Asymmetrical 3x1 Disk Patch Array with Rugby Ball Slot Microstrip Antenna for LoRa IoT B-OSA (Bidirectional Outdoor Sectoral Area) System

Hutama Arif Bramantyo[1], Irfan Mujahidin[2*], Akio Kitagawa[2], Roni Apriantoro[1], Rizkha Ajeng Rochmatika[1], Catur Budi W[1]

[1]Telecommunication Engineering Study Program, Department of Electrical Engineering, Semarang State Polytechnic, Indonesia
[2]Department of Information and Communication Engineering, Kanazawa University, Japan
*) Co-Author

Abstract— Using minimal transmission power, Long-Range Wide Area Networks (LoRaWAN) enable the transmission of data via radio connections from sensors, which may be remote or challenging to reach, to gateways and servers linked to mobile networks for data processing, exchange, or relay, so generating numerous applications for object monitoring and tracking. Nonetheless, owing to its attributes of low data rates for low-power communications, information transmission utilizing LoRa technology is inadequate for rapid real-time data monitoring. Moreover, the narrow bandwidth of LoRa modulation techniques will yield minimal accuracy in localization efforts, as it cannot effectively address multipath issues. This paper proposes a multi-standard 3X1 Antenna Array and a LoRa end device that accurately measures locations using 3X1 technology and transmits this location data to the gateway and Internet of Things Network via LoRa. Measurement outcomes in both indoor and outdoor environments indicate that Antenna Array 3X1 achieves localization accuracy at the sub-meter level, specifically between 10 and 33 cm. Furthermore, Antenna Array 3X1 demonstrates ranges of 124 m in Line-of-Sight (LOS) scenarios and 55 m in Non-Line-of-Sight (NLOS) scenarios, respectively.

Keywords—: *IoT B-OSA, Patch Array, Microstrip slot*

1. Introduction

The LoRaWAN protocol enables object-to-gateway connectivity, resulting in the creation of diverse monitoring applications, such as intelligent resource management, predictive maintenance, supply and inventory tracking, object and animal tracking, and personal medical monitoring. This underscores extensive monitoring potential based on the physical variables detected by the sensor. In addition to these monitored variables, it is often crucial for the gateway to ascertain the sensor's location, especially if it is integrated into a mobile object or tag, as when the latter navigates an indoor environment.. Localizing mobile sensors poses a challenge for LoRa's operational frameworks, as this communication method is not inherently optimized for such applications, particularly when high accuracy is required or when it must function effectively in both indoor and outdoor environments. The primary benefit of LoRa communication in a LoRaWAN network is its capability to transmit sensing information over considerable distances, generally between 5 km in urban settings and 15 km in rural locations, from sensors to gateways [4,5]. LoRa techniques facilitate extensive communication among numerous low-power devices that gather and transmit minimal data.

Furthermore, the network LoRaWAN possesses substantial capacity and can manage millions of messages from numerous gateways. Nonetheless, despite these benefits, this technology remains inadequate for gateways to accurately and frequently locate mobile sensors [7]. To maintain low power consumption, LoRa sensors transmit data at reduced packet rates, typically delivering one or two packets daily. This is inappropriate for scenarios where the monitored object is in motion within its environment and necessitates real-time or at least partial real-time monitoring, which is unattainable with the comparatively low data rates of LoRa technologies. Furthermore, if the monitored object necessitates precise placement and/or is situated in an indoor setting, radio communication with a broad frequency bandwidth is essential to address the multipath issue [10]; however, this does not apply to narrowband LoRa communications, which possess a bandwidth of several MHz.

On the other hand, especially in complex surroundings such buildings, industrial facilities, hospitals, airports, and construction sites, Ultra-Wide Bandwidth (Antenna Array 3X1) is the main technology used for object localization and asset tracking. It is applied in temporal distance and localization techniques using Time-of- Flight (ToF) and Time-Difference of Arrival (TDoA) [13] either one-way or two-way distance measurements. This helps to precisely estimate location and distance, especially when the distance data is transmitted between the reader and the target over a 500 MHz or higher frequency bandwidth. Although a reading range of usually 100 to 200 meters in Line-of- Sight applications is generally sufficient for indoor scenarios, it is classified as a short-range communication technology, which is inappropriate for networks in very remote outdoor environments, where objects may be separated by greater distances, as seen in LoRaWAN networks.

Consequently, this study proposes the integration of LoRa technology with array antennas and B-OSA systems as an Internet of Things (IoT) framework. This combination enables the LoRa gateway to accurately detect sensors within its vicinity, providing real-time positional information even as they move. Antenna Array 3x1 targets can also be positioned on remote data links, including LoRa links. The solution involves employing 3x1 Antenna Array technology in mobile target LoRa sensors to facilitate real-time tracking by LoRaWAN gateways with high precision. The outcome is a multi-standard antenna array 3X1-LoRa transceiver, capable of operating as either a sensor tag or reader based on its position within the communication chain. We thus suggest to deploy the proposed Antenna Array 3x1-LoRa reader device as an intermediary node between the target item and the gateway and outfit the mobile LoRa sensor with Antenna Array 3x1 technology (LoRa-Antenna Array 3x1 sensor tag). Using Time of Flight (ToF), the reader picks real-time location data from the sensor-tag using the Antenna Array 3X1 and sends it to the gateway via a LoRa signal.

