EENG663 Project 1: Frequency Estimation

Project summary

Overview: Use audio or radio hardware to estimate the center frequency of a narrow-band signal.

Setting: Develop in class, then refine at home.

Curricular elements: both tinkering and gaming

Prerequisites: basic familiarity with MATLAB

Topics/concepts covered: maximum likelihood estimation, Cramer-Rao lower bound

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

- derive a maximum likelihood estimator and implement it on measured data
- evaluate the accuracy of a noise model
- implement other common frequency estimators

Expected time to complete: two 2-hour lab sessions and 4-8 hours of work outside of class

Required hardware/materials: Minimum: a speaker and microphone attached to or embedded within a computer, both controlled by MATLAB. Optional: a software radio controlled by MATLAB (e.g. an RTL-SDR or a HackRF) and a 900 MHz consumer device (e.g. a baby monitor) that transmits on demand.

Required instructor interaction: partially supervised, with occasional guidance

Common mistakes/pitfalls: The audio and radio devices have different idiosyncracies when being operated by different computers. The students may need extra time to get the hardware operational.

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

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1 Introduction

This is a very open-ended activity. Everyone will have a different approach, or a different "answer." This is likely to be a very frustrating exercise at times, but that is ok; the instructor is here to help you, and you should not hesitate to ask questions. A lot of information is intentionally missing from this lab description; you will need to ask questions the complete this lab. The goal of the activities in this course is to encourage a "maker" mindset wherein you feel free to tinker and explore different approaches. We want you to fail, rapidly and frequently, because that is how you identify and correct errors. Your goal is to get comfortable with the idea of rapid prototyping and rapid response.

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 cannot work with the same lab partner more than once. You may work individually if you prefer. If hardware limitations dictate, you may work in groups of three for all or part of an assignment.

The available equipment for this class includes the following:

- Microphone 1: Cyber Acoustics Desktop Unidirectional Microphone (CVL-1064), about $7
- Microphone 2: Power Gear 98950 PC Microphone with Detachable Laptop Mic, Skype and VOIP Compatible, about $8
- Microphone 3: Andrea 2S Superbeam Array Microphone, about $10 (only one available)
- Speakers 1: AmazonBasics USB Powered Computer Speakers (A100), about $14
- Speakers 2: Logitech S150 USB Speakers with Digital Sound, about $15
- Radio transmitter 1: Sony NTM-910YLW Baby Call 900MHz Nursery Rechargeable Monitor with Transmitter, about $35
- Radio transmitter 2: Fisher-Price Time for Sleep Monitor with dual receivers (operates near 900MHz), about $28
- Radio receiver 1: NooElec R820T2 SDR & DVB-T NESDR Mini 2, about $20
- Radio receiver 2: HackRF One, about $300 (only three available)

You may use alternate equipment if you like.

2 Getting started

Obtain a transmitter and receiver from the instructor. Audio hardware is recommended due to its ease of use, reliability, and more accurate "truth" data; but radio hardware is encouraged too. Plug in your equipment, make sure each device is turned on, and make sure each is set to the default device of its type. The next step is to generate a narrowband signal with your choice of transmitter and ensure that you can receive the signal and import it into MATLAB. The exact steps for doing this will vary with your choice of hardware.

If you are using the audio equipment, explore the following MATLAB commands:

- `audiorecorder`
- `record`
- `play`
- `stop`
- `resume`
- `pause`
- `getaudiodata`
- `sound`

The explanation in the help files should be straightforward; the only parameter you will need to choose is the sampling rate `fs`. Audio CDs use 44.100 kHz and that will work well; but a sampling rate of 20 kHz should be sufficient. Progress to the point where you can record a snippet of speech and then play it back over the speakers. If you can accomplish these tasks, you have sufficient understanding of the audio interface to complete the entire project.

If you are using the RTL-SDR, download the quick start guide and matlab script from the course website. Install the matlab toolbox from https://www.mathworks.com/hardware-support/rtl-sdr.html (this will require you to have administrative privileges on on your machine). Work through the quick start guide until you can run the spectrum analysis matlab tool. Some useful MATLAB commands include:

- `comm.SDRRTLReceiver`
- `dsp.SpectrumAnalyzer`
- `sdrinfo`
- `release`

Turn on a radio transmitter and verify that transmission or lack thereof corresponds to an appearance or disappearance of a signal spike in the spectrum analysis tool. The baby monitors operate within the 902 MHz to 928 MHz band, and the RTL-SDR dongles cover 24 MHz to 1766 MHz. For additional information, explore http://www.rtl-sdr.com/about-rtl-sdr/ .

If you are using the HackRF, installation and configuration is up to you. You can find further information on the manufacturer's website, https://greatscottgadgets.com/hackrf/ . Turn on a radio transmitter and verify that transmission or lack thereof corresponds to an appearance or disappearance of a signal spike in the spectrum analysis tool. The baby monitors operate within the 902 MHz to 928 MHz band. The HackRF can observe higher frequencies than the RTL-SDR, up to 6 GHz, so you may also use transmitters that operate in the 2.4 GHz or 5 GHz unlicensed bands; devices that operate here include WiFi and various wireless applications that connect with smart phones.

3 Tasks

For this project, you will need to study the course material on maximum likelihood estimation (MLE), the Cramer-Rao lower bound (CRLB), and frequency estimation algorithms. 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.

The core task in this assignment is to transmit a narrow-band signal, receive it, and accurately estimate its center frequency. To enable this, explore the following issues:

(i) What is the "truth" data for the signal you are sending? I.e., what is the true center frequency? If you don't know it exactly, is it reasonable to estimate it in a low noise environment using many samples, and compare to that value later when operating under more challenging conditions?

(ii) Is your data real-valued in the time domain or complex-valued? I.e., are you dealing with raw samples or data that has been downconverted from a real passband representation into a complex baseband representation?

(iii) Most frequency estimation algorithms assume you are looking for one or more complex exponentials (cisoids). If you transmitted a real-valued sine wave, what are the frequencies of its constituent complex exponentials?

(iv) How accurate is it to assume that the background noise is additive white Gaussian noise (AWGN)? To evaluate this, you will need to measure a variety of signals and perform some statistical analysis of the data.

(v) Putting all of this together, what is the formal, precise mathematical statement of your signal model?
(vi) How can you vary the signal to noise ratio (SNR) for your transmission in a controlled way? As you "turn a knob" to vary the SNR, how can you quantify what the SNR actually is?

Once you have grappled with these preliminaries, undertake some of the following tasks:

- Implement and test one or more frequency estimators. The course videos cover the MLE, the periodogram, and the MUSIC algorithm. Other popular methods include Prony's method, IQML, Pisarenko Harmonic Decomposition (PHD), Root-MUSIC, and ESPRIT. The Scharf textbook covers these methods.
- Evaluate the bias and variance of your estimators as a function of SNR.
- Compute the CRLB for estimating one or more frequencies. Explore the dependence of the CRLB on parameters such as SNR, number of unknown frequencies, separation of unknown frequencies, or anything else that seems interesting.
- Compare performance across devices or device settings. You could swap out one speaker for another, or compare audio performance to radio performance.
- Compare your results for measured data to results from a pure MATLAB simulation.
- Test your performance on a frequency-hopping signal (either automated or manually controlled). Try to show the tracking performance in real time.

You do not need to do all of these tasks; rather, they are meant as a guide. Feel free to try a more clever or innovative approach, include more data and analysis than was asked for, or diverge from the stated tasks if you think the situation warrants it. "Out of the box" thinking will always be rewarded. Failed attempts are of value too, as long as you can explain why the approach didn't work using lessons learned from the course material.

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 realizations 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.

Consider looking through some published IEEE articles for additional guidance on format and content.

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:

- Most extensive algorithm performance comparison
- Best analysis and discussion of the theory
- Best real-time demo

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 these are subjective, winners will be determined by presentations and voting as indicated on the course schedule. 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.