Investigation of Angle Dependent Errors in Phase-based Ranging with Different Antennas

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Abstract

Antenna orientation is an often overlooked factor in radio-based localization. Our experience with phase-based ranging suggests that antenna orientation has an impact on measured distances. Therefore, we investigate the impact of antenna orientation on phase-based ranging in the 2.4 GHz ISM band. Four different antenna types are tested in an anechoic chamber. Our evaluation is conducted end-to-end; we do not compare antenna properties by measuring parameters via a vector network analyzer but compare the measured distance between two wireless sensor nodes. Our evaluation shows that some antenna types report varying distance results at different rotation angles while other types are hardly influenced at all.

Categories and Subject Descriptors

B.8 [**Performance and Reliability**]: Performance Analysis and Design Aids

General Terms

Antenna, Localization, Measurement, Performance

Keywords

Phase-based Ranging, IEEE 802.15.4, Active Reflector

1 Introduction

Localization is an important tool in industry and logistics. Knowing the exact position of goods is helpful to optimize supply chains and production processes. In such scenarios, the goods are often localized by attaching a special wireless sensor node – called tag – to them. This tag then is localized by measuring some physical property, e.g. the Time of Flight (ToF), Received Signal Strength (RSS), or phase of a radio signal to an anchor node in a known location. The distance to the anchor is computed from the measured data. This process is known as *ranging*. Multiple distance measurements to different anchors allow localization in 3D space. We focus on ranging via radio signals. Using radio signals has the advantage, that robust sensor nodes can be built to survive in harsh industrial environments. In particular, we employ the Active-Reflector (AR) principle [8] for phase-based ranging in the 2.4 GHz ISM band.

Radio-based localization suffers from inaccuracies due to unwanted signal propagation. For example, propagation via reflections or through obstacles – also called multipath or Non-Line-of-Sight (NLOS) propagation – distort the radio signal. A valid distance estimation is hardly possible in such conditions [13]. In industry scenarios, it is impossible to control spatial relation between tag and anchor, hence it is impossible to avoid adverse radio channel conditions.

One additional parameter often neglected in research is the orientation of the antenna. Pelka et al. [11] evaluated the impact of antenna orientation for Ultra Wide Band (UWB) ToF ranging. They show that an error of up to 25 cm in distance can be attributed to the antenna orientation.

However, no evaluation was done for ranging methods based on the AR principle. While it is generally accepted that an additional distance error d_{offset} originates from the signal path between antenna and radio transceiver chip, it is unknown how this offset is affected by the incident angle of the measurement signal into the antenna. To the best of the authors' knowledge, this is the first evaluation of ranging errors induced by the antenna angle for phase-based ranging.

When designing antennas, the radiation pattern, which shows the antenna's signal strength for different angles, is an important parameter. However, for most antennas the phase shift of a signal for different angles remains unknown. Thus, choosing a suitable antenna for phase-based ranging based on data sheets is hardly possible. In this paper, we evaluate the end-to-end impact of antenna orientation on phase-based ranging. We test four different antenna types in an anechoic chamber.

Further, polarization of antennas plays an important role for radio-based localization. Monopole antennas (see Figure 1 b)), are commonly used for anchors. These antennas are Linear Polarized (LP). When two such antennas are oriented parallel to each other, they show optimal performance. If they are perpendicular to each other, communication is impossible. If antenna orientation cannot be controlled, this can influence system performance. Alternatively, Circular Polarized (CP) antennas (see Figure 1 a)) can be used. These work independently of their orientation. Such antennas are for ex-

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ample used to transmit video streams from quadrocopters. CP and LP antennas can also be mixed: Using a CP antenna with an LP antenna still results in orientation independence. However, the received signal will be attenuated by 3 dB. To demonstrate the effect of polarization mismatch, we deliberately place Monopole antennas perpendicular to each other and compare performance to a setup with parallel antennas.