This paper is structured as follows generally: Section 2 defines relevant studies on localization with LoRa technology. Part 3 initially delineates the Antenna Array 3x1-LoRa localization system in its entirety, subsequently detailing the design and architecture of the proposed Antenna Array 3X1-LoRa transceiver. The final subsection concentrates on the design of the antenna structure incorporated within the transceiver. Part 4 presents the results of the characterization of the two antennas, commencing with the reflection coefficient and extending to their emission patterns. Part 5 discusses and characterizes the localization achieved by the transceiver, emphasizing the range and accuracy of the Antenna Array 3X1 localization between the sensor tag and the reader, as well as the transmission of location information from the reader to the network. Ultimately, the conclusion summarizes the contributions and findings of this paper.

2. Related Jobs

Prior studies have achieved localization using LoRa technology, predominantly employing the Time Difference of Arrival (TDoA) method [7,15,16], which necessitates a minimum of three gateways to determine the object's location. In [16], multiple sets of messages transmitted via the target sensor were utilized to compute the Time Difference of Arrival (TDoA) of these messages and conduct location estimation at the gateway level. The authors evaluated the efficacy of the localization performance, revealing that the localization error was significantly affected by noise from the timestamps received at the base station. In [17], a comparable methodology was employed to establish a LoRaWAN tracking system that utilizes transmitted packets to ascertain the current location. By leveraging LoRa signals and implementing a multilateration algorithm on the timestamps received at the gateway, the findings indicated that it was viable to determine the device's position in a static environment with an accuracy of approximately 100 meters, although this precision was inadequate for indoor contexts.

The imprecision of the arrival time is attributable to the interference of unwanted multipath signals at the receiving gate, which are induced by the environment and are unavoidable. This issue arises primarily because the temporal width of the LoRa signal (~142 ns for a 920 MHz channel) is insufficiently narrow to differentiate multipath signals from the intended path signal. Moreover, the aforementioned studies employed three or more gateways to ascertain sensor positions through the TDoA method, presenting an additional challenge, as the existing LoRaWAN networks do not consistently meet these geographical requirements.

A separate study employed the ToF method to ascertain the distance between a singular gateway and an object [2]; however, the server can only compute this distance utilizing the packet metadata supplied by the gateway, which is transmitted at a low data rate, thereby complicating real-time monitoring. Additionally, in [18], the researchers introduced a Time-of-Flight (ToF) localization technique utilizing fingerprint maps to mitigate accuracy concerns and minimize localization errors resulting from noise and multipath effects. However, this fingerprinting approach is contingent upon the environment and necessitates updates for effective location estimation, rendering it challenging and time-consuming.

Alternative methods involve utilizing the Received Signal Strength Indicator (RSSI) to deduce distance. In [19], the researchers assessed RSSI in a short-distance indoor setting under both LOS and NLOS conditions. The findings indicated that power loss was experienced by the received signal, despite the short measurement distance, with a more pronounced loss in NLOS conditions relative to LOS conditions. In [20], the authors examined the precision of LoRa positioning utilizing RSSI measured at the gateway, and under realistic conditions where the power attenuation due to radio contact was indeterminate, the study reported an accuracy error of up to 588 m. A recent study [21] introduced a comprehensive position estimation algorithm aimed at reducing a posteriori RSSI error in multi-anchor cooperative estimation scenarios, demonstrating that location could be estimated with an accuracy of under 7 m. Nevertheless, the system was exclusively evaluated in outdoor environments, which are generally less demanding than indoor settings. Localization via the RSSI method relies on signal strength, rendering it highly susceptible to multipath effects and incapable of delivering precise information. The relationship between received power and distance is considerably affected by environmental factors, thus undermining its ability to accurately deduce target location data [22,23].

This paper addresses the issue of low localization accuracy and the necessity for extensive gateways or algorithms to enhance precision by integrating the antenna array with the B-OSA system within the LoRa application. Additionally, real-time localization is facilitated by the high data rates of the Antenna Array 3X1, which allows for the detection of tags as required, as evaluated by the gateway. With a main focus on localization rather than the sensing capabilities of LoRa sensor tags, this work offers a 3X1 LoRa antenna array transceiver intended to operate as a sensor tag and an intermediary reader between the sensor tag and the gateway. With the distance between the mobile sensor tag and the Antenna Array 3X1-LoRa reader computed at the reader node, the proposed approach benefits in that the localization of the tag occurs before any data is sent to the gateway. This lets one compare the present location data with the past information, therefore forwarding the data to the gateway just if it changes. Location via LoRa initially involves transmitting a data packet that includes the flight time, followed by the computation of distance. Furthermore, the potential drawbacks of the proposed solution primarily involve assessing the application's flexibility regarding the integration of a reader node between the sensor tag and the gateway.

3. Antenna Array 3X1-LoRa Localization Method

First, this part describes the Antenna Array 3X1-LoRa localization scheme's transmission chain; then, it presents the architecture (reader and sensor tag) and components of the Antenna Array 3X1-LoRa transceiver, so extending from the module to the necessary integrated Antenna Array 3X1 and LoRa antennas.

