

3.1.1 Signal Data

In wireless communication, evaluating signal strength is essential for optimizing network performance and mapping coverage. This study selected Received Signal Strength Indicator (RSSI), Reference Signal Received Power (RSRP), and Reference Signal Received Quality (RSRQ) as key parameters for assessing 5G network perfor-mance. Each of these metrics provides insights into different aspects of sig-nal behavior, allowing for a comprehensive analysis of network conditions.

RSSI is a fundamental indicator of signal presence, measuring the total received power, including interference and background noise. It is widely used in wireless communication as it helps determine whether a device is within the coverage area of a base station. However, RSSI does not distinguish between useful signals and unwanted interference, making it less reliable for precise network quality assessments. To obtain a more accurate measurement of network coverage, RSRP was selected as the primary signal strength metric. RSRP measures only the power of the reference signal transmitted by a base station, excluding noise and interference. This makes it a more reliable indicator of network strength, particularly in environments with overlapping signals from multiple base stations. RSRP is also used by LTE and 5G devices to determine which base station to connect to, influencing handovers between cells. It provides more consistent and precise data compared to RSSI, making it an essential parameter for coverage mapping.

While RSRP indicates signal strength, RSRQ was included to assess signal quality. RSRQ evaluates the ratio of RSRP to RSSI, providing insights into how interference affects signal

reception. This is particularly useful in high-density network environments, where strong signals may still suffer from poor quality due to congestion. RSRQ plays a key role in optimizing networks by identifying areas with high interference, ensuring efficient resource allocation.

By combining RSSI, RSRP, and RSRQ, this study ensures a comprehensive evaluation of 5G signal performance. RSSI offers a general strength measurement, RSRP provides an accurate coverage assessment, and RSRQ helps determine signal reliability. The selection of these parameters allows for precise indoor positioning and effective 5G coverage mapping, making them ideal for this research.

The Android phone is used to collect signal data in terms of dBm which provides a standardized metric to assess the power level of a signal, where higher values indicate stronger signals and lower values represent weaker signals. In this project the dBm value range is between - 70 to -130.

dbm value can be calculated with formula 3, but This formula is a theoretical model used to determine the power level in decibel-milliwatt (dBm) and is valid under ideal conditions.

$$x(dbm) = 10\ log_{10} \frac{P}{1mW} \qquad (3)$$

However, it is not possible to apply it in practice. One of the most important reasons for this is that the formula assumes a lossless environment. In the real world, the signal is weakened by walls, buildings and other obstacles, and is also subject to reflection, refraction and scattering because of multi-path propagation. The effects of ambient noise and other signals can also impair the accuracy of the measurements. In addition, real measurements cannot be made with full accuracy in practice, because signal analyzers and antennas work with certain margins of error. Since the power measurement is

calculated not directly but over voltage or current, factors such as antenna gain, cable losses and environmental effects play a major role in real measurements, although they are not included in the formula. In addition, variables such as weather, temperature and humidity can also affect the propagation of radio signals and cause deviations from the ideal model. For these reasons, the formula is only suitable for theoretical calculations; To obtain more accurate results in the real world, it needs to be supported by empirical models and experimental measurements.

Table 2. RF Conditions

RF CONDITIONS	RSRP(DBM)
EXCELLENT	> - 80
GOOD	- 80 to - 90
MID CELL	- 90 to - 100
POOR	< -100

3.1.2 Mobile Application

For the development of the Android application, Android Studio was chosen as the primary integrated development environment (IDE). Android Studio offers a rich set of development tools, debugging features, and making it the ideal platform for creating robust and efficient Android applications. It also provides an android phone emulator for developing environment.

In addition to the choice of IDE, the Kotlin programming language was selected for application development. Kotlin is an officially supported language for Android development and offers a range of advantages such as conciseness, null safety, interoperability with existing Java code, and enhanced developer productivity.

By leveraging the capabilities of Android Studio and Kotlin, the project developed a custom Android application that utilized the device's APIs and frameworks to access and retrieve the signal strength information. The application collected dBm data periodically during android phone is moved along Technobothnia.

First, a data class named Signals is defined. That represents a signal object with two properties: signalStrength and dbm.

```
data class Signals(val signalStrength: String, val dbm: String)
```

The Signals data class represents various aspects of signal strength in an LTE network, with its primary properties being signalStrength and dbm, both stored as strings. The signalStrength field contains a textual representation of the signal's quality, while the dbm field represents signal strength in decibels-milliwatts (dBm). Various parameters are collected from the device to determine signal quality and strength.