Our findings help system designers to choose a reasonable antenna design for a localization application. We are not recommending a specific antenna. Instead, our work can help to evaluate antennas for localization systems.

The rest of the paper is structured as follows: In Section 2 we discuss related research on the topic of directional errors of antennas. Afterwards, we give a short introduction to the AR method and phase-based ranging in Section 3. We introduce our evaluation setup and the different antenna types in Section 4. The results of the evaluation are presented in Section 4.3. In Section 5 we discuss the implications of our findings on phase-based ranging and radio-based localization systems in general. The paper is concluded in Section 6.

2 Related Work

Pelka et al. [11] conducted an experiment to evaluate the angle induced ranging error for symmetrical double-sided two-way ranging with UWB transceivers. In their experiment, a tag is positioned at 20 different locations in a hallway. At each location, the tag is rotated at 90° angles and distances to 5 anchor nodes are measured. The authors observed up to 25 cm error originating from different measurement angles. They suspect that range bias, which is prevalent in UWB ranging systems based on DW1000 radio transceivers, is the cause of this error. Range bias is an error that changes with signal strength of the received UWB signal. With rotation of the antenna the received signal strength might change, thus influencing the range bias. However, Pelka et al. show that this error cannot be explained by range bias. As their experiment was conducted in a hallway, the effect of multipath propagation mixes with the effect from antenna orientation.

He et al. [6] evaluate the ranging error induced by a human body blocking the Line-of-Sight (LOS). In their setup, the receiving antenna is mounted to the human body and the sending antenna is placed at 5 m distance. Both antennas are connected to a vector network analyzer to evaluate the time it takes for a signal through the system. Then, the human body is rotated in 30° steps and the delay is measured. The authors derive a statistical model to simulate the ranging error induced by the human body at different rotation angles. The tests are conducted for different signal bandwidths, simulating UWB ranging.

Pöhlmann et al. [12] exploit the properties of a multi-mode antenna to estimate the Direction of Arrival (DoA) of a radio wave. A multi-mode antenna has no single connector like regular antennas, but multiple connectors. Due to the special design of such antenna, the signal strength at the antenna's ports differs, depending on the incident angle of the received signal. However, ambiguities remain for certain angles which cannot be distinguished from each other.

3 Phase-based Ranging via the AR principle

Our ranging system [15] employs the Active-Reflector (AR) principle [8] to measure the phase response Φ_{PMU} of a radio channel. We employ AT86RF233 radio transceivers [2] with an integrated Phase Measurement Unit (PMU). The PMU allows to measure the phase angle of an incident radio wave relative to a local reference.

3.1 Active-Reflector principle

The Active-Reflector (AR) principle [8] allows to measure the distance between two wireless transceivers. The two transceivers are called *initiator* and *reflector*. The initiator initiates the measurement and gathers the results, hence its name. The reflector acts as the target of the measurement. In a radar setup, the reflector would be a surface that reflects the signal. Here, the reflector *actively* reflects the signal. The measurement works as follows:

The initiator sends a Continuous Wave (CW) signal at measurement frequency f_1. The phase angle φ_{R1} is measured by the reflector. Next, both nodes change roles. The reflector sends a CW signal at frequency f_1 while the initiator measures the phase angle φ_{I1}. This is repeated on a second frequency f_2 and φ_{R2} and φ_{I2} are measured. The measurements are conducted with the local clock of the sensor nodes as reference. Thus, the measured values are meaningless on their own. By subtracting them, the unknown local clock offset is removed, see Equation 1. A detailed explanation of the AR principle can be found in [10].

$$\varphi_n = \varphi_{Rn} - \varphi_{In} \tag{1}$$

The distance can be computed according to Equation 2 via the frequency hub between f_1 and f_2 and the propagation speed in the medium c which is the speed of light for radio waves.

