Estimating DoA From Radio-Frequency RSSI Measurements Using an Actuated Reflector

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***Abstract*—We describe a proof-of-concept device and method to estimate the direction-of-arrival (DoA) of a radio signal by a receiver that is suitable for wireless sensor network (WSN) applications. The device estimates the DoA by identifying the peak of received signal strength indicator (RSSI) measurements using an actuated parabolic reflector. Automatic localization is an important requirement for deployment of wireless sensor networks. Localization from distance measurement alone is a challenging problem, but becomes easier if relative angular position measurements between pairs of radio nodes are available. Methods of DoA estimation such as phased arrays are unsuitable for wireless sensor networks due to size, cost and complexity limitations. The device and the algorithm we describe is compact and simple enough to be suitable for WSNs. Experimental results show that the error in the measured DoA has a mean smaller than 4° and standard deviation of smaller than 8°, in both indoor and outdoor environments in line of sight situations. Presence of moving objects in the vicinity of the transceivers seem to have an adverse effect of the measurement accuracy.**

***Index Terms*—Angle-of-arrival (AoA), direction-of-arrival (DoA), estimation, parabolic reflector, received signal strength indicator (RSSI), wireless sensor network (WSN).**

I. Introduction

THIS PAPER describes a proof-of-concept device to measure the radio frequency (RF) angle-of-arrival (AoA) of a radio wave at a radio receiver by using a rotating reflector. The device is meant to enable relative angular position measurement between two sensors in a wireless sensor network (WSN). A WSN is a network of devices that have sensing, actuation, processing, and wireless communication capability. WSNs are useful in applications such as climate control, agriculture, intrusion detection and disaster management. The key benefit of WSNs come from the small size and low cost of the nodes, which makes it possible to deploy a large number of them in a wide geographic area. For effective use of the data from the sensors, the locations of the sensors must be known. Measuring the location of the nodes manually is expensive and sometimes infeasible. Therefore, nodes must be able to self-localize, that is, estimate their own locations after deployment. Current approaches to self-localization are based on measurements of pairwise distances between nodes, which can be obtained from received signal strength (RSS) or time-of-flight (TOF) measurements [1], [2]. However, self-localization based on distance measurements, especially when the measurements are corrupted by noise, is recognized to be a challenging problem [3], [4]. If, however, both distance and angle measurements are available between pair of nodes, then the *relative position* between a pair of nodes can be obtained, which makes the network localization problem more tractable [5], [6]. The location of an arbitrary node with respect to a single beacon, or reference node, can be obtained by adding the relative position measurements between pairs of nodes lying in a path from the node to the beacon, and can be computed in a distributed fashion [7]. Therefore, there is a need to equip wireless sensor nodes with the ability to measure the relative angle between pairs of them.

To be applicable to WSNs, a device to measure relative angle between a receiver-transceiver pair must be small enough so that it can be integrated into a wireless sensor node. Ideally, such a device should use a commercial-off-the-shelf (COTS) radio. A specialized radio hardware requirement will not only increase the cost but also make it difficult to take advantage of continuous improvements in protocols for wireless sensor-networking that is seen in recent years. A widely used method for measuring direction-of-arrival (DoA) of RF waves is through a phased array of antennas. Accuracy considerations require the antenna elements to form a *coherent receiver*, which leads to increased cost, the need for careful calibration, and sophisticated signal processing algorithms [8]. These therefore usually do not satisfy the size, cost, and processing power constraints for WSN applications. Another potential method that satisfies the size constraint is a switched beam antenna such as the one reported in [9], which needs specially designed radio hardware.