3.1 LoRa-Antenna Array 3X1 Sensing and Range Approach

Within the framework of the operational environment for the LoRa-Antenna ARRAY 3X1 transceiver, figure 1 shows the transmission chain operation. Following traditional methods, the network consists of several LoRa sensors placed at different sites interacting with the LoRaWAN gateway. Alongside these tags, LoRa sensor tags fitted with Antenna Array 3X1 are used to enable direct communication with the gateway for data transmission, or with Antenna Array 3X1-LoRa reader devices to enable bidirectional coverage, acquire Time-of- Flight (ToF) on the reader node, and calculate the distance between the two measurements. Then the reader uses LoRa signals to provide coverage data to the gateway. Knowing the reader's location already, the gateway can determine the position of the sensor tag and follow its movement in the surroundings.

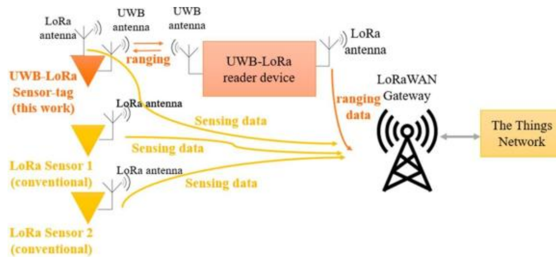

Figure 1. The communication chain structure from sensor tags to networks and gateways.

Figure 2 more precisely defines the purpose of every node and shows the operational organigram of the system. Comprising a LoRa gateway, a sensor tag, and a 3X1-LoRa antenna array reader acting as an intermediary node between the two parts, it Under this arrangement, the gateway has to find the location of the sensor-tag, especially if this place is dynamic in its surrounds.

The reader sends an interrogation signal to the sensor tag using a 3X1 Antenna Array technology and then answers with an acknowledgment signal based on range. The reader estimates a range dn by using Time-of- Flight measurements of these signals, therefore indicating the distance between the sensor tag and the reader. The reader then reaches the decision phase—that is, whether to send the collected location estimate to the LoRa gateway—despite completing all stages using the Antenna Array 3X1 technique. The choice is reached by means of a predefined comparison between the current distance value and the previous value. Only if the sensor has moved since the last measurement will the reader forward the location of the sensor to the gateway. Between the LoRa module and the Antenna Array 3X1 reader, the Microcontroller Unit (MCU) permits communication. The research will be submitted to the sensor tag and the new distance of the dn estimate will be ignored if it is exactly dn−1. If it differs, the tag has moved and its location has changed. While dn is updated by replacing dn−1 for the upcoming iteration of the loop, the estimate is sent to the LoRa module, which then relays it to the LoRa gateway via the LoRa antenna.

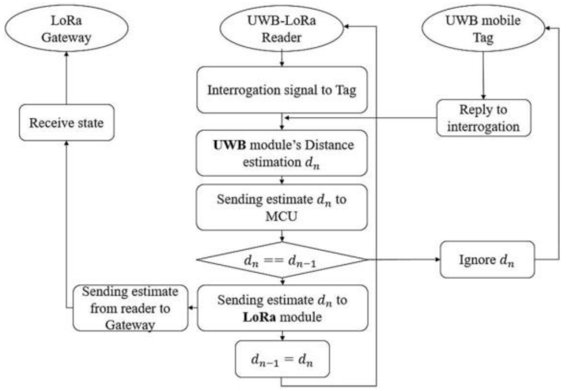

Figure 2. An organigram of a localization system that works by highlighting the role of each node.

The primary benefits of the proposed localization method are as follows:

- The The localization precision ranges, around 15 to 20 cm, from the level of a 3X1 antenna array and occasionally, from even less. Given LoRa is a narrowband communication technology, this degree of accuracy cannot be reached with a traditional LoRa localization technique. More difficult than with the small time pulse of Antenna Array 3X1 is precisely determining the arrival time during the reception phase of broadband time-series.
- The capability to attain real-time localization through Antenna Array 3X1 while minimizing power consumption. Since the LoRa module has to send the received packets from the tag to the gateway, real-time localization using a LoRa-specific mechanism is not possible. This packet contains the flight length, so constant estimation of the gateway's position is necessary; without knowledge of the tag's movement, the continuous transmission of the packet will consume power, so violating the LoRa concept.
- The proposed system primarily utilizes an active Antenna Array 3X1 and LoRa-based systems, as the batteries supply power to both the Antenna Array 3X1 and the LoRa modules. Due to the minimal power consumption of LoRa, no additional power unit is required.

3.2 LoRa-Antenna Array 3X1 Transceiver Design

Made for high-accuracy, long-distance localization and location data transfer to the LoRa gateway, the Antenna Array 3X1-LoRa transceiver is a multi-standard device. Its main purposes are to act as an intermediary reader node between the sensor tag and the gateway or a sensor tag itself. It tells the gateway should the tags have moved in space and localizes them.