$$d = \frac{\varphi_2 - \varphi_1}{f_2 - f_1} \cdot \frac{c}{2\pi} \tag{2}$$

3.2 Complex-valued Distance Estimation

Computing the distance as shown in Equation 2 is prone to errors, as noisy phase measurements result in large distance errors. To mitigate this problem, the phase response Φ can be measured across multiple frequencies. The distance can be computed with various algorithms [9,10,14,15]. However, in our previous evaluation [14] the Complex-valued Distance Estimation (CDE) algorithm performed best among the competitors. CDE computes a complex signal from the measured phase response Φ and applies a Fast Fourier Transform (FFT). The maximum peak in the resulting spectrum is proportional to the distance. Additionally, the algorithm provides a Distance Quality Indicator (DQI). This indicator is a confidence value for the found distance estimation. It ranges from 0 (no confidence) to 1 (high confidence). The DQI can be used as a threshold to filter out erroneous measurements.

We will employ the interpolated Complex-valued Distance Estimation (iCDE) algorithm for all distance computations throughout the paper. This version of CDE uses interpolation to refine the distance estimation.

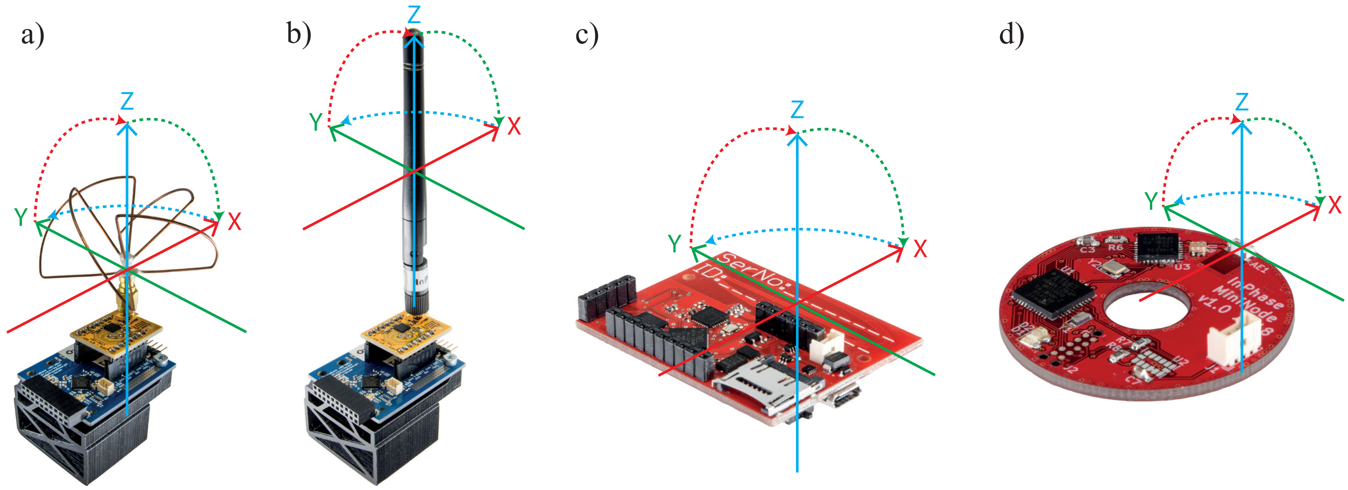

Figure 1. Evaluated antenna types. a) Skew-Planar Wheel antenna, b) Monopole antenna, c) PCB antenna, d) Chip antenna. Note: Pictures are not to scale.

3.3 Antenna Offset

The signal path from the antenna to the radio transceiver induces a constant distance error. The signal speed (speed of electromagnetic waves) in PCB traces (copper) is significantly lower than in air. Thus, even short signal paths result in an additional distance that is measured together with the distance between sensor nodes. It depends on the sensor node and antenna type and needs to be determined in advance. This offset is termed *antenna offset* and denoted as d_{offset}. Note, that d_{offset} has two components, one for each participating sensor node. This offset is not considered to be direction dependent.