In this paper, we test the feasibility of a simple method for estimating the DoA (direction of arrival) of an incoming radio-wave from a transmitter by using a mechanically actuated parabolic reflector at the receiver. The parabolic reflector is used to make the unidirectional antenna of a COTS radio into an effectively directional antenna. Most radios that are applicable to WSNs have the capability of measuring the received signal strength. This information is usually provided in the form of a received signal strength indicator (RSSI). When the reflector is aligned in such a way that the incoming signal is focused at the receiver antenna, a high RSSI value is observed. At other orientations of the reflector, a lower RSSI is observed. The DoA can then be determined by searching for the direction in which the highest RSSI is observed. Due to the random fluctuations in the RSSI, some filtering may be required. As in the case with other

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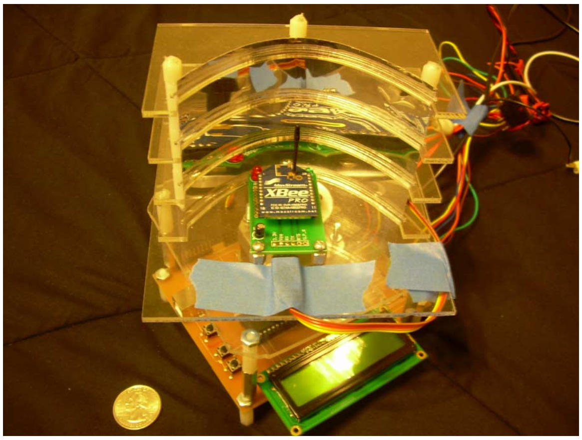

Fig. 1. The DoA measuring device (receiver). The coin shown on the side is a U.S. quarter.

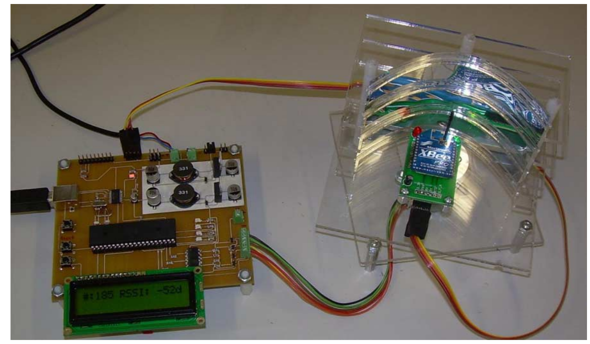

Fig. 2. The processor board and the antenna assembly (the radio and the reflector) shown separately.

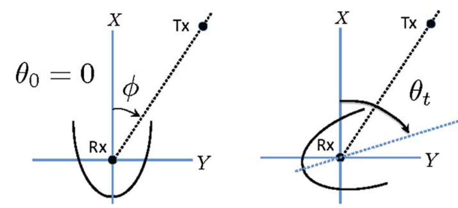

Fig. 3. Top view of the reflector, and the coordinate system for measuring DoA. If (A) is the initial configuration, then the DoA of the radio wave from the transmitter (Tx) at the receiver (Rx) is ϕ. (B) is the configuration at some time t when the reflector is rotated by an angle θ_t from its initial orientation.

DoA measuring methods, the accuracy of the estimates obtained with this method will depend on how much error multipath and fading effects introduce.

Preliminary experimental results are quite promising. The proposed method works equally well in indoors and outdoors. The mean of the estimation error was found to be less than 4° and the standard deviation less than 8°. Little change in estimation accuracy was observed between indoor and outdoor environments, though one might expect multipath effects to be more severe in indoor settings. In addition, the DoA estimates appear to be insensitive to the distance between the transceiver pair, at least for the distances tested. However, it was observed that presence of moving objects caused received signal strength to vary widely over time. This phenomenon, which may have been due to fading, was observed in both indoor and outdoor environments. Hence, the proposed method is effective only when there are no moving objects in the vicinity of the transceiver pair. The experimental results are described in Section III. The device used in taking RSSI-versus-angular position measurements is described in Section II.

II. Experimental Apparatus and Method

The DoA measuring device, shown in Fig. 1 consists of a transceiver, rotational actuator, parabolic reflector, and a processor board. The transceiver is the MaxStream[1] XBee Pro with whip antenna, operating in the 2.4 GHz band, which has the on board capability of measuring received signal strength [10]. A 200 steps-per-revolution stepper motor is used to rotate the transceiver and reflector. The receiver is fixed to the parabolic reflector such that the motor shaft and the antenna lie in the focal axis of the reflector. The parabolic reflector is a sheet of 0.005″ alloy 1100 aluminum sheeting, bent into a parabolic shape and held in place using slots four 0.125″ acrylic guides spaced vertically at 0.75″ intervals. The processor board contains a microcontroller, switching power supply, LCD display, UART to USB serial converter, stepper motor controller and a transceiver connection. Fig. 2 shows the processor board and the antenna assembly separately. A wiring harness connects the motor and receiver to the processor board. Due to this wiring restraint, the receiver/reflector assembly can only make one full revolution in one direction. One full revolution is sufficient for DoA estimation.