One of the key parameters is Received Signal Strength Indicator (RSSI), which provides a general measurement of signal power in the LTE network. Another critical measurement is Reference Signal Received Power (RSRP), which specifically evaluates the power level of the received LTE signal. To assess signal quality, Reference Signal Received Quality (RSRQ) is used, which factors in both power levels and interference. Additionally, Reference Signal Signal-to-Noise Ratio (RSSNR) measures the ratio of the received signal strength to background noise, providing insights into signal clarity.

The Channel Quality Indicator (CQI) is another essential metric that indicates how well the channel can support data transmission. It is represented by two fields: cqiTableIndex, which refers to the specific CQI table used for reporting, and cqi, which provides the actual quality indicator value. Furthermore, Timing Advance (TA) measures the time difference between the transmission and reception of signals, helping determine the distance between the device and the base station.

The level field represents an overall signal strength level based on the collected parameters, while parametersUseForLevel indicates which parameters were considered in determining this level. A value of 0 for this field suggests that none of the parameters were explicitly used or were unavailable during the assessment. Together, these attributes provide a comprehensive view of LTE signal performance and quality.
Together, these properties within the Signals data class encapsulate the necessary information related to the signal, including both a descriptive representation (signal-Strengt) and the numerical dBm value (dbm). This data class can be used to store and manipulate signal data within the application, enabling easy access and retrieval of signal strength information.

```
fun getSignalData():Signals{
    val telephonyManager = getSystem-Service(Context.TELEPHONY_SERVICE)
as TelephonyManager
    val signal = telephonyManager.signalStrength?.cellSignalStrengths
    val signalDbm = signal?.get(0)?.dbm.toString()
    println(signal)
    return Signals(signal.toString(),signalDbm)
}
```

In the signal data collection section of the application, signal strength data is collected and processed using the device's TelephonyManager API. For this purpose, a function called getSignalData() has been created, which retrieves the signal strength information of the device, stores it in a Signals object and returns it.

First, information about the device's telecommunication services is obtained by accessing the TelephonyManager class in the function. The TELEPHONY_SERVICE service is called via the getSystemService(Context.TELEPHONY_SERVICE) method and the resulting object is converted to the TelephonyManager class. TelephonyManager provides access to data about the device's network connection and signal strength.

After this stage, current signal strength information is obtained using the signalStrength property. Thanks to the cellSignalStrengths property, a CellSignalStrength object list containing signal strength information for different radio types of the device is obtained.

To determine the signal strength value, the first element of the cellSignalStrengths list is accessed and the dBm (decibel-milliwatts) value of the relevant signal is obtained. The dbm property represents the measured power of the signal in dBm. This value obtained is converted to a text format using the toString() method and stored by assigning it to the variable.

Finally, the obtained data is encapsulated in a Signals object and returned as the output of the function. This data class has two properties, including the text format representation of the signalStrength information and the dBm value. This structure allows the application to easily process and manage signal strength data.

In general, the getSignalData() function accesses the current signal strength data of the device, processes this data to extract the dBm value, and returns the obtained information by organizing it in a Signals object. This approach simplifies the data collection processes for signal strength analysis and allows the application to evaluate the network connection quality.

3.1.3 Data Logging Server

Data Logging Server is a server that collects, stores, and accesses data from a specific source (e.g. sensors, devices, or applications) when needed. Such servers usually provide time-stamped storage, analysis, and reporting of data. The data logging server ensures that data is stored correctly, analyzed when needed, and transmitted to external systems when needed.

In this project, Node-RED was used as the data logging server. Node-RED is an open-source development tool and is widely used especially for connecting and managing sensor data, device information, and various IoT (Internet of Things) devices.
Node-RED provides a visual programming interface. This feature makes it easy to visually design complex data flows. Users can easily design connections and data flows by dragging and dropping, which speeds up the software development process. It can easily receive and send data via MQTT, HTTP, WebSocket and other protocols.

Node-RED is open source and can be customized with various nodes. This allows flexibly configuring and extending Node-RED according to the needs of the project. Additionally, many third-party node packages are available, allowing integration with different databases and data retrieval over different protocols.

In this study, Node-RED was used to receive signal strength and dBm data collected via MQTT. It also received position data coming via WebSocket and was used to save this data to a file in CSV format. CSV (Comma Separated Values) is a widely used format for storing data in a plain text file, allowing the data to be organized in rows and columns.