4 Evaluation

The goal of our evaluation is to show the direction dependent error of different antenna designs. This information can be helpful when deciding on an antenna type for a specific localization application.

4.1 Antenna Types

We evaluated four different antenna designs which are introduced in the following paragraphs in more detail.

4.1.1 Skew-Planar Wheel Antenna

The *Skew-Planar Wheel Antenna* has four wings and resembles a wheel, hence its name. It is made from four wires, each being the wavelength of the desired center frequency, see Figure 1 a). Thus, the antenna is large and fragile. However, this antenna geometry results in a CP wave. The direction (right-hand or left-hand) is dictated by the mounting direction of the wings. Here, it is Right-Hand Circular Polarized (RHCP). A pair of CP antennas only can be used for transmission if they are both polarized in the same direction. Otherwise the receiving antenna cannot pick up any signal. A CP antenna can also be used in conjunction with an LP antenna. However, due to the polarization mismatch the signal will be attenuated by 3 dB.

We use a second antenna of this type at the *initiator* node for all experiments to ensure that polarization mismatch does not happen when rotating LP antennas. Only when evaluating polarization mismatch with Monopole antennas (see below), the *initiator* is equipped with a Monopole antenna. The second antenna is always mounted pointing upwards.

4.1.2 Monopole Antenna

The Monopole antenna is an off-the-shelf 2.4 GHz IEEE 802.11 antenna [5], see Figure 1 b). It can be folded at an angle via a joint close to its connector. This antenna has a length of half a wavelength and is covered in a rigid plastic housing. It emits LP waves which are polarized along the length of the antenna. Common linear polarization planes are horizontal and vertical with respect to the earth's surface. However, such antennas can be mounted at any angle resulting in arbitrary polarization planes. If two such antennas are mounted at a 90° angle, the polarization planes mismatch and transmission from one antenna to the other is theoretically impossible. In our setup the Monopole antenna is always used unfolded as seen in Figure 1 b).

Note, that we use a second antenna of this type at the *initiator* for evaluation of polarization mismatch. The antenna orientation at the *initiator* changes in these experiments, to either force or avoid polarization mismatch.

4.1.3 PCB Antenna

The Printed Circuit Board (PCB) antenna is part of an existing wireless sensor node design, see Figure 1 c). The INGA sensor node [4] is used in a multitude of different research projects, some of them being related to phase-based ranging and localization. Its antenna design is similar to a reference design by Atmel [1]. The design is a folded dipole antenna with the ends of the two poles touching, thus forming a closed loop. It is matched to the 100 Ω output impedance of the radio transceiver. The antenna is linear polarized along the long side, i. e. edge of the PCB. PCB antennas are very cost-efficient as no extra component is needed. Further, such an antenna is as robust as the PCB it is integrated into.

4.1.4 Chip Antenna

The evaluated chip antenna is a 2450AT18D0100 by Johanson Technology [7]. While the data sheet does not state the polarization of this antenna, chip antennas generally are

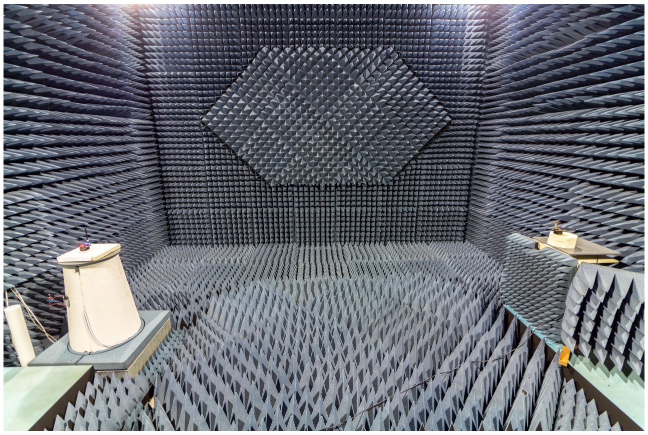

Figure 2. Experimental setup in anechoic chamber. Left: Rotating reflector node. Right: Static initiator node.

linear polarized across the long edge of the antenna. The chip antenna is mounted on a small PCB with the radio transceiver and micro controller, see Figure 1 d). The PCB has a large mounting hole in the center. The chip antenna measuring 3.2x1.6 mm is the smallest antenna in this evaluation, even with the needed clearance area on the PCB of 6x4 mm.

