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Research Article

Design and Implementation of Directional Sensors for Privacy-Ensured Device-Free Target Localization in Indoor Environment

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This paper presents two radio frequency (RF) sensors with different directivities designed and tested for device-free localization (DFL) in an indoor environment. Mostly, in smart homes and smart offices, peoples may be irritated by wearing the device on them all the time. As compared with device-based localization, the proposed sensors can localize both cooperative and non-cooperative targets (intruders and guests etc.) without privacy leakages. Both sensors are tested to detect the change in received signal strength (ΔRSS) due to the presence of an obstacle. RF sensors, i.e., antennas are designed to operate in the ISM band of 2.4–2.5 GHz. Experimental results show that the sensor with higher directivity provides better ΔRSS that helps in improved accuracy to detect a device-free target.

1. Introduction

Accurate indoor localization of objects and people is among the most researched areas nowadays for many applications such as indoor navigation, location-based services, and advertisements [1–3]. One of the significant challenges in indoor localization is the use of device or tag by the target to be localized, such as RFID tags and smartphones [4–7]. Device-based localization is not suitable in case of non-cooperative targets (passive targets) such as intruders and guests. Mostly, in smart homes [8] and smart offices, people may be irritated by wearing the device on them all the time. Tag-based localization is highly prone to the leakage of privacy and personal information, e.g., a person's daily routine [9–12]. Many techniques have been proposed for the localization of non-cooperative targets such as thermal infrared sensors, pressure sensors, sound source, light sensors, electric field, ultrasonic sensors, and radio frequency- (RF-) based localization schemes [13–15].

In pressure sensor-based localization, pressure sensors are installed beneath the floor. This is a traditional way of passive localization. Position identification is made by sensing pressure on the floor [16–18]. Different systems are proposed in this regard. One of them is a load cell system that uses load sensors for user localization, and larger size tiles are used to reduce the number of sensors [19]. There is a tradeoff between system complexity and the number of targets detected simultaneously versus the size of the tile used. Another approach is the use of a pixelated surface (mat), which uses sensors made of binary switches. These sensors are costly to be used in larger areas. Magic carpet [20] and electromechanical film (EMFi) are commercially available systems, but their installation is complicated. Alternatively, the Z-tile system [21] and smart carpet [22] are easily scalable and commercially available solutions. Overall the installation of a pressure sensors system is complicated and laborious and needs modification of the floor, which is sometimes not feasible in already constructed buildings.

Another way to localize a device-free target is to use infrared sensors [23]. The wavelength of infrared light ranges from 750 nm to 1 mm. This wavelength corresponds to temperature radiated by the objects having temperatures between 0 and 70°C [24]. An infrared camera uses a microbolometer detector, which is used to create a thermal image for localization [25]. Many devices use the microbolometer detector, but these are very expensive. Other detectors such as quantum detectors and Golay cell [26, 27] are inefficient in the home environment. Alternatively, pyroelectric and thermopile detectors are affordable as they detect a change in heat and generate an electric signal [28]. In thermal infrared sensing metals, lamps and heater disrupt the image and make difficulties for the identification of persons or objects. So, the quantity and placing of the sensors are critical considerations to increase the performance. Multitarget tracking is another issue in thermal infrared sensing, although many techniques and algorithms are being developed [29].

The localization of sound sources is categorized in active and passive sources. Active sources send a signal and detect the presence of the user by the reflected signal as in sonar, while passive sources only detect the sound signal generated by the target [30]. Microphones are used as a sensor in sound sources localization. Generally, an array of microphones is used to measure the time difference of arrival (TDOA) to calculate the position of a target. Accuracy is increased by placing many sensors and using triangulation and keeping the same frequency characteristic of all sensors [31]. Main algorithms for sound source localization are TDOA [32], steered beamforming [33], and high-resolution spectral estimation [34]. There are many drawbacks of sound source localization, as it gives false detection due to echo, noise, and sound from other sources [35].