The transmitter node used in the experiments consisted of an XBee Pro transceiver, microcontroller and LCD. During experiments, the transmitter continuously transmitted a signal for rapid RSSI data collection at the receiver. The receiving XBee is configured for API mode such that the RSSI of the current data received is a part of the data packet transferred from the receiver to the microcontroller. Both the transmitter and receiver are configured for RF power level of 10 dBm. All other settings are left as the default.

Since our focus is on testing the feasibility of the concept, two simplifications were made. First, RSSI measurements were collected in laptop computer (via a USB connection) and post processed to estimate the DoA. Second, DoA is measured with reference to a local coordinate frame that is defined by the initial orientation of the parabolic reflector, as shown in Fig. 3, instead of a global Cartesian reference frame. The line segment joining the two tips of the reflector defines the Y axis and the line perpendicular to it that passes through the antenna defines the X axis. The true angular position of the transmitter in this reference frame is the angle subtended by the line segment from the transmitter to the receiver antenna on the X axis, measured positive in the CW direction. In all the experiments described here, the initial orientation of the reflector is set up so that the true angular position of the transmitter, i.e., DoA of the incoming RF signal is 90°. This is done by visually aligning the transmitter antenna with the two endpoints of the reflector (see Fig. 4). This method of initialization adds an extra source of uncertainty to the DoA measurements. To minimize the effect of this uncertainty, multiple tests are conducted with the same configuration by repeating the initialization. The angular position of the reflector at

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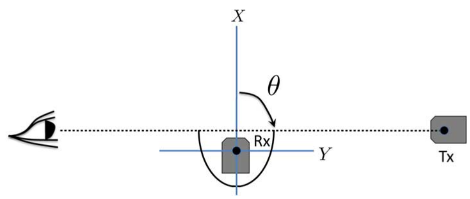

Fig. 4. Initializing tests by manually aligning the two endpoints of the reflector with the transmitter antenna. This established the true DoA θ as $90°$. Due to the much larger distances between the Tx and the Rx compared to the dimension of the radio and the reflector, the error due to the Rx antenna not lying on the dashed line is small, and is therefore ignored.

any time instant is the angle between its center-line and the X axis, which is computed by multiplying the stepper motor's angular motion resolution $(1.8°)$ with the number of steps the motor has moved until that time. During experiments, RSSI measurements are taken at every angular position of the reflector, which leads to a curve of RSSI versus angular position. The estimated DoA is the angular position of the reflector where the maximum signal strength is observed. Due to random fluctuations in RSSI, the raw RSSI values are not used. The algorithm used to search for the maximum signal strength is described in Section II-A.

A field-deployable device will incorporate an electronic compass, which will eliminate the need for manual initial positioning as well as enable measuring DoA in a global N-S-E-W reference frame. In addition, the algorithm for processing the RSSI measurements (described in Section II-A) is simple enough that it can be run by an on-board processor with limited memory and processing power. Thus, these simplifications made in testing the proof-of-concept device do no prevent it from being packaged into a compact standalone device that is integrated with an wireless sensor node.

The algorithm used to process the RSSI measurements to estimate the DoA is described next. Due to the random fluctuations observed in the RSSI measurements over time at a fixed angular position of the reflector, the raw RSSI measurements are not directly used for DoA estimation.