4.2 Experimental Setup

All measurements were conducted in an anechoic chamber, see Figure 2. Two nodes were placed 3.3 m apart. The *reflector* was fixed on a expanded polystyrene pillar. The *initiator* was positioned on a table which itself was surrounded by absorbent material to avoid interference.

The *initiator* node of the AR measurement remained static during the measurement. It was connected to a Skew-Planar Wheel antenna pointing towards the ceiling, resulting a RHCP signal. For the evaluation of polarization mismatch, a Monopole antenna was used at the *initiator*. This antenna was oriented to either force (perpendicular) or avoid (parallel) polarization mismatch. Measurement data was recorded via a USB connection to a laptop computer that was placed outside the anechoic chamber to avoid interference.

The *reflector* node was rotated automatically in 1° steps by a rotating table integrated into the polystyrene pillar and powered via a battery to rotate freely. Each antenna/sensor node was rotated around three orthogonal axes for a full 360° turn. Figure 1 indicates the axes and rotations. Solid lines indicate axes and dashed lines of the same color indicate rotation around the corresponding axis. An arrow's end indicates the 0° position of the rotation, while its head points towards increasing angles. As the setup only allows to rotate around one axis, the sensor node was placed on different sides in subsequent measurement runs to measure all axes. Note that at some angles, the sensor node itself blocks the LOS signal path and might interfere with the measurement.

4.3 Results

For each angle, 50 measurements were recorded. Each measurement consists of 200 phase samples recorded between 2.400 GHz and 2.500 GHz at 500 kHz intervals. Distances were computed via the iCDE algorithm with a FFT bin count of 512. We showed that the performance of iCDE is superior to other available algorithms in realistic scenarios [14]. The constant antenna offset d_{offset} (cf. Section 3.3) is subtracted from all results. Thus, the plots only indicate the *change* in measurement errors. d_{offset} is computed as the median of all distance errors for an antenna.

All result plots show median values with blue lines and minima/maxima as grey areas around it. We choose the median over the arithmetic mean, as AR measurements are sometimes highly erroneous, resulting in large outliers. These outliers would heavily influence the arithmetic mean value. However, outliers are considered for the grey min/max areas. The result plots additionally show the DQI as returned by the iCDE algorithm. Note, that the distance error is reported on a logarithmic scale for most antennas. An optimal result would indicate a distance error of 0 m for all angles across all axes and a DQI of 1.0 which indicates a perfect measurement. A gap in a graph indicates, that no distance measurement was possible at this angle.

4.3.1 Skew-Planar Wheel Antenna

This antenna exhibits the lowest angle dependent error among the tested antennas, see Figure 3. Performance degrades at 90° and 270° when rotated around the X-axis. This can be explained by the radiation pattern of Skew-Planar Wheel antennas: The antenna has a zero point in the +Z and -Z directions. A similar error is visible at 0° when rotating around the Y-axis. These measurement errors are also visible in the DQI plot, thus could be filtered out by applying a DQI threshold. This antenna type is advisable when arbitrary antenna orientations are expected in a localization scenario.