Signal strength and dBm data are retrieved from specific MQTT topics using MQTT nodes. Position data is retrieved by websocket nodes continuously. The data is processed and organized in Function Node. Real-time data can be monitored using Debug nodes. Using File Node, the data is saved to a specified file in CSV format. These operations are performed automatically according to the frequency of data collection. The flow can be seen in the Figure 8. Nodered ServerFigure 8

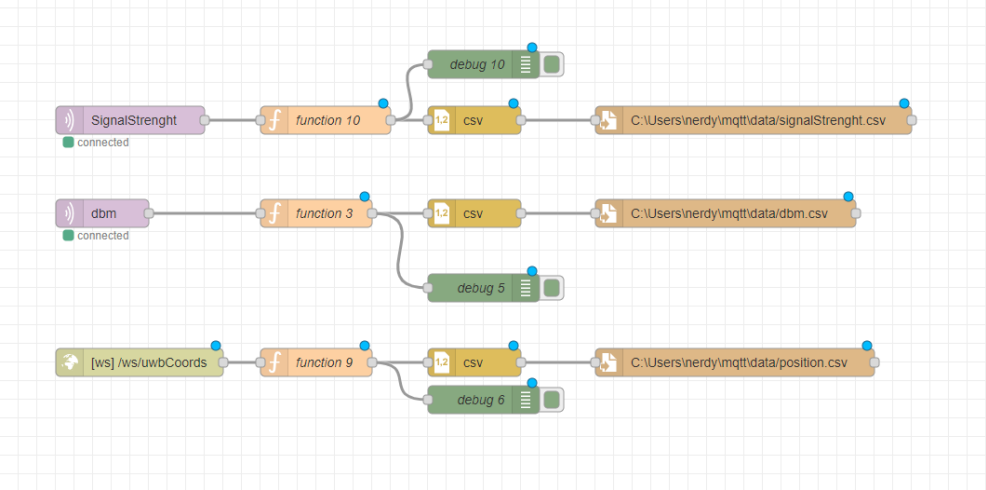

Figure 8. Nodered Server

Both periods of signal-strength and position data are set to 500ms. In the function part, the time stamp is added to the data samples. Then they are transformed into a CSV file and saved to a local file for further analysis.

3.1.4 Sending Data via MQTT Protocol

In this study, MQTT (Message Queuing Telemetry Transport) was chosen as the primary communication protocol due to its lightweight nature, efficiency in low-bandwidth environments, and suitability.

MQTT consumes much less bandwidth than other protocols. Since HTTP works with a request-response model, it creates unnecessary overhead by establishing a new connection for each data exchange. Similarly, AMQP's message headers are larger and more complex, which can slow down data transmission. In contrast, MQTT's Publish-Subscribe model allows devices to subscribe only to the data they are interested in without sending unnecessary requests. This allows efficient use of bandwidth in applications that require constant data flow, such as 5G signal monitoring.

The project aimed at transmitting data from mobile phone to Node-RED, a flow-based programming tool for further work. MQTT (Message Queuing Telemetry Transport) is a lightweight messaging protocol that helps in facilitating communication between android applications and Node-RED.

Although CoAP is a lightweight protocol designed for low-power devices, it is vulnerable to data loss because it runs on UDP (User Datagram Protocol). UDP does not check whether data packets have reached the other party, so messages can be lost in the event of network congestion or interference. MQTT, on the other hand, runs over TCP, which ensures that data transmission is guaranteed and in order. In addition, MQTT's QoS (Quality of Service) levels prevent message loss and guarantee that critical signal strength data is received completely. Especially in applications that require precise measurements, choosing MQTT instead of CoAP increases data accuracy.

MQTT provides data flow without the need to constantly reconnect, with its persistent connections and Keep-Alive mechanism. This allows battery-powered 5G data collectors to operate for longer periods of time. HTTP consumes a lot of power because it establishes a new connection for each data exchange. Similarly, AMQP’s complex message processing processes cause devices to consume more processing power, which in turn increases energy consumption.

Efficiency, low network overhead and reliable message delivery were some of the factors that influenced the selection of MQTT as a communication protocol. Passing collected signal strength data from the Android phone to the Node-RED platform was easy through it.