A. *DoA Search Algorithm*

At every angular position of the reflector, a number of RSSI measurements (at most 50) were taken within a time-out period of 3 s. Let N_j be the number of measurements taken at the angular position $\theta = \theta_j$ of the reflector, where $j = 1, \ldots, 200$ with associated angular positions $\theta_j = 0, 1.8°, \ldots, 358.2°$, and $N_j \leq 50$ for every j. Let $r_k(j)$ denote the value of the kth RSSI measurement taken at the angular position θ_j, where $k = 1, \ldots, N_j$. For the Xbee radios used, the measured RSSI value is an integer between -36 and -100 (in dBm). A normalized 2D histogram of RSSI versus angular position is constructed in the form of a 65×200 matrix P. The $(i,j) - th$ entry of P corresponds to the ratio of the number of RSSI measurements of $-i$ dB collected at angular position θ_j to the total number of RSSI measurements collected at that position expressed as a percentage, i.e.,

$$P(i,j) := \frac{\#\text{ of } k\text{'s so that } r_k(j) = -idB}{N_j} \times 100. \qquad (1)$$

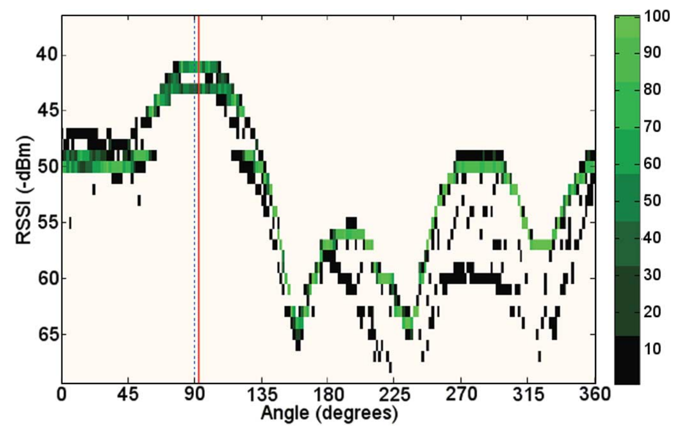

Fig. 5. Normalized signal strength versus angular position for an indoor test. The dashed line corresponds to the true DoA $(90°)$, while the solid line corresponds to the DoA estimated according to the algorithm described in Section II-A.

Rows of P with increasing index correspond to lower signal strength measurements. At position (i.e., column index) j, the smallest row index i for which $P(i,j)$ is nonzero corresponds to the largest signal strength that is observed with nonzero probability at that location. In the interest of robustness to random fluctuations, we search for the minimum row index i so that the row sum $\sum_j P(i,j)$ is above a threshold ϵ. The column indices on this row where the entries are above ϵ correspond to the angular positions where the largest signal strength was observed. The average of these angular positions is taken as the estimated DoA. The value of the threshold was set to $\epsilon = 2$.

An example is shown in Fig. 5, where the RSSI measurements from an indoor test (described in more detail in Section III-A) are processed according to the **DoA search algorithm** to estimate the DoA. The estimated DoA is computed to be 93°, whereas the true DoA is 90°.

The algorithm described above was chosen over several other candidates, such as looking for the mode of the normalized RSSI measurements as a function of angular position etc. It was found to be the most robust to changes in the experimental conditions among the candidates we examined. Although the entire 65×200 matrix P was constructed first and then the search algorithm was executed, it is not necessary to do so in practice. In fact, a real-time version of the algorithm can be easily implemented in a microcontroller by keeping only those angular positions in memory at which the normalized RSSI measurement exceeded a threshold. This will minimize the memory requirements.

III. Experimental Results

It was found during initial testing that the presence of moving objects in the vicinity of the transceivers during communication may cause large fluctuations in the RSSI measurements. Fig. 6 shows the RSSI as a function of time in a fixed location of the reflector, but with and without moving objects in the vicinity, which shows the large fluctuations in RSSI measurement caused by moving objects. Subsequent tests were therefore conducted by making sure there were minimal motion in the environment. The results reported in the sequel correspond to experiments conducted in this fashion.