Ultrasound localization is based on the travel time of waves from one position to another position. Time difference of arrival (TDOA) and time of flight (TOF) are two methods used for ultrasound-based positioning. The TDOA-based technique uses two transmitters and a receiver and calculates the difference for locating the target; however, this method is sensitive to noise. While in the TOF method, time to travel from the transmitter to the receiver is calculated for localization [36]. In [37], ultrasound localization is done by calculating TOF of receive wave reflected off person's head. The complexity of the system increases sharply by increasing the region of interest. Synchronization and multipath are other challenges in an indoor environment.

Electric field positioning is based on the principle that the human body conducts low-frequency signals [38]. Mainly two modes are proposed for localization, i.e., human shunt and human transmitter. In the human shunt mode, the potential difference (ΔV) between transmitter and receiver electrodes generate a displacement current, that flows from transmitter to receiver, and when a person enters in the vicinity of an electric field, displacement current decreases due to shunt of the electric field to ground, which helps in locating a person. In the human transmitter method, the human body acts as an electric field transmitter as a person moves toward the receiver, electrode displacement current increases, which helps to locate a person. Some practical solutions are tile track [39], electric field resonance coupling [40], and electric sensors with intelligence (ELSI) system [41]. These systems are inexpensive, but installation is expensive and complex.

Light sensors detect a change in the level of light to estimate the position of the target. AOA-based measurements are used as a sensing parameter. AOA from different sensors is used to estimate the location of the target through the intersection of directional lines. However, these sensors work only in the presence of light, which is not feasible to use in all environments [42], for example, at night.

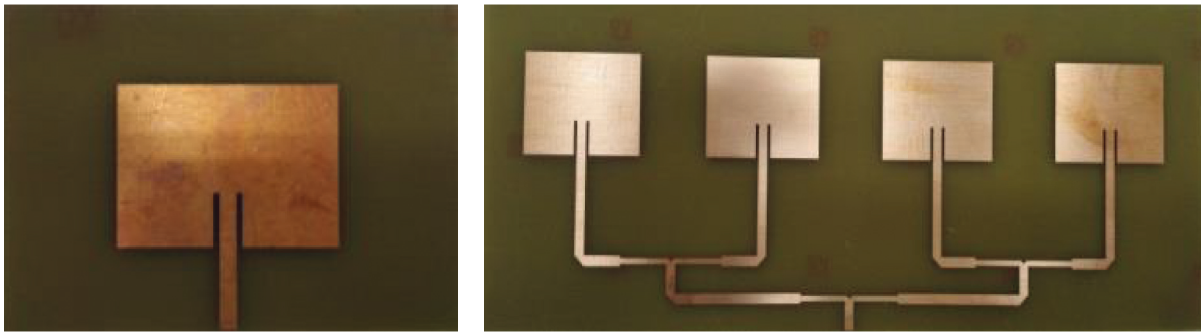
The device-free localization (DFL) techniques pose some challenges such as environmental dependency, installation complexity, and resizing. However, RF-based localization caters to these challenges and shows effective results. RF-based passive localization using Wi-Fi infrastructure detects the change in RSS, but this change is insignificant due to the omnidirectional pattern of the Wi-Fi antenna. RF-based DFL works on the principle that obstacles affect the strength of radio signals. Saeed et al. [14] presented a system using Wi-Fi access point as a transmitter and laptop as the receiver to detect human presence. This system needs a human presence profile for calibration during the initial installation. The system deployment on a large-scale area increases the calibration overheads. These systems are not accurate and often produce false alarm [43–45]. The antenna radiation pattern is very important while implementing the localization system, as it affects the RSS value according to its radiation pattern.

Directional antennas have been used for estimating the angle of arrival (AOA) to localize the active target (target bearing a tag) [46–48]. However, to the best of our knowledge, directional antennas have not been used for DFL. To overcome the limitations of DFL systems based on antennas with poor directivity, we proposed a localization system based on antennas with higher directivity.