Node-RED acted as an MQTT broker for receiving data sent by the Android application. It served as a hub for aggregating, analyzing and visualizing received signal strength data. In addition to these capabilities, Node-Red’s intuitive visual programming interface

supported real-time processing, connecting with other sources if needed, and making comprehensive coverage maps all at once.

```
val options = MqttConnectOptions()
        options.isCleanSession = true
        val brokerUrl = "tcp://192.168.${ip}:1883"
        val topic = "SignalStrength"
        val dbmTopic = "dbm"
        val client = MqttClient(brokerUrl,MqttClient.generateClien-
tId(), MemoryPersistence())

            fun connectMqtt(client:MqttClient, op-tions:MqttConnectOp-
tions){
                client.connect(options)
            }

            Fun sendMessage(client:MqttClient,signal:String,
dbm:String,dbmTopic:String,signalTopic:String){

                val message = MqttMessage(signal.toByteArray())
                val dbmMessage = MqttMessage(dbm.toByteArray())
                client.publish(dbmTopic, dbmMessage)
                client.publish(signalTopic, message)
            }
```

In this code block, certain configurations have been made to provide data exchange between a client and a broker using the MQTT protocol. First, an object from the MqttConnectOptions class was created and the basic settings of the MQTT connection were defined. In this context, the isCleanSession parameter was set to true as boolean, allowing the client to clean previous session data each time it connects.

The MQTT broker address where the connection will be made is defined as the brokerUrl variable, and this URL is in the format tcp://192.168.${ip}:1883. Here, the ip value is determined dynamically via the user interface. The topics used to route messages in the MQTT protocol are also predefined. In this study, the topic where the signal strength data will be published is determined as "SignalStrength", and the topic where the dBm (decibel-milliwatts) data will be published is determined as "dbm".

A client object from the MqttClient class was created to make the connection. This object is configured with the parameters brokerUrl, client ID (MqttClient.generateClientId()) and MemoryPersistence(), which provides memory-based persistence. A function called connectMqtt(client: MqttClient, options: MqttConnectOptions) is defined to manage the connection of the MQTT client, and this function allows the client to communicate with the broker via the connect() method.

The sendMessage function is for publishing MQTT messages. This function works by taking the parameters client object (client), signal strength data (signal), dBm data (dbm), topic specified for dBm (dbmTopic) and topic specified for signal strength (signalTopic). In the function, two different MqttMessage objects are created for both signal strength and dBm data, the data is converted to a byte array with the toByteArray() method and the content of the messages is determined. Finally, by calling the publish() method of the client object, the dBm data is sent to the dbmTopic topic and the signal strength data is sent to the signalTopic topic.

This structure manages a dynamic data transfer process using the MQTT protocol and provides communication between the client and the broker. In addition, the integration of the system with the Node-RED server allows the visualization and processing of incoming data.

3.2 Indoor Position Data

Indoor positioning refers to the process of determining the precise location of objects or individuals within an indoor environment. Traditional positioning methods, such as GPS, often struggle to provide accurate results indoors due to signal attenuation and multipath effects. To deal with the positioning problem, Ultra-Wideband (UWB) technology is used as a solution for indoor positioning. UWB utilizes short-range radio waves with a wide frequency band, enabling precise ranging and localization capabilities. UWB

systems typically consist of anchors and tags. Anchors are strategically placed reference points within the environment with measured by hand, while tags are attached to the objects or individuals whose positions need to be determined. By measuring the time-of-flight (ToF) or other ranging techniques between the anchors and tags, UWB systems can accurately calculate the positions in real time. UWB-based indoor positioning has found applications in diverse areas, including asset tracking, indoor navigation, robotics, healthcare, and smart buildings, offering high accuracy, reliability, and scalability for various indoor positioning needs.

3.2.1 Collecting Position Data

To collect indoor position data, a UWB (Ultra-Wideband) setup is created. The UWB system should consist of at least three anchors and one tag. For this project, to increase the precision, four anchors, one tag and one listener is used. The anchors were strategically placed within the indoor environment, and their positions are determined using a laser meter and set manually via DRTLS manager app provided by the manufacturer.

It was ensured that the scanning area for UWB signals was as small as possible and free from obstacles such as walls and shelves. In the following figure one of the setup is shown, red triangles represent anchors. The black circle is the Tag that traveled with the Android device and sends position data simultaneously with signal strength data.

