Transmitter Localization with a Phased Array Antenna Receiver and Radiation Gain Estimation

Rachel Morgan, Zulkayda Mamat, Ryan Sander — Massachusetts Institute of Technology — 6.013 Spring 2018

***Abstract*—In this paper, we explore the use of a phased array receiving antenna system to localize a transmitter in the far field. By varying the relative phases between the two receiving antennas and matching measured received power values to theoretical predictions, on average we are able to localize the transmitter to within 7° of its actual position.**

I. Introduction

Localization and tracking has many applications within the fields of control and communications, such as implementation via RADAR or GPS measurements [1]. However, RADAR localization systems are limited by range and material reflectivity, and GPS requires additional sensors and has limited accuracy. Here, we use a phased array receiving antenna system to compare power received under different phase settings to theoretical calculations in order to predict the location of a transmitter. This technique could be applied to tracking and beam steering for communication with a moving target, such as a flying drone or satellite [2]. It could also be applied to tracking a transmitting target without detection. Using the transmitted signal directly to predict the transmitter location reduces the system's dependence on range and reflectivity compared to RADAR [1].

To demonstrate this system, we built a phased antenna array of two $\frac{\lambda}{4} = 3.75cm.$ monopoles mounted onto a conductive ground plane, and separated by a distance of $\frac{\lambda}{2} = 7.5cm.$ We used a Vector Network Analyzer (VNA) to calculate power received from a transmitter (Cantenna) under three different phase offset settings (0°, 90°, 180°) in order to predict the location of the transmitter to within an average of 7°.

II. Approach

This system is based on phased array theory, in which the system's antennas function by adjusting their individual phase offsets to control the radiation pattern of the system. Changing the relative phases of the antennas changes the regions of constructive and destructive interference in order to steer the radiation pattern of a transmitting or receiving antenna [2].

Our application uses a two-monopole phased array receiving antenna system and adjusts the phase offset between the dipoles to three different phase settings. The power received from a transmitter is measured at the three phase settings and compared to theoretical calculations to predict the location of the transmitter. A block diagram of the full system is shown in Fig. 1.

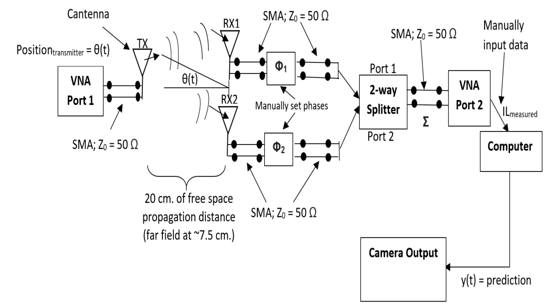

Fig. 1: **Block diagram of full system**. The VNA transmits a 2 GHz signal through an antenna (Cantenna) to two receiving monopoles, whose signals (IL) are then phased shifted and summed together at the VNA output. From these IL values, our Python functions generate a predicted angle, which is then displayed via camera.

The power received is measured using a VNA in the form of Insertion Loss (IL) of the system, which is the ratio of received to transmitted power in dB. These measurements are then compared to theoretical IL calculations based on phased array radiation theory. First, the theoretical radiation pattern is calculated for each phase setting using the equation for far-field radiation [3]:

$$Gain_{theoretical}(dB;\theta) = \sum_{i=0}^{N-1} e^{-jkDsin\theta_i + j\phi_i}$$

Where k is wavenumber, D is the separation distance between each monopole (in this case, $\frac{\lambda}{2} = 7.5cm$), θ is the transmitter angle, N is the number of antennas in the phased array (in this case, 2), and ϕ is the phase offset relative to the first monopole.

The transmitter gain is calculated via a calibration test, in which we measure the signals received by a single monopole. This measurement was conducted daily before any full system testing to account for variations in media or system performance. The VNA was used to measure IL, which was converted to the ratio of power received to power transmitted, and used to calculate the transmitter gain with the Friis transmission equation [4]:

$$Gain_{Tx} = \frac{10^{IL/10}(4\pi r)^2}{\lambda^2 Gain_{Rx}}$$

Where IL is the measured insertion loss (negative by this convention), G_{Rx} is the receiver gain, assumed to be 1.5 for a monopole, λ is the transmitter wavelength (0.15m.), and r is the transmission distance (0.2m).

The phase offsets are implemented using SMA connectors. At our operating frequency of 2 GHz, each SMA connector has been measured to induce 45° of phase offset [5].