4.3.2 Monopole Antenna

The results of the Monopole antenna are presented in Figure 4. It yields low errors when rotated around its Z-axis. When rotated around the other axes, this antenna exhibits measurement errors. We suspect that some polarization mismatch to the Skew-Planar Wheel antenna at the other sensor node might be the reason. To validate this, we tested the Monopole antenna in two more experiments. In both experiments the other sensor node was not equipped with a Skew-Planar Wheel antenna, but with another Monopole antenna of the same type. When antennas are oriented parallel, and thus polarization is matching, the antenna works reasonably well in all orientations, see Figure 5. In the next experiment, we deliberately mismatched the polarization. As the antennas did not produce meaningful results at 90° polarization angle, we set up the experiment with the polarization being at 80° angle. This attenuates the signal without blocking it completely. In this case, the Monopole antenna exhibits larger measurement errors, see Figure 6. However, the DQI also exhibits low values when errors are high. The erroneous measurements can thus be filtered out. The results indicate, that Monopole antennas should only be used in situations where the antenna orientation can be precisely controlled such that polarization matches.

4.3.3 PCB Antenna

The PCB antenna exhibits errors when rotated around X-axis and Z-axis, see Figure 7. It is apparent, that these errors change quickly with small angle changes. This antenna type might be viable in scenarios, where only limited localization accuracy and a cost-efficient antenna design is needed.

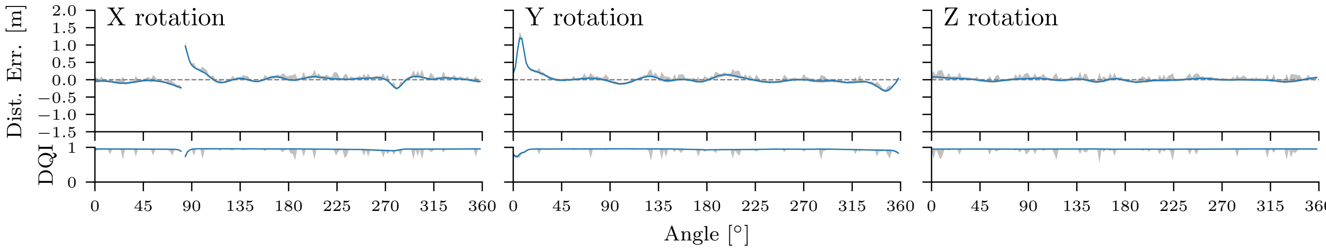

Figure 3. Experimental results of Skew-Planar Wheel antenna.

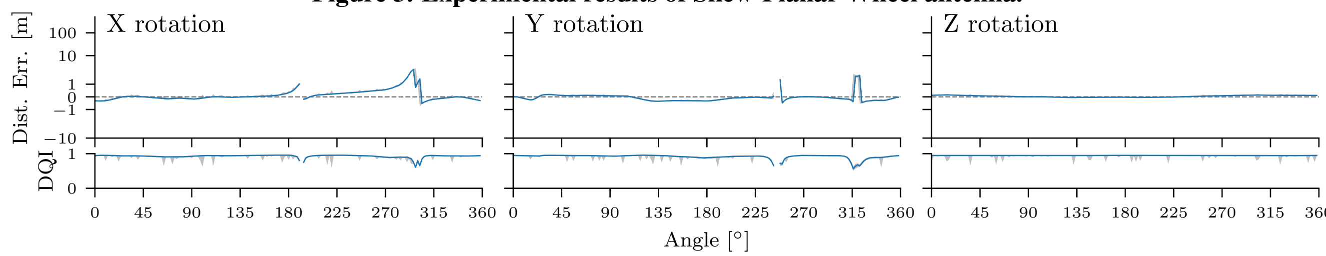

Figure 4. Experimental results of Monopole antenna with Skew-Planar Wheel antenna at the other node.