Readers consist of LoRa modules interacting via MCU units and a 3X1 Antenna Array module (from STMicroelectronics [24]). The reader has a LoRa antenna for RF connection with LoRa gateways and a 3X1 antenna array for RF communication with any 3X1 module. Operating within a frequency range of 3.75 GHz to 4.25 GHz across two channels, the Antenna Array 3X1 module coupled with the reader antenna and tag Included in the unlicensed Industrial, Scientific, and Medical (ISM) band, LoRa modules and antennas run inside the 863 to 868 MHz frequency range, set aside for LoRa communication in Europe.

The inferior layer partitioned by an air gap. The uppermost layer comprises an Antenna Array 3X1 and LoRa antenna transmission elements situated on the identical FR4 substrate. The lower layer comprises a ground plane and a LoRa module, alongside a FR4 substrate featuring branch line coupling that facilitates the circular polarization of the Antenna Array 3X1. Additionally, the MCU and Antenna Array 3X1 modules are integrated at a specified distance.

Figure 3. Structure of Antenna Array 3X1-LoRa transceiver Structure of Antenna Array 3X1-LoRa transceiver: (**a**) perspective view; (**b**) Side view. The structure consists of two layers: the lower layer of electronics and the upper layer of the antenna, which are connected through the signal vias.

As it provides better localization and range information than linear polarization, circular polarization is the recommended choice for 3X1 antenna arrays; its advantages are discussed in our previous work [14,25]. The same air gap between the two antennas serves both as the air gap for a typical Planar Inverted F-Antenna (PIFA) design and simultaneously indicates the required separation between the substrate and ground, therefore guaranteeing a bandwidth of 500 MHz for patch antennas driven by Antenna Array 3X1 probes.

Regarding the electronic components of the transceiver, the design process has kept the system's complexity at a low degree. Among the main parts are LoRa modules, Antenna Array 3X1 modules, microcontroller units

(MCUs), and power supply devices. With circuit connections set in line with traditional systems, the first three are required and match the LoRa/LoRaWAN end devices now in use on market. Establishing the necessary connections for the Antenna Array 3X1 module follows the model and firmware derived from the STMicroelectronics Antenna Array 3X1 MEK1 localization board [20]. Eventually the Antenna Array 3X1 module interacts with the MCU, which is also connected to the LoRa module.

Moreover, the market price of widely used LoRa modules and microcontroller units (MCUs) is minimal (approximately 10 USD), and with the recent introduction of STM32WL microcontrollers by STMicroelectronics, a further reduction in cost is anticipated due to the integration of LoRa modules within the same microcontroller architecture. The cost of Antenna Array 3X1 modules currently fluctuates based on the integration board. This module is offered as a sample and is exclusively marketed with the MEK1 board; however, alternative Antenna Array 3X1 modules are accessible at a comparatively low cost (approximately 25 USD), including those from Decawave. The proposed Antenna ARRAY 3X1-LoRa localization concept is viable and remains feasible, irrespective of the selected LoRa or Antenna Array 3X1 module.

3.3 Antenna Structure Design

Comprising a ground and antenna patch both operating at 270 MHz, the antenna configuration is Using CST Microwave software, the design and simulation are done with an eye toward just the board's antenna component. The location of the electronic module is considered to guarantee enough area for its later integration during the manufacturing process.

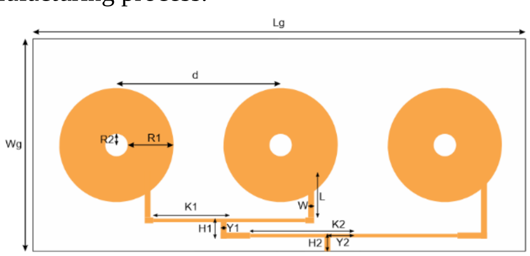

Figure 4. 3x1 antenna array patch design with a frequency of 920 MHz

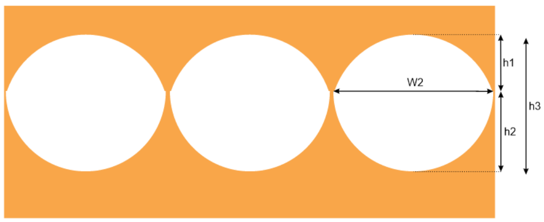

Figure 5. 3x1 antenna array Ground design with a frequency of 920 MHz

The dimensions of the antenna array (Figure 1) are as follows: substrate length Lg = 285 mm and width Wg = 123 mm. The design is intended to function at a mid-frequency of 920 MHz. The dimensions of the 3x1 antenna array for LoRa IoT applications are provided here.

Table 1. Summary of the physical dimensions of the antenna

Parameters	Dimension (mm)
R1	26.5
R2	6.5
Lg	285
Wg	123
d	95
K1	44
K2	60
H1	11.5
H2	10.105
Y1	3.372
Y2	15.3
W	3.372
W2	93.043
L	26
H1	32.824
h2	46.45
H3	79.228

4. Result

Figure 5 shows a prototype of the LoRa transceiver created here. Along with the feed and shorting connection from the ground plane to the upper layer PIFA element, the upper and lower layers are built independently and then joined by soldering the feed connection from the coupler output to a small capacitive patch adjacent to the transmitter element for the Antenna Array 3X1 antenna. Whereas both antenna inputs (LoRa and Antenna Array 3X1) receive power from their corresponding modules, the transceiver board is energized by a small external battery as seen in Figure 3.