2. Methodology

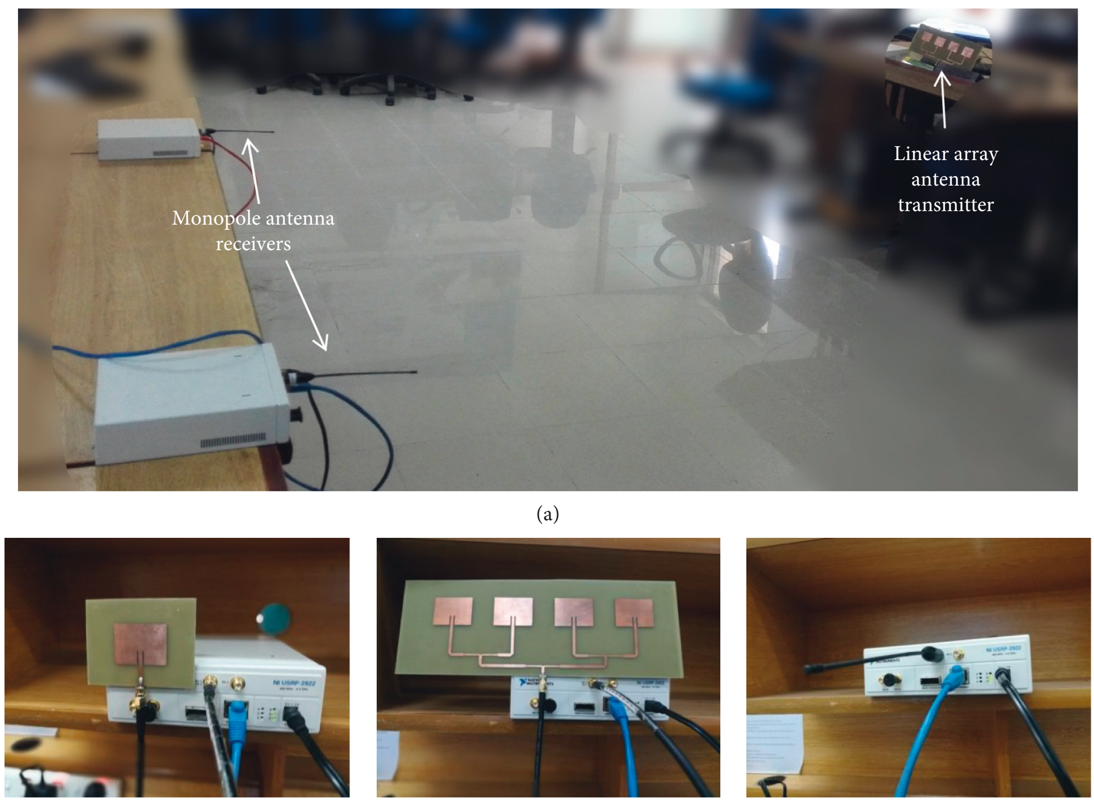
Directional antennas incorporate AOA measurements with RSS-based measurements, which help to detect the target with more accuracy. We have designed a microstrip patch antenna and a linear array of patch antennas at 2.45 GHz. These antennas are used as RF sensors to test for DFL. An experiment is carried out to detect the change in RSS first using a sensor with lower directivity and then a sensor with higher directivity. These antennas are used in transmitting mode, while two monopole antennas are used as receivers. We have measured the RSS values from two different angles at receivers with and without target (human).

2.1. Sensor Design. The simulations and optimization of proposed RF sensors were done through finite integration technique-based CST microwave studio 2014. A low cost and easily available FR4 substrate was used with the relative permittivity of 4.4 and a dielectric loss of 0.02, while the thickness of the substrate is 1.6 mm. Two-sided copper



(a) (b)

Figure 1: Fabricated antennas: (a) single microstrip antenna and (b) linear array of microstrip antennas.



(a)

(b) (c) (d)

Figure 2: (a) Localization experiment environment. (b) Single microstrip antenna attached with USRP. (c) Linear array of microstrip antennas attached with USRP. (d) Monopole antenna attached with USRP.

cladding is used for the radiating patch (top) and ground (bottom) of the substrate. For practical realization and to demonstrate the proposed designs experimentally prototypes of both the designs are fabricated. A standard technique for designing the printed circuit board (PCB) called wet etching is used for fabrication of proposed RF sensor designs. The fabricated prototypes are shown in Figure 1.