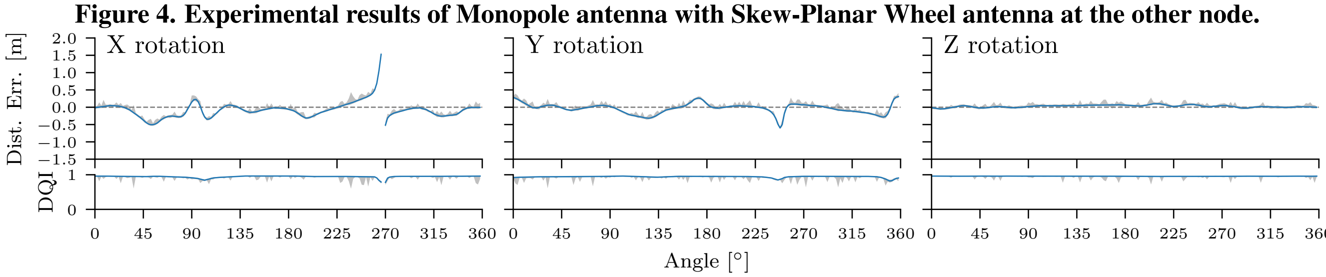

Figure 5. Experimental results of two Monopole antennas. Polarization is matched (antennas parallel).

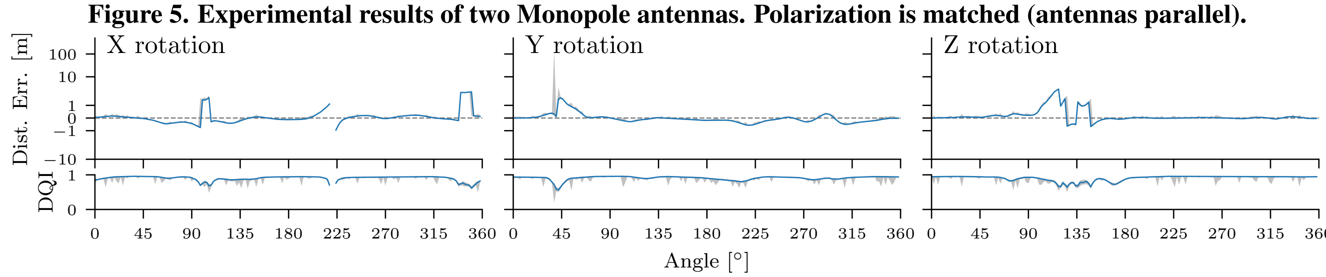

Figure 6. Experimental results of two Monopole antennas. Polarization is mismatched (antennas at 80° angle).

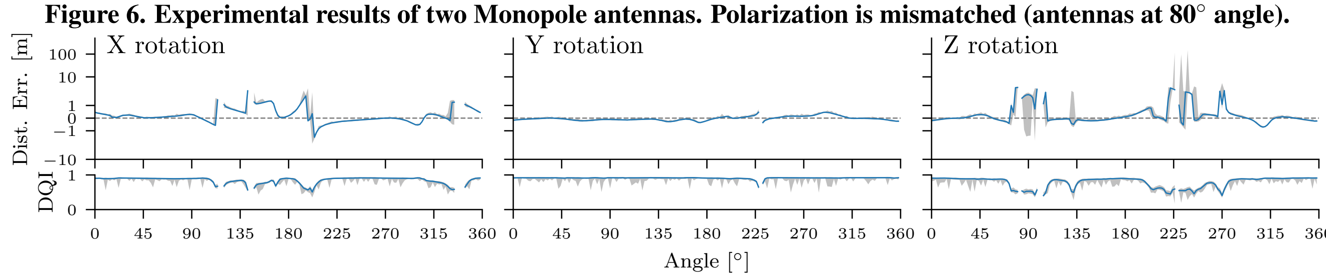

Figure 7. Experimental results of PCB antenna.