Figure 6. Prototype of the 3x1-LoRa Antenna Array transceiver board

4.1 Antenna Measurement

4.1.1 Impedance Matching

UFL-type connections are pre-designed on both branch line coupling inputs (representing the two input ports of the Antenna Array 3X1) and UFL-to- SMA cables are used for measurements with the Vector Network Analyzer (VNA), as shown in Figures 5 and 6 to evaluate antenna impedance matching before testing the board.

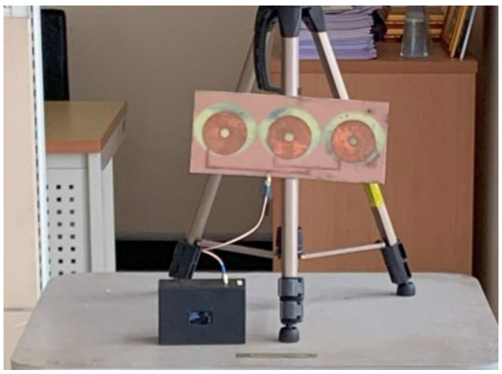

Figure 7. Stand-alone antenna matching experiments using SMA connectors for LoRa antennas and UFL-to-SMA cables from coupler inputs to characterize Antenna Array 3X1.

The SMA connector of the cable linked to one of the coupler's isolated input ports is subsequently energized via a 50 Ω lighter. The LoRa antenna's feed is directly linked to the SMA connector for measurement (Figure 5). Foam possessing an identical dielectric constant to air is utilized between the two layers of the board to aid in the assembly process.

S-Parameter

Image 10 illustrates the S-Parameter results of the LORA antenna design utilized in the IoT with the B-OSA system. Our findings indicate the frequency discrepancy between simulation and measurement. This discrepancy arises from the antenna fabrication process, resulting in a design that deviates from the antenna simulation model. The measurement results indicate that the antenna impedance is calibrated at -10 dB from approximately 770 MHz to 940 MHz, encompassing the targeted LoRa channel (920 MHz) for IoT systems.

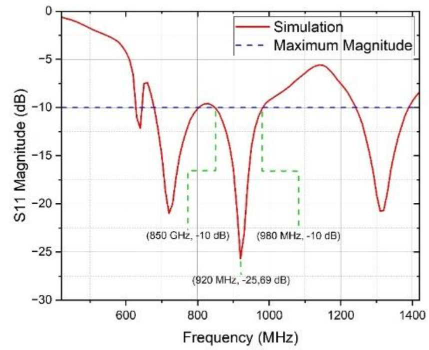

Figure 8. Simulation results of S-Parameters of antenna design

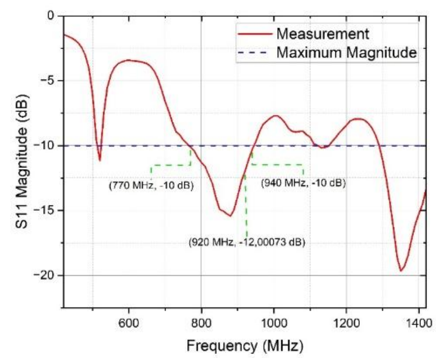

Figure 9. Measurement results S-Parameter 3x1 920 MHz array antenna

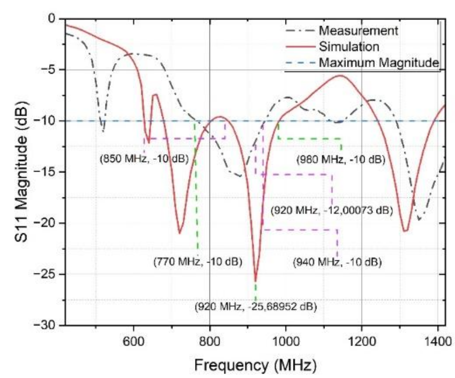

Figure 10. Comparison of simulation S-parameter data with measurement.

VSWR (Voltage Standing Wafe Ratio)

The VSWR results depicted in Figure 13, derived from simulations and measurements, exhibited a discrepancy at the target frequency of 920 MHz. The simulation indicated a VSWR value of 1.10958, whereas the antenna measurement recorded a value of 1.67082. Despite the discrepancies between the simulation and measurement of the antenna design, both values remain compliant with the suitability criterion, which is a VSWR value below 2. The disparity between simulation and antenna measurement arises from the antenna fabrication process relative to the simulation design implemented.