2.2. Localization Experiment. Figure 2 shows the experimental setup used to test the effect of the directivity of the designed RF sensors at 2.45 GHz for target localization. To perform localization experiments, we have used National Instrument USRP (Universal Software Radio Peripheral) kits as transceivers. Fabricated antennas are used as transmitters, and two monopole antennas are used as receivers, which are placed at 0° and 20°. First, the localization experiment is carried out by using the single patch antenna as a transmitter and then the linear array antenna as a transmitter. In this experiment, we have measured the RSS at both receivers when no target is present. Then, the RSS is measured again in the presence of the target (human). To verify the effect of antenna directivity on RSS, we have measured the RSS by placing the target at 0° and then at 20°.

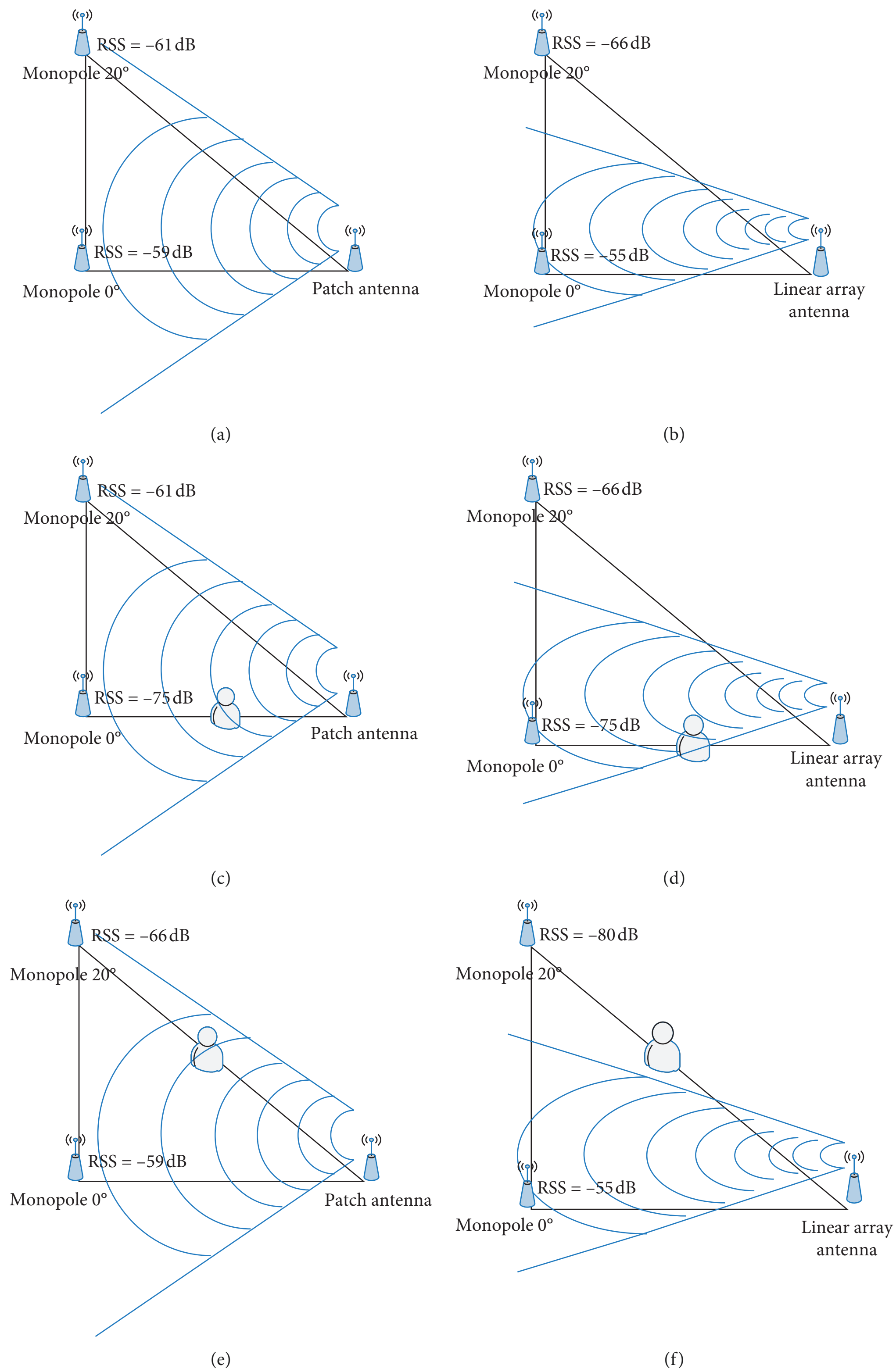


FIGURE 3: Localization experiment scenarios: (a) patch antenna without target; (b) linear array antenna without target; (c) single patch with target at 0°; (d) linear array with target at 0°; (e) single patch with target at 20°; (f) linear array with target at 20°.

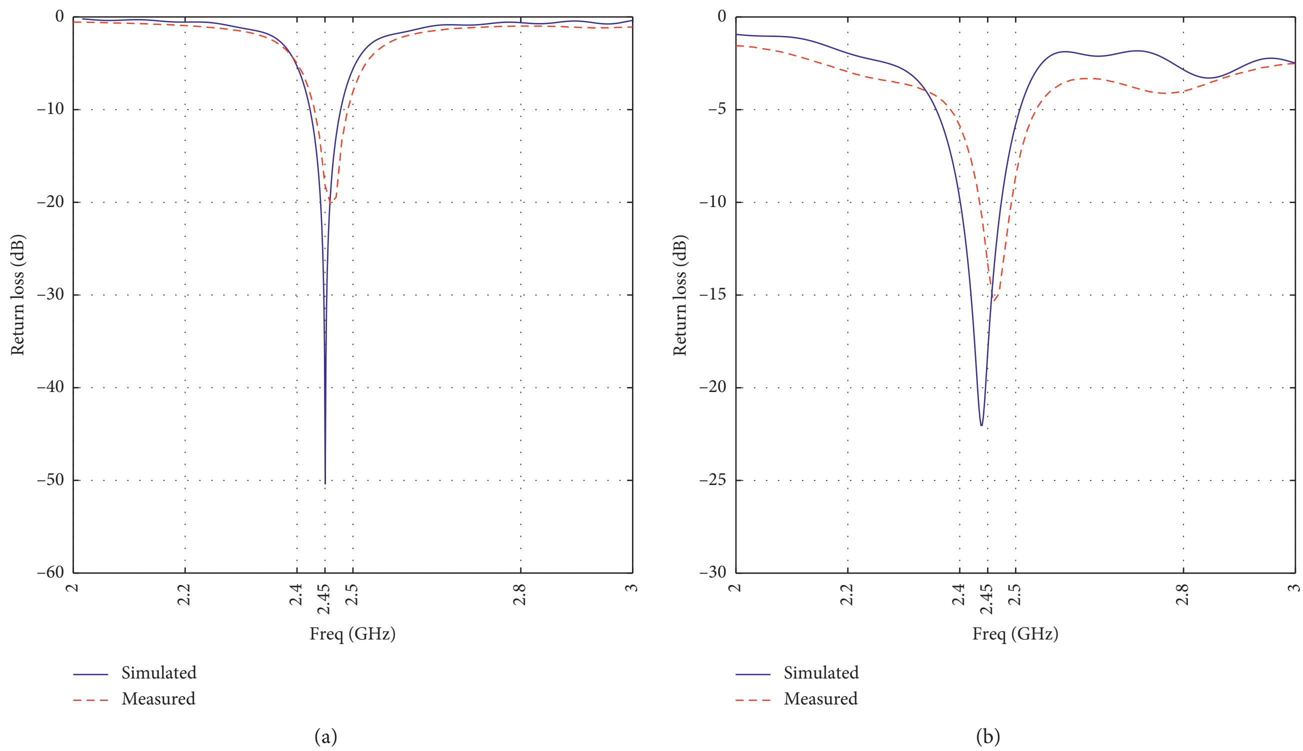


Figure 4: Simulated and measured return loss: (a) single microstrip antenna and (b) linear array of microstrip antennas.