The gain pattern is then used to compute predicted IL values at all angles through the Friis transmission equation [4]:

$$IL_{predicted}(dB) = 10\log_{10}(\frac{P_{rx}}{P_{tx}}) = 10\log_{10}(\frac{G_{tx}}{4\pi r^2}\frac{G_{rx}\lambda^2}{4\pi})$$

Where G_{tx}, G_{rx} are the transmitter and receiver gains, λ is the transmitter wavelength (in free space at 2 GHz, this is 0.15m.), and r the distance between the transmitter and receiver (in our experiments this was 0.2m).

The procedure for predicting transmitter location is as follows:

1) Measure the insertion loss at each phase offset setting.
2) Calculate the theoretical insertion losses at each phase offset setting.
3) Calculate the error between the theoretical and measured IL values for each angle between [-90°,90°] (in 1° increments) for each phase offset setting.
4) Calculate the total error for each angle by summing the errors from each phase offset setting. The predicted angle is the angle with least total error.

III. Results

Our preliminary testing results consistently demonstrate average predicted accuracy within 7° of the transmitter's actual position, though this accuracy is dependent upon the chosen combination of phase offsets.

We ran several initial calibration and measurement trials to determine how well this system could predict the angle of the transmitter relative to the receiver. For all phase offset combinations tested, we observed the best localization performance at angles around 0°, and the worst performance at 90° and 270°. This variable performance potentially arises from radiation patterns producing similar theoretical IL values for angles near +90° and -90°, so our functions cannot differentiate them. A plot of the predicted angle error as a function of angle is shown in Fig. 2.

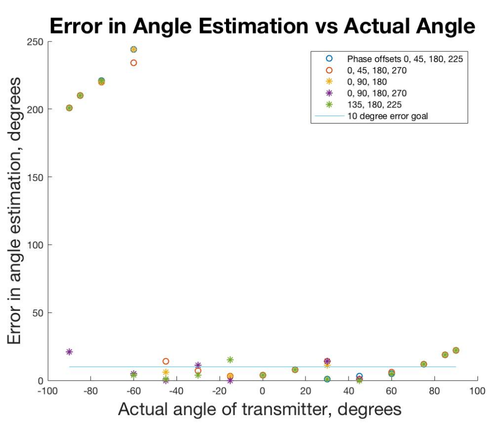

Fig. 2: **Error in angle estimation as a function of actual transmitter angle for different phase offset combination settings.** The phase offsets were generated through addition of SMA connectors consistently to one monopole, inducing 45° phase offset per SMA connector.

Based on the results of testing different phase offset combinations, we concluded the combination of 0°, 90°, and 180° of phase offset provide the best performance for the localization region of interest.

An example output for a transmitter angle of 315° is shown in Fig. 3. Our system predicted the angle to be 313°, which is within 2° of the actual angle. The average error was 6.7° for the angles tested within the testing range of +/- 60°. Outside of these angles, the absolute error was larger, compromising the system's functionality. This is potentially due to the similarity across radiation patterns across the axes.

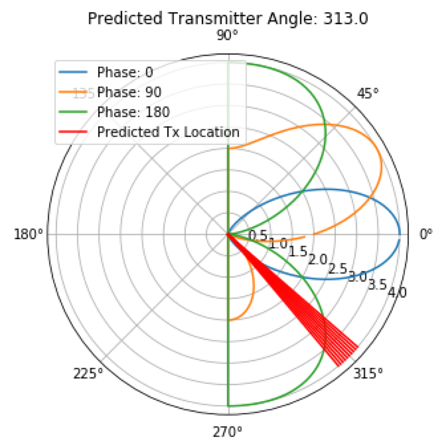

Fig. 3: **Theoretical radiation pattern for the selected phase offset settings of 0°, 90°, and 180°**. The radiation patterns were generated using Python script implementation of the Friis equation. The red lines indicate the top ten candidate angles, and the predicted angle output was 313° for an actual transmitter angle of 315°.

IV. Conclusion

This system exhibits reasonable localization accuracy and immunity to error within an angular bandwidth of [-60°,60°]. As mentioned above, having the ability to localize incident radiation within a 7° (average) accuracy range has many applications in aerospace and defense.

A more advanced implementation of this system would rely on the use of more antennas and digitally-controlled RF phase shifters. More antennas and phase settings would improve the resolution of the system and improve the angular range of operation, while digital phase shifters would decrease the time needed to make a location prediction.

V. References

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[5] Prof. Kenneth Kolodziej, 6.013 Instructor and Engineer at MIT Lincoln Laboratory.