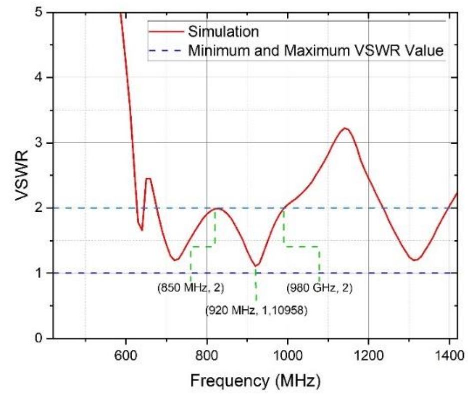

Figure 11. VSWR results from a simulation of a 3x1 antenna array design for a frequency of 920 MHz

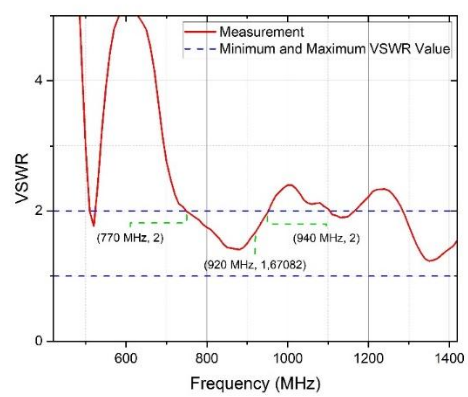

Figure 12. VSWR results from 3x1 antenna array design measurements for 920 MHz frequency

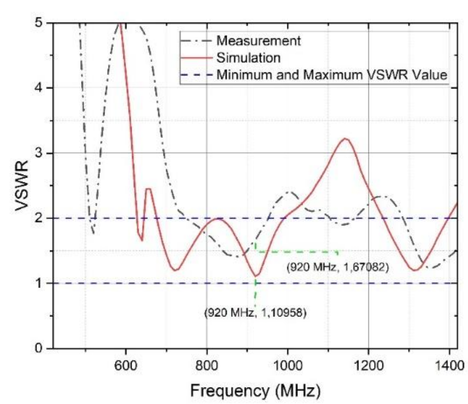

Figure 13. The results of the VSWR value comparison from the simulation and measurement results.

Figure 8 shows the 3X1 Antenna Array's measured and simulated reflection coefficients. By switching the isolation load between the two inputs of each port connected with the branch line coupler, one measures the coefficient independently twice. Both times one of the ports has to be closed with a 50 Ω load. Choosing the input port for the antenna helps one to establish the interpretation of circular polarization, more especially with relation to polarization. Figure 15 shows the simulated and measured 3X1 antenna arrays' efficiency and gain. In both simulation and measurement, the results show constant gain and efficiency inside the designated frequency range (3.75–4.25 GHz). With a difference of less than 1 dB, the measured gain ranges from 5.1 dBi to 6 dBi at various frequencies, so affirming that the performance of the antenna is consistent over all channel frequencies. The radiation efficiency falls between -1.26 and -1.4 dB, meaning between 72 and 75%.

4.1.2 Radiation Patterns

At a frequency of 920 MHz, Figure 16 shows the simulated radiation pattern—achieved gain—of a LoRa antenna around the transceiver board. The results show that the antenna has an omnidirectional radiation pattern with two radiation nulls along the PCB axis. The antenna reaches a measured peak gain between 0 and 1 dBi.

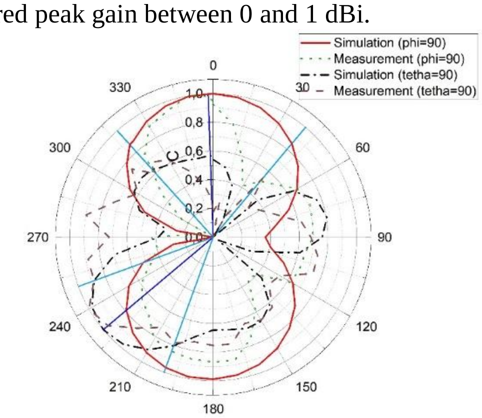

Figure 16. The LoRa antenna radiation pattern at a frequency of 920 MHz.

5. Discussion

The evaluation of localization performance involves two examined steps. The initial component is the operational two-way Antenna Array 3X1, which establishes the range between the sensor tag and the reader, while the subsequent component involves the transmission of location data to the gateway and LoRa network. The subsequent sections provide a detailed account of these steps.

- *From Sensor Tag to Reader*

Two Antenna Array 3X1-LoRa transceachers were used for range measurements; one was a sensor tag and the other a reader. The wide bandwidth of Antenna Array 3X1 signals and their transmission at power spectral density levels equivalent to the noise levels of conventional radio receivers, including WiFi and Bluetooth, make experimental testing with these signals insensitive to interference from other devices in the same environment [27,28].

Figure 17 illustrates the measurement configurations and surroundings. Outdoor environments are favored due to their greater spatial availability compared to structures, facilitating performance measurement on the line of sight and analysis of the maximum detection range attained via Antenna Array 3X1 localization. This range pertains solely to the Antenna Array 3X1 segment of the system, not the entire Antenna Array 3X1-LoRa range. This maximum distance indicates the optimal placement of the intermediate reader node within the system, specifically the permissible distance from the sensor tag for effective detection.

.

Figure 17. The measurement is done through two LoRa transceivers, with the first being the sensor tag and the second being the reader.