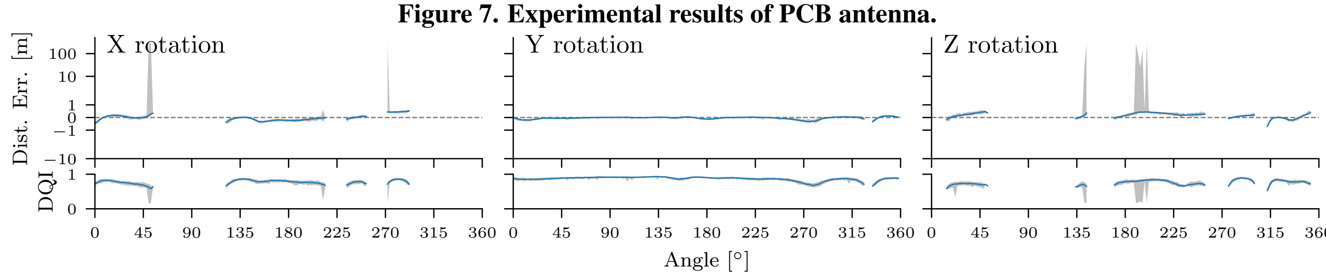

Figure 8. Experimental results of Chip antenna.

4.3.4 Chip Antenna

Figure 8 shows the results of the Chip antenna. This antenna was not able to produce measurements at many angles. We suspect that the received signal from the Skew-Planar Wheel antenna at the other node is too weak. However, when rotated around the Y-axis, the antenna produced reasonable results. The DQI plot indicates errors with low values. With this antenna, measurements often have a low DQI value. When using the DQI as a threshold, this will result in many discarded measurements. The antenna is a viable choice when antenna orientation can be controlled, signal strength is high, and a very small antenna is needed.

5 Discussion

The results presented above merely are a first step towards understanding and possibly mitigating the impact of antenna orientation on localization and phase-based ranging.

Our investigation cannot show the impact of the used distance estimation algorithm (here: iCDE) on the computed distance. However, our previous work [14] showed that in the presence of multipath propagation, different algorithms yield comparable (inaccurate) results. We suspect that errors from antenna orientation lead to ranging errors, independently of the used algorithm.

As directional errors can be severe, mitigation strategies need to be developed. When using an FFT-based algorithm like iCDE, the DQI value can be used to discard erroneous measurements. This was found to be a valid approach in realistic scenarios [15]. Another option might be to use multiple antennas at different orientations. If the distances from different antennas do not match, the measurement might suffer from directional error and should be discarded.

Distance errors from antenna orientation can be in the order of several meters, depending on the antenna type. A study of the impact of antenna orientation outside the anechoic chamber should be conducted. Depending on the multipath conditions, the errors introduced by antenna orientation could be negligible compared to errors that arise from multipath propagation [13].

Our evaluation shows that errors from antenna orientation are highly dynamic and change rapidly with small orientation changes. The evaluation in [11] considered only four directions per antenna in a 2D plane. While they also observe errors, their reported error might be inaccurate as other orientations could result in higher errors. Further research should investigate, how phase-based ranging and UWB ranging are comparable regarding directional error.

We can only present results for the PMU of the AT86RF233 [2] radio transceiver. The impact of antenna orientation might differ in other frequency bands. Especially the AT86RF215 [3] radio transceiver, which can operate in the sub-GHz band might yield different results. Such investigation should be conducted in the future.

The four antennas in our evaluation were chosen as they are largely different antenna designs. When available, the exact product type was given. The objective of our investigation was to show how diverse directional errors can be for different antennas. The names of the types are used throughout the paper to increase readability and should not be considered a generalization of the results to these categories of antennas. Other antennas from these categories may exhibit different error patterns. Such evaluation should be executed per antenna, when it is considered for an application.

6 Conclusion

Our evaluation shows that directional errors differ largely among the tested antenna types. The Skew-Planar Wheel antenna shows good performance across all rotation axes. The Monopole antenna works well when both antennas remain parallel to each other and polarization is matched. The PCB and Chip antennas are not recommended for precise localization applications, as they exhibit large errors.

The antenna offset which is currently considered to be independent of antenna orientation has a directional component. This needs to be taken in consideration when implementing highly accurate ranging and localization systems.

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