For precise calculation, anchors should be in sight of each other. The listener is responsible for transferring data of the tag’s position to the laptop via USB cable and data is transferred to Node-Red server for further analysis. Data was collected by moving the phone that collected signal data and TAG together in Technobotnia. Data is collected simultaneously but transferred through different devices. To keep them in order, data stored with a timestamp.

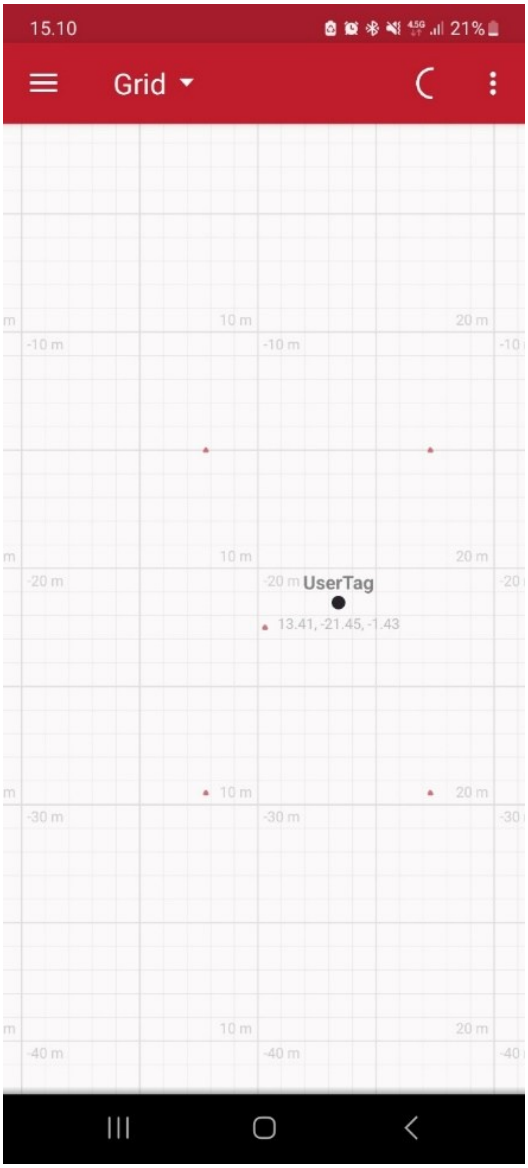

Figure 9. Screenshot of UWB setup from DRTLS manager app

4 Results

4.1 Raw Data

The data on signal strength and data on position are collected simultaneously but from different devices and transferred via different protocols. So as to merge them, timestamp is used as the index value. Using the merge_asof function from pandas' library, position and dbm dataframes are merged. The combination of two DataFrames based on the nearest key is implemented by this function. In this case, the key is a timestamp. X and y coordinates are split from the "position" column and added as new columns. Initially all values in raw data were strings; therefore, they have been converted into float or int values correspondingly. Lastly, the missing values are cleared to get a clean data.

Table 3. Output Data

timestamp	dbm	position	x	y
866188896	-119	POS,0,0CB1,-18.68,-13.41,0.65,78,x07	-18.68	-13.41
866189508	-113	POS,0,0CB1,-18.15,-12.79,-0.82,77,x07	-18.15	-12.79
866190122	-113	POS,0,0CB1,-18.34,-13.04,0.03,76,x07	-18.34	-13.04
866190747	-113	POS,0,0CB1,-18.35,-13.54,1.09,72,x07	-18.35	-13.54
….	….	….	….	…..

4.2 Scatter Plot of the Data

In a scatter plot, plt.scatter is to show raw data. Floormap is shown over a plot using imshow() function. The extent parameter allows to display the floormap with certain limits on x and y axes. Limits are selected as real dimensions of Technobotnia in meters. The dbm value which ranges between -85 to -130 can be seen through color-bar.

