Fall 2021   EE 313 Linear Systems and Signals   Prof. Evans

Mini-Project #2: Wireless Localization

Assigned on Sunday, October 24, 2021. Updated Thursday, October 28, 2021.
Due on Wednesday, November 3, 2021, by 11:59pm pm via Canvas submission

Late submission is subject to a penalty of two points per minute late.

Reading: McClellan, Schafer and Yoder, *Signal Processing First*, 2003, Chapters 5-7.
Companion Web site with demos and other supplemental information.

E-mail address for Mr. Faris Tabbara (TA) is firas.tabbara@utexas.edu. Lecture hours and office hours for Mr. Tabbara and Prof. Evans on Zoom (see links on the Canvas calendar) follow:

Time Slot	*Monday*	*Tuesday*	*Wednesday*	*Thursday*	*Friday*
9:30 am				Evans (Zoom)	
10:00 am				Evans (Zoom)	
10:30 am					
11:00 am		Evans (EER 1.516)		Evans (EER 1.516)	
11:30 am		Evans (EER 1.516)		Evans (EER 1.516)	
12:00 pm		Evans (EER 1.516)		Evans (EER 1.516)	
12:30 pm		Evans (Zoom)			
1:00 pm		Evans (Zoom)			
1:30 pm					
2:00 pm					Evans (Zoom)
2:30 pm					Evans (Zoom)
3:00 pm					Tabbara (Zoom)
3:30 pm			Tabbara (Zoom)		Tabbara (Zoom)
4:00 pm			Tabbara (Zoom)		Tabbara (Zoom)
4:30 pm			Tabbara (Zoom)		

You may work individually or in a team of two or three persons. If you're in a team of 2-3 people, then create one report together. Each of you would submit the same report on Canvas. Be sure that the mini-project report represents the independent work of the author(s) on the report. Cite your references.

Context of the Mini-Project for Our Course

At the beginning of the semester, I had asked about your interests in taking this course. Collectively, your goals included proficiency in Matlab; intuitive understanding of signals; learning more about applications; and describing signals by looking at them. In terms of applications, you expressed interests in speech processing; image processing; 5G & 6G cellular technologies; USB & PCI Express; automotive sensors (e.g. engine control); optical communications; and quantum computing. Mini-Project #1 concerned speech analysis and synthesis [1], and Mini-Project #2 concerns wireless localization which is critical to 6G cellular systems and automotive sensors (radar).

1.0 Introduction

Locating objects in an environment has applications in automotive, cellular, sonar, and ultrasound systems. Automotive systems fuse data from radar systems and cameras mounted on the vehicle to detect stationