EENG663 Project 2: Signal Geolocation

Project summary

Overview: Use an RTL-SDR software radio dongle to geographically locate a radio station.

Setting: Develop in class, then collect data around Dayton.

Curricular elements: both tinkering and gaming

Prerequisites: basic familiarity with MATLAB

Topics/concepts covered: maximum likelihood estimation, MMSE estimation, error ellipses, CRLB

Learning outcomes: After completing this project, students should be able to:

- Derive ML and MMSE estimates for position using signal strength measurements.
- Derive the CRLB on unbiased position estimates using signal strength measurements.
- Use a software radio to make power measurements of a radio station.
- Plot confidence intervals (error ellipses) and CRLB ellipses.

Expected time to complete: two 2-hour lab sessions and 10 hours of work outside of class

Required hardware/materials: One RTL-SDR dongle and a laptop running MATLAB.

Required instructor interaction: partially supervised, with occasional guidance

Common mistakes/pitfalls: Signal strength data is highly variable, so many measurements at disparate locations are needed.

Method of assessment: instructor graded, based on final product; plus peer voting on subjective evaluations of the competitions

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1 Getting started

A lot of information is intentionally missing from this lab description; you will need to ask questions the complete this lab.

Pick a lab partner for this project. You will collaborate on the process, but you will write up individual reports and receive separate grades. You must work with a different partner for each project in the class.

Obtain a software radio dongle from the instructor. The default device is a NooElec R820T2 SDR & DVB-T NESDR Mini 2, though for simplicity we will refer to it as an "RTL-SDR" receiver, or simply as an "SDR." Refresh your memory on the MATLAB-based receiver commands from prior projects. Progress to the point where you can locate a transmitter of interest in the spectrum (such as an FM radio station or one of the 900 MHz baby monitors used in prior labs) and numerically assess the power level of the signal. If you can accomplish these tasks, you have sufficient understanding of the hardware interface to complete the entire project.

2 Concepts

This project will make use of the following course concepts: Maximum Likelihood Estimator (MLE), the Cramer-Rao Lower Bound (CRLB) on a real-valued vector parameter, standard Bayes estimators (MMSE, MMAE, MAP), the relationship between the MAP estimator and the MLE, and error ellipses. Videos covering these concepts are available on the course website, and you are encouraged to read additional background material in any of the suggested reference textbooks.

Geolocation, also called source localization, involves using data from a sensor network to estimate the position of a radio or audio transmitter. The most common approaches use Received Signal Strength (RSS), Angle of Arrival (AOA), and/or Time Difference of Arrival (TDOA) measurements. In this assignment, you will use RSS [1]. The core task is to measure the received power of a signal at multiple receivers and then use that information to estimate the location of the transmitter. The language in the handout generally refers to a radio transmission, but transmitting and receiving an audio signal is acceptable as well. You may wish to compare the two, and to compare performance between local (e.g. within a room or building) and regional (e.g. FM radio stations) configurations.

RSS measurements are typically modeled as log-normal [2], [3], [4], which means that they are Gaussian in the dB scale. These dB values (10 log10 of the power) are distributed as

$$\mathbf{p} = [p_1, \cdots, p_n, \cdots, p_N]^T,$$

$$\mathbf{p} = \mathbf{m} + \mathbf{w}, \tag{1}$$

$$\mathbf{w} \sim \mathcal{N}\left(\mathbf{0}, \sigma^2 \mathbf{I}\right). \tag{2}$$

The fading standard deviation is typically in the range 4 dB $\leq \sigma \leq$ 12 dB, with extremes corresponding to deserts and urban canyons, respectively. The mean values are given by

$$m_n = \underbrace{10\log_{10}\Gamma_0}_{p_0} - \eta \cdot \underbrace{10\log_{10}\left(\frac{d_n(x_0,y_0)}{d_0}\right)}_{\bar{d}_n(x_0,y_0)}. \tag{3}$$

You can assume that $\sigma = 6$ dB in this project and that it is known. The path loss exponent η is not always known, but it is 2 in free space and is typically in the range of 1.5 to 4. The reference power p_0 is the power that would be measured at a reference distance d_0. Typically, $d_0 = 1$ m, which you can assume here. Usually p_0 (measured in dBm) is unknown, but it is typically constant over long periods of time, so it may be possible to measure it in advance.

The locations of the sensors are $(x_n, y_n), n = 1, \cdots, N$ and are known; whereas the location of the emitter is (x_0, y_0) and is unknown. Thus, the distances are given by

$$d_n = \sqrt{(x_n - x_0)^2 + (y_n - y_0)^2}. \tag{4}$$

Note that x_0 and y_0 have a very nonlinear relationship with the measurements.

3 Tasks

Explore the following issues:

(i) What is the best way to quantify the received power?

(ii) What is the CRLB on the unknown position? Are there any other unknowns? Should you treat them as known or unknown when deriving the CRLB?

(iii) What is the MLE on the unknown position? Are there any other unknowns? How do they affect the MLE?

(iv) Define a physical region of interest that almost certainly contains the transmitter. If you assume a uniform prior across that region, what is the MAP estimator for the transmitter location? How does it relate to the MLE? What are the MMSE and MMAE estimators, and how might you compute them?

(v) Can you use a simple method to approximate the unknowns other than the position, and then use a more sophisticated estimator to refine just the position estimate?

(vi) How does simulated performance compare to real-world performance? How do your real-world estimator variances compare (quantitatively or qualitatively) to the CRLB?

(vii) How does the geometry of where you took measurements relative to the transmitter position affect your accuracy and precision? This is most quickly explored by using the CRLB. What is a good way to visually compare performance for different geometries?

You do not have to explore everything. These are just some possible threads you can pull on.

4 Deliverables

You will turn in a report written using the LaTeX word processing system. A template is available on the course webpage. The report should conform to the style guide for IEEE Signal Processing Society conferences, such as ICASSP, ICIP, or GlobalSIP. At a minimum, explain your measurement methodology, your data processing methodology, and your results. Both format and content matter – in particular, use correct grammar and spelling, and revise your text as needed to make sure you are explaining yourself coherently. Include code sparingly, if at all; in general, it is better to include an algorithm in pseudo-code as a figure.

You should strive to always explain why you did what you did, not just what you did. Your results should all be repeatable – maybe not exactly, but comparably. That is, another researcher may not have access to the exact same environment as you or record the exact same realization of random noise, but you want to enable them to follow the exact same process as you. Analysis is also highly encouraged – explain why the results are what they are, not just what they are. For this project, plots of the geometry may help with that.

To improve your grade, try innovative approaches, and feel free to diverge somewhat from the stated tasks if you think the situation warrants it. “Out of the box” thinking will always be rewarded.

5 Presentations and Competitions

You are also required to make a brief presentation of your approach. Since you are already turning in a report, the presentation itself will not be graded. Instead, this allows your peers to see alternative approaches. It also lets you participate in competitions. There are three challenges:

- Locate an FM radio station as accurately as possible. Your search space or prior (if you use one) must include at least 1 km on all sides of the true location.
- Locate a hand-held transmitter (audio or radio) as accurately as possible using 10 measurements. Your search space or prior (if you use one) must include at least 1 km on all sides of the true location. No measurements may be taken closer than 2 m from the transmitter.
- Compare as many algorithms and/or types of measurements and simulations as possible. The winner will be determined by which comparison is the most interesting and informative, as judged by class vote.

Each measurement can be averaged for as long as you like – this is because RSS measurements are spatially ergodic rather than temporally ergodic. To put it another way, waiting longer won't average out the noise, because the noise depends primarily on where you measure rather than when you measure. If you use a search grid, your effective error will be the maximum of your measurement error and the size of a grid cell. This keeps you from inadvertently cheating by defining a very course grid where one of the grid points just happens to be at the true location.

These competitions can mean whatever you want them to mean. If you think your approach is applicable to a given competition, feel free to enter. As the third competition is subjective, winners will be determined by class vote after the presentations. The first place group in each category will receive a 2-point bonus (for each group member) and the second place group members will each receive 1 point; and no individual may receive more than 2 points total per project.

References

[1] N. Patwari, J. N. Ash, S. Kyperountas, A. O. Hero, III, R. L. Moses, and N. S. Correal, "Locating the Nodes: Cooperative Localization in Wireless Sensor Networks," *IEEE Signal Processing Mag.*, vol. 22, no. 4, pp. 54–69, July 2005.

[2] M. Kieffer and E. Walter, "Centralized and Distributed Source Localization by a Network of Sensors Using Guaranteed Set Estimation," in *Proc. Int. Conf. Acoustics, Speech, & Signal Proc.*, Toulouse, France, May 2006, vol. 4, pp. 977–980.

[3] A. J. Weiss, "On the Accuracy of a Cellular Location System Based on RSS Measurements," *IEEE Transactions on Vehicular Technology*, vol. 52, no. 6, pp. 1508–1518, Nov. 2003.

[4] T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice-Hall, Englewood Cliffs, NJ, 1996.