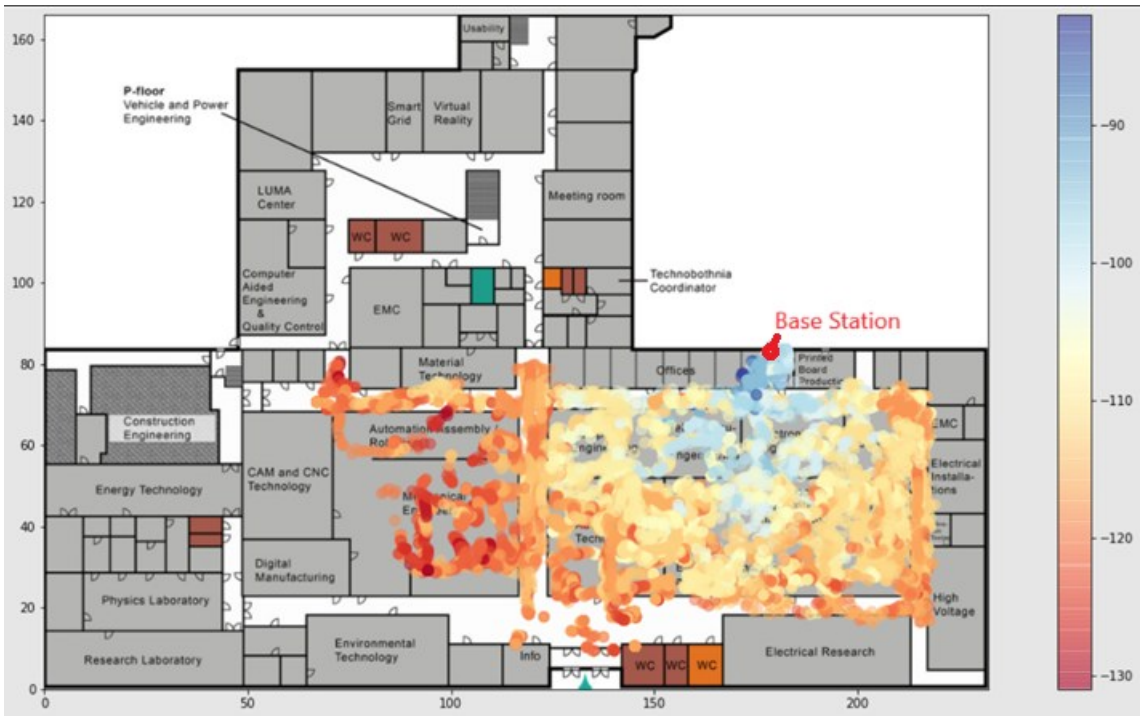

Figure 10. Scatter Plot of the raw Data on the map of Technobothnia

4.3 Gaussian Filter

This filter is used extensively in image processing due to its efficient noise reduction and smoothening abilities. It is a linear-type filter that uses weighted averages on the pixels of an image, with weight values taken from a Gaussian distribution. The use of the Gaussian filter is especially helpful in reducing high-frequency noise while still maintaining important features and edges. It accomplishes this by assigning higher weights to pixels closer to each other and lower weights to those farther away, thus practically - but not quite – imitating the natural blurring characteristics of the human visual system. With such tools as Gaussian filtering, one can retain salient details while eliminating disturbing noises and artifacts leading to cleaner and more visually appealing images. Furthermore, Gaussian filter is useful for various image processing applications including image smoothing, feature extraction, image enhancing as well as preprocessing steps towards subsequent analysis or computer vision algorithms.

An array of zeros is initially defined with the dimensions of the image. By subtracting -135 from the array, the non-value areas are set below the minimum value of the dbm (signal strength) to create distinct regions for visualization. Unlike a scatter plot, in this case, Gaussian interpolation has been applied, which results in a smoother image. By using the Gaussian filter for interpolation, the visualization exhibits a more fluid appearance with reduced pixelation and enhanced continuity.

4.4 Heat Map

In this code, a two-dimensional Gaussian filter is applied to an image using the Hanning window as the kernel. The size of the generated Hanning window is fixed at 25 and then normalized to give the resulting window. signal.convolve2d() function from scipy.signal module performs convolution. The blurred image is saved in variable ‘blurred’. This code then displays the floor map image and the blurred image using imshow() with additional parameters like colormap, transparency and origin settings. Generally, what the code does is that it applies Gaussian filtering for enhancement of the picture and provides a visual representation of both the filtered image (Blurred) and also original floor map.