6. Conclusion

This research analyzes the possibilities of reaching high-precision, long-range localization utilizing Antenna Array 3X1 and LoRa technology. A multi-standard transceiver board is presented as a solution. The board comprises a 3X1 antenna array module, a LoRa module, and a microcontroller unit (MCU) that permits communication between the two. Transceivers may work as sensor tags inside LoRa system, as reader devices, or serve both purposes. This enables the localization of sensor tags with Antenna Array at a 3X1-level precision (a few centimeters) and the transfer of position data to LoRa gateways situated many kilometers from the sensor tag to the network. A 3X1 LoRa transceiver antenna array was built, and two prototypes were utilized for distance measuring in both outdoor and interior conditions. The findings indicate the localization range and precision of the 3X1 antenna array, coupled with successful transmission to the LoRa gateway for real-time sensor monitoring, all while conforming to the low power requirements of LoRa communications. Future efforts should focus on increasing the compactness of the proposed localization transceiver's antenna, particularly for sensor tags, in order to simplify their incorporation into various monitored objects. Miniaturization is achieved by selecting a higher frequency channel and modifying the antenna correspondingly. Another aspect of improvement is the incorporation of direction detection capabilities alongside range, which is possible through the design of an antenna array on the reader side, which can capture the range signal using array elements and determine the angle of arrival related to the directional component..

References

1. Khutsoane, O.; Isong, B.; Abu-Mahfouz, A.M. IoT devices and applications based on LoRa/LoRaWAN. In the Proceedings of IECON 2017-43th Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, October 29-November 1, 2017; Thing. 6107-6112. [CrossRef]
2. Merhej, D.; Ahriz, I.; Garcia, S.; Terré, M. LoRa-Based Indoor Localization. In the proceedings of the 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), Helsinki, Finland, June 19-22, 2022; pp. 1 - 5. [CrossRef]
3. Marquez, L.E.; Calle, M. Understanding LoRa-Based Localization: Foundations and Challenges. *IEEE Internet Things J.* **2023**, *10*, 11185-11198. [CrossRef]
4. Mekki, K.; Bajic, E.; Chaxel, F.; Meyer, F. Comparative study of LPWAN technology for large-scale IoT deployments. *ICT Express* **2019**, *5*, 1-7. [CrossRef]
5. Augustin, A.; Yi, J.; Clausen, T.; Townsley, W.M. A Study on LoRa: Long-Range Networks & Low Power for the Internet of Things. *Censorship* **2016**, *16*, 1466. [CrossRef] [PubMed]
6. Devalal, S.; Karthikeyan, A. LoRa Technology-An Overview. In the Proceedings of the Second International Conference 2018 on Electronics, Communications and Aerospace Technology (ICECA), Coimbatore, India, March 29-31, 2018; pp. 284 - 290. [CrossRef]
7. Muppala, R.; Navnit, A.; Devendra, D.; Matera, E.R.; Accettura, N.; Hussain, A.M. Feasibility of Independent TDoA-Based Localization Using LoRaWAN. In the Proceedings of the 2021 International Conference on Localization and GNSS (ICL-GNSS), Tampere, Finland, 1-3 June 2021; pp. 1 - 7. [CrossRef].
8. Kombo, O.H.; Kumaran, S.; Bovim, A. Design and Implementation of Low-Cost, Low-Power, LoRa-GSM IoT-Enabled Systems for Groundwater Resources Monitoring With Energy Harvesting Integration. *IEEE Access* **2021**, *9*, 128417 - 128433. [CrossRef]
9. Ferrero, F.; Truong, H.-N.-S.; Le-Quoc, H. Multi-harvest solution for autonomous sensing nodes based on LoRa technology. In the Proceedings of the 2017 International Conference on Advanced Technologies for Communication (ATC), Quy Nhon, Vietnam, October 18-20, 2017; pp. 250 - 253. [CrossRef]
10. Dardari, D.; Closas, P.; Djuric, P.M. Indoor Tracking: Theory, Methods, and Technology. *IEEE Trans. Wow. Technol.* **2015**, *64*, 1263-1278. [CrossRef]