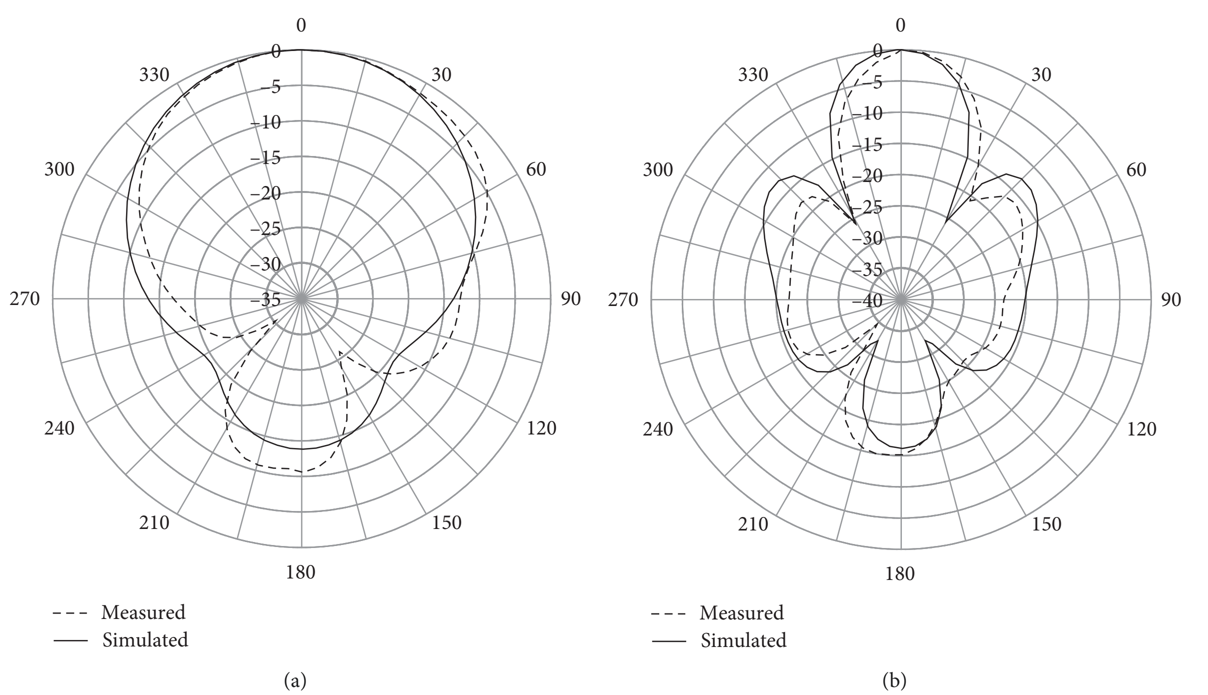


Figure 5: Simulated and measured radiation patterns: (a) sensor with lower directivity and (b) sensor with higher directivity.

RSS is measured at both receivers with monopole antennas in six scenarios as follows:

(1) The single patch antenna as the transmitter without a target

(2) The single patch antenna as the transmitter with the target (human) at 0°

(3) The single patch antenna as the transmitter with the target (human) at 20°

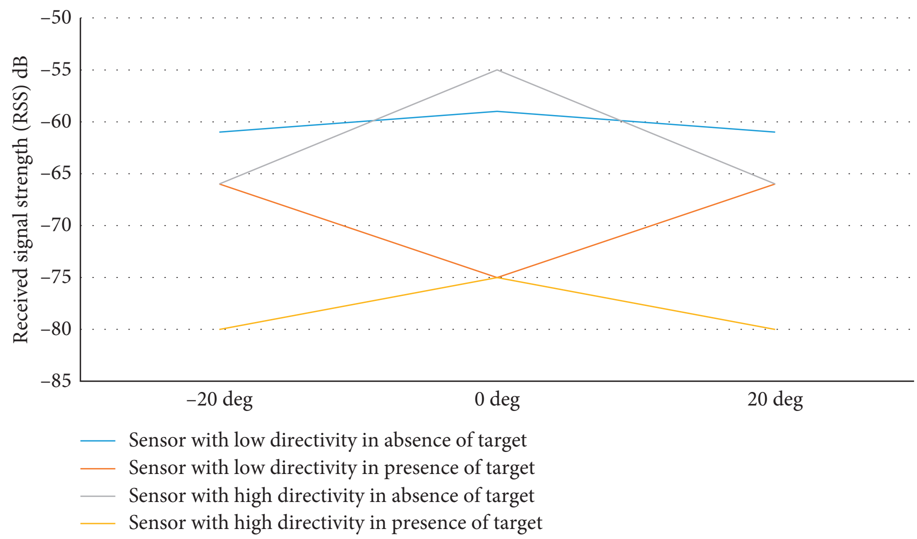


FIGURE 6: Measured RSS values for localization experiment scenarios.

TABLE 1: Comparison of change in received signal strength for all measurements.

Antenna type	Scenario	In the absence of target	In the presence of target	$\lvert\Delta RSS\rvert$
Single patch antenna	RSS at 0° (dB)	−59	−75	16
	RSS at 20° (dB)	−61	−66	5
Linear array antenna	RSS at 0° (dB)	−55	−75	20
	RSS at 20° (dB)	−66	−80	14

(4) The linear array as transmitter without any target

(5) The linear array as transmitter with the target (human) at 0°

(6) The linear array as transmitter with the target (human) at 20°

These six scenarios are pictorially represented in Figure 3.

3. Results

The RF sensors were simulated in CST, and the fabricated sensors were tested for return loss using VNA, and the radiation pattern measurements were done in an anechoic chamber.

In order to carry out the RSS measurements, a single frequency signal is enough, and covering the entire ISM band is not necessary. The only requirement is that the antennas should resonate in the ISM license-free band. Return losses of the simulated and the fabricated patch antenna and linear array antenna are shown in Figure 4. Both antennas resonate in the desired frequency band (2.4–2.5 GHz), and the simulated and fabricated return losses of both the designs are in close agreement. The slight shift of the resonance is due to the fabrication and measurement losses.

Both the simulated and measured radiation patterns of the patch antenna and the linear array antenna are shown in Figures 5(a) and 5(b), respectively. From the comparison of Figures 5(a) and 5(b), it is evident that the linear array antenna is more directive than the single element patch antenna. Moreover, the simulated and fabricated radiation patterns of both the antennas are in close agreement.

These sensors were used to carry out the localization experiment for performance evaluation. Figure 6 shows that in the case of the sensor with lower directivity at 0° with respect to broadside the RSS values drops from −59 dB to −75 dB resulting a $\lvert\Delta RSS\rvert = 16$ dB as compared with a drop in RSS for sensor of higher directivity from −55 dB–75 dB resulting a $\lvert\Delta RSS\rvert = 20$ dB that is improved by 4 dB. At the angles of ±20° with respect to broadside for the sensor with lower directivity the RSS values drops from −61 dB to −66 dB resulting in a $\lvert\Delta RSS\rvert = 5$ dB as compared with a drop in RSS for the sensor of higher directivity from −66 dB–80 dB resulting in a $\lvert\Delta RSS\rvert = 14$ dB that is improved by 9 dB. These results are summarized in Table 1.

4. Discussion

In the localization experiment, we have proved that by using directive sensors, we can detect a significant change in RSS. The accuracy of localization depends on the change in RSS due to the target. As the target comes in the range of the system, we detect the change in RSS at all receivers. The change in RSS using sensors with low directivity is almost the same when the link is interrupted. If the change is the same at all receivers, we cannot locate the target with certainty. For this purpose, the improvement in this value is required. This can be done if we use sensors with higher directivities, as their transmit power is only significant at the receiver, which is placed in its line of sight. Therefore, in the localization experiment, we have compared the change in RSS by using a high-directive antenna (sensor with higher directivity) and a relatively low-directive antenna (sensor with low directivity). We have got very prominent localization results, which endorse our proposed solution.

5. Conclusion

In this paper, the potential application of directional sensors for device-free indoor localization has been proposed. Patch antenna and linear array antenna were designed and tested in an indoor environment for device-free target localization. The results show that the change in RSS is more significant for sensors with higher directivity making them a better candidate for localization systems developed to localize device-free targets in indoor environments.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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