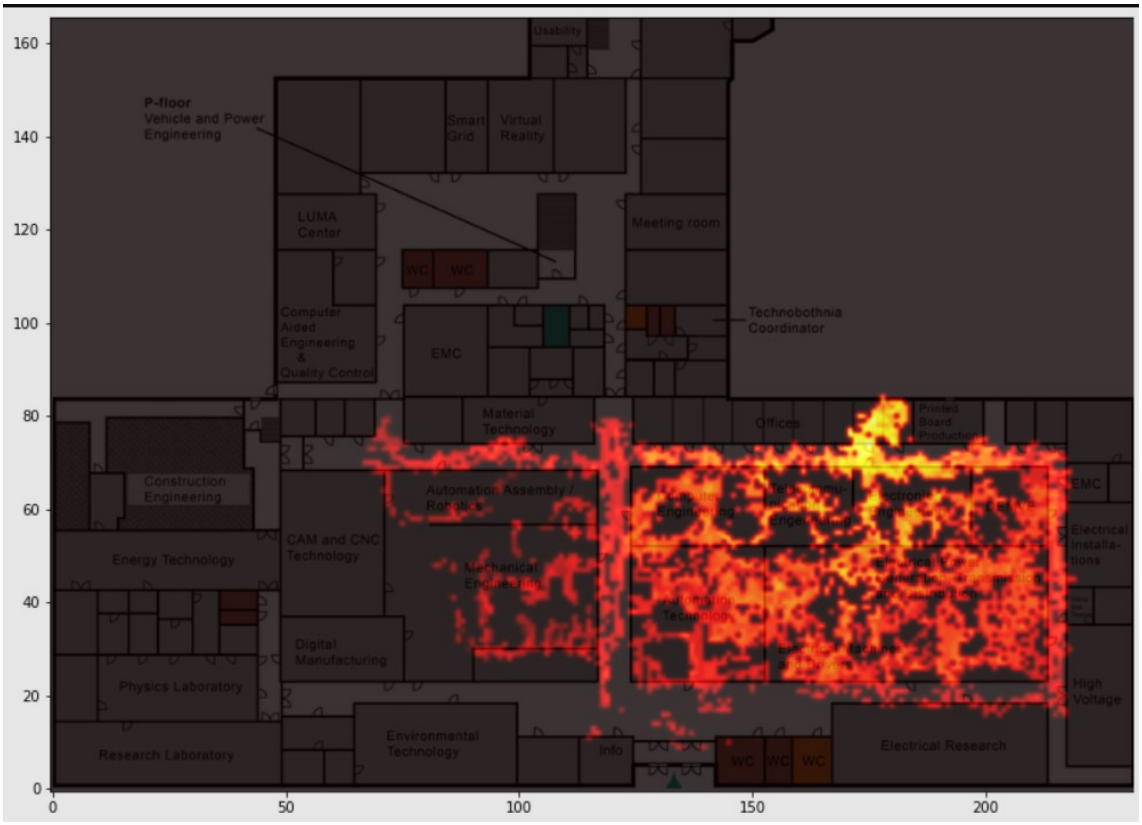

Figure 11 Heat map distribution of the signal

5 Conclusion

This study focused on evaluating 5G signal strength and coverage mapping using key LTE and 5G parameters, including RSSI, RSRP, and RSRQ. The findings highlight the significance of RSRP as the primary metric for assessing signal coverage, as it provides a more accurate representation of network strength than RSSI by filtering out noise and interference. Additionally, RSRQ was used to measure signal quality, offering insights into how interference impacts overall connectivity. By leveraging these metrics, the study effectively mapped 5G network performance in an indoor environment also demonstrating the potential of UWB-based positioning for accurate location tracking in 5G coverage analysis.

With the rapid expansion of 5G networks, optimizing coverage and identifying weak signal areas are critical for enhancing network reliability and efficiency. This study is useful for network operators, infrastructure planners, and IoT developers. It enables to find a low cost mapping for improved connectivity and seamless communication. These results can be applied, especially in dense urban environments, smart cities, and industrial applications.

While this research provides valuable insights into 5G signal strength and coverage mapping, several areas remain open for further exploration. One promising direction is the application of machine learning algorithms for signal optimization. By analyzing historical signal data and environmental conditions, AI-driven models can predict weak coverage areas. These models can also suggest optimal base station placements. This leads to more efficient 5G deployment strategies.

Another area for future research is the multi-floor analysis of 5G coverage in complex indoor environments. These environments include factories, shopping malls, hospitals, and office buildings. 5G signals behave differently across vertical spaces due to wall penetration losses and reflection effects. An in-depth study of signal distribution across multiple levels would provide a better understanding of indoor 5G performance. Additionally,

integrating real-time signal monitoring systems with edge computing could enhance adaptive network management. This would ensure better connectivity in dynamic environments.

By addressing these challenges and incorporating advanced signal processing techniques, future research can further enhance the efficiency and accuracy of 5G coverage mapping, ultimately contributing to the seamless deployment and optimization of next-generation networks.

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