11. Dardari, D.; Conti, A.; Ferner, U.; Giorgetti, A.; Win, M.Z. Ranging with Ultrawide Bandwidth Signals in a Multipath Environment.
Proc IEEE **2009**, *97*, 404 - 426. [CrossRef]
12. *IEEE Std 802.15.4z-2020*; IEEE Standards for Low-Level Wireless Networks - Amendment 1: Ultra Wideband (ANTENNA ARRAY 3X1) Enhanced Physical Layer (PHY) and Related Coverage Techniques. IEEE: New York City, NY, USA, 2020; thing. 1-174.
13. Coppens, D.; Shahid, A.; Lemey, S.; Marshall, B.V.H.C.; De Poorter, E. An Overview of the Ultra-WideBand (ANTENNA ARRAY 3X1) Standards and Organizations (IEEE 802.15.4, FiRa, Apple): Aspects of Interoperability and Future Research Directions. *IEEE Access* **2022**, *10*, 70219-70241. [CrossRef]
14. Benouakta, A.; Ferrero, F.; Lizzi, L.; Staraj, R. Contribution of Antenna Characteristics to Real-Time ANTENNA ARRAY 3X1 Enhancement Finds System Read Range and Multipath Mitigation. *IEEE Access* **2023**, *11*, 71449 - 71458. [CrossRef]
15. Pospisil, J.; Fujdiak, R.; Mikhaylov, K. Investigation of TDoA-Based Localization Performance Through LoRaWAN in Theory and Practice. *Sensor* **2020**, *20*, 5464. [CrossRef] [PubMed]
16. Daramouskas, I.; Mitroulias, D.; Perikos, I.; Paraskevas, D.; Kapoulas, V. *Localization in LoRa Networks Based on Arrival Time Differences* ; Springer: Cham, Switzerland, 2022; pp. 130 - 143. [CrossRef]
17. Fargas, SM; Petersen, MN GPS-free Geolocation uses LoRa in a low-power WAN. In the Proceedings of the 2017 Global Things Internet Summit (GIoTS), Geneva, Switzerland, 6 - 9 June 2017; pp. 1 - 6. [CrossRef]
18. Ha, G.Y.; Seo, S.B.; Oh, H.S.; Jeon, W.S. LoRa ToA-Based Localization Using the Fingerprint Method. In the Proceedings of the International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Republic of Korea, October 16-18, 2019; pp. 349 - 353. [CrossRef]
19. Aarif, L.; Tabaa, M.; Hachimi, H. Experimental test and performance of RSSI-based indoor localization in LoRa Network. *Procedia Comput. Sci.* **2022**, *203*, 420 - 425. [CrossRef]
20. Strzoda, A.; Marjasz, R.; Grochla, K. How Accurate Is LoRa Positioning Under Realistic Conditions? In the Proceedings of the 12th ACM International Symposium on Network Design and Analysis of Smart Vehicle Networks and Applications, Montreal, QC, Canada, October 24-28, 2022; Computing Machine Association: New York, NY, USA, 2022; pp. 31-35.
21. Li, B.; Xu, Y.; Liu, Y.; Shi, Z. LoRaWAPS: Wide Area Positioning System Based on LoRa Mesh. *Appl. Sci.* **2023**, *13*, 9501. [CrossRef]
22. Kwasme, H.; Ekin, S. RSSI-Based Localization Using LoRaWAN Technology. *IEEE Access* **2019**, *7*, 99856 - 99866. [CrossRef]
23. Lam, K.-H.; Cheung, C.-C.; Lee, W.-C. RSSI-Based LoRa Localization System for Large-Scale Indoor and Outdoor Environments.
IEEE Trans. Wow. Technol. **2019**, *68*, 11778-11791. [CrossRef]
24. B-ANTENNA ARRAY 3X1-MEK1-Evaluation Kit for the B-ANTENNA ARRAY 3X1-MOD1-STMikroelektronika Ultra-Wideband Module. Available online: https: www.st.com/en/wireless-connectivity/b-Antenna Array 3x1-mek1.html (accessed on February 3, 2023).
25. Benouakta, A.; Ferrero, F.; Lizzi, L.; Brochier, L.; Staraj, R. Measurement of the effect of antenna polarization on Ultra-Wideband monitoring and localization. In the Proceedings of the 2021 IEEE Conference on Antenna Measurement & Applications (CAMA), Antibes Juan-les-Pins, France, November 15-17, 2021; pp. 589-590. Benouakta, A.; Ferrero, F.; Lizzi, L.; Staraj, R. Reconfigurable and Polarized Patch Antennas Circular Through Dual Wideband Channels. In Proceedings of the 16th European Conference on Antennas and Propagation (EuCAP) 2022, Madrid, Spain, 27 March - 1 April 2022; pp. 1 - 5. [CrossRef]
26. Ghavami, M.; Michael, L.B.; Kohno, R. *Ultra Wideband Signals and Systems in Communication Engineering*, 1st ed.; Wiley: Hoboken, NJ, USA, 2007. [CrossRef]
27. Duran, M.A.C.; D'Amico, A.A.; Dardari, D.; Rydström, M.; Sottile, F.; Ström, E.G.; Taponecco, L. Chapter 3-Terrestrial Network-Based Positioning and Navigation. In *Satellite and Terrestrial Radio Positioning Techniques*; Dardari, D., Falletti, E., Luise, M., Eds.; Academic Press: Oxford, England, 2012; pp. 75 - 153. [CrossRef]
28. Ghassemzadeh, S.; Greenstein, L.; Kavcic, A.; Sveinsson, T.; Tarokh, V. Empirical Indoor Trajectory Losses Model for Ultra-Wideband Channels. *J. Commun. Netw.-JCN* **2003**, *5*, 303 - 308. [CrossRef]
29. Frattasi, S.; Rosa, F.D.; Dardari, D. Ultra-wideband Positioning and Tracking. In *Mobile Positioning and Tracking*; Frattasi, S., Rosa,
FD, Eds; Wiley: Hoboken, NJ, USA, 2017. [CrossRef]
30. Rubio, L.; Reig, J.; Fernández, H.; Rodrigo-Peñarrocha, V.M. Disadvantages of Experimental ANTENNA ARRAY 3X1 Propagation Canal Trajectories and Time Dispersion Characterization in a Laboratory Environment. *Int. J. Propag Antenna.* **2013**, *2013*, e350167. [CrossRef]