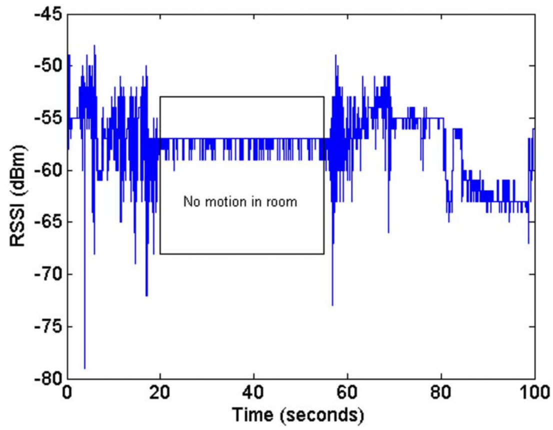

Fig. 6. Effect of moving objects in the vicinity of the transceivers on RSSI measurements in an indoor experiment. Without moving objects, RSSI shows little variation over time (see the boxed region). When moving objects are present, however, the RSSI fluctuates widely over even short-time intervals.

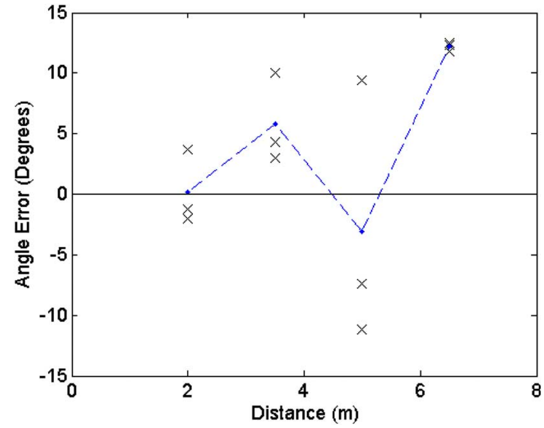

Fig. 8. Results of outdoor tests: estimated DoA from all 12 tests as a function of distance between the transceiver pairs. The blue dashed line is the mean of the three DoA estimates at each location.

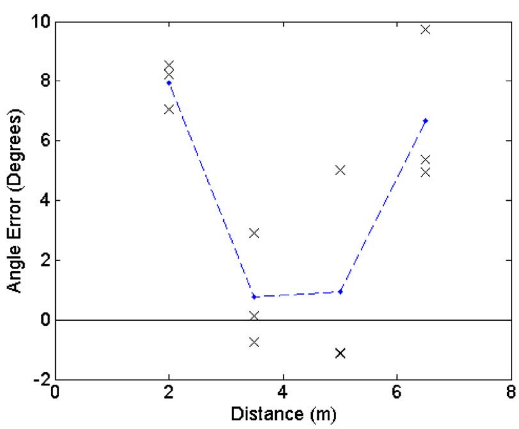

Fig. 7. Results of indoor tests: the estimated DoA from all 12 indoor tests as a function of the distance between the transceiver pairs. The blue dashed line is the mean of the three DoA estimates at each location.

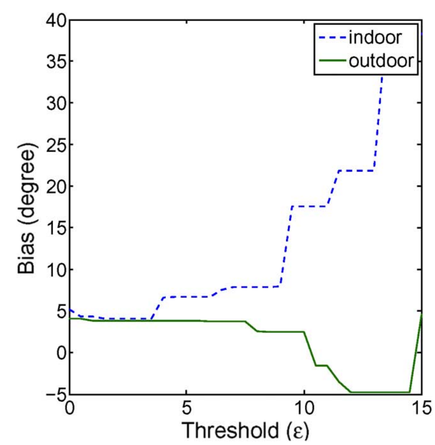

Fig. 9. Effect of changing the threshold ϵ on the DoA estimation error.

Tests were conducted both indoor and outdoor environments. For each of the environments, tests were repeated three times at a particular configuration of the transceiver pair, and then repeated by varying the distance between the transceiver pair. Each test consisted of a single 360° revolution of the reflector.

A. Indoor Experiments

The indoor experiment was conducted in a 7.6 m-by-8.3 m room. Three tests were repeated at a fixed location of the transceiver pair, and these were again repeated by varying the distance between the transceiver pair. The estimated DoA from all the 12 indoor tests are shown in Fig. 7. The mean and the standard deviation of the error in the DoA estimates from the 12 tests are computed to be 4° and 4°, respectively. Fig. 7 suggests that the DoA estimation error does not have a clear trend with the distance between the transceivers, at least for the distances we tested.

B. Outdoor Experiments

The outdoor test was conducted in a dry retention pond between two buildings. As in the indoor test, the true DoA was configured to be 90°. Fig. 8 shows the estimated DoA from 12 tests as a function of distance between the transceiver pairs. The mean and standard deviation of the estimation error were computed from these 12 samples to be 4° and 8°, respectively. As in the indoor tests, the error seems to have no relation to distance.

C. Effect of Parameters

The **DoA search algorithm** described in Section II-A needs the two parameters that the user has to specify: 1) number of RSSI samples (measurements) collected at every angular position and 2) the threshold ϵ. We studied the effect of these parameters on the resulting estimation accuracy, which are reported next.

Fig. 9 shows the bias in the DoA estimation error as a function of the threshold ϵ, which was computed by repeating the **DoA search algorithm** on the same data set while varying ϵ. The figure shows that the algorithm is robust to changes in the threshold ϵ, as long as the threshold is kept between 0.5 and 4. The results for the standard deviation are similar and not shown here.

The **DoA search algorithm** was executed with the first N of the 50 samples collected at each reflector position, where N was varied from 1 to 50. Tests were performed at both indoor and outdoor settings without the time out, so that 50 samples of RSSI were collected at every angular position of the reflector.

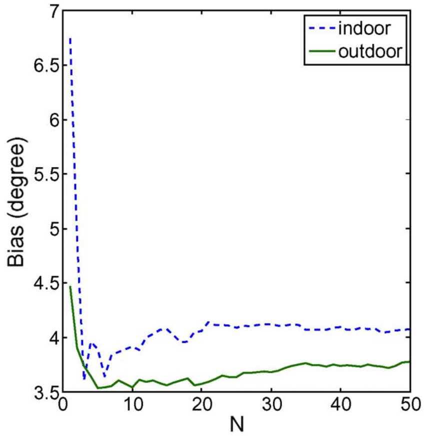

Fig. 10. Effect of changing N (number of RSSI measurements at each position of the reflector) on the DoA estimation error.

Fig. 10 shows the results of varying N on the mean DoA estimation error for both the environments. The figure shows that the bias of the DoA estimation error is not affected significantly by the number of RSSI samples as long as that number is larger than 5. The results for the standard deviation are similar and not shown here. Hence, ten samples per angular position are sufficient for DoA estimation. Note that reducing the number of RSSI samples taken at every position of the reflector also speeds up DoA estimation.

IV. Discussion and Future Work

The results of the experiments showed that it is possible to measure DoA from RSSI by using an actuated parabolic reflector, as long as there are no moving objects in the vicinity of the transceivers. The error observed had a bias and standard deviation in the order of 4° and 8°. The main conclusions from our studies are summarized below.

1) *The DoA seems to perform equally in indoor and outdoor environments*. The mean and the standard deviation of the DoA estimation error were quite similar in both indoor and outdoor experiments.
2) *The DoA estimates are highly sensitive to the presence of moving objects in the vicinity of the transceivers*. The reason for this is that RSSI measurements show large random fluctuations over time when moving objects are present; presumably due to fading. This limits the situations in which the proposed method can be used.
3) *The DoA estimates are insensitive to distance between the transceivers*. This DoA estimation errors did not appear to have any relationship with distance between the transceiver pairs. This was observed in both indoor and outdoor tests. This feature enhances the applicability of the proposed method since no correction for distance has to be made.

Several improvements in the device and testing procedure can be made. Work is ongoing in making the device smaller by reducing the size of the reflector, and implementing the **DoA search algorithm** in the processor board. These two improvements will make the device a compact, standalone one. For future testing, a compass will be incorporated in the device to measure absolute orientation. In addition, the current method of establishing the true DoA (ground truth) by manual alignment introduces some uncertainty. A more reliable method for establishing ground truth needs to be developed. In the future, we also plan to include a range measurement capability. Two devices that are equipped with DoA and range measurement capability will be able to measure relative position between them, which will aid in sensor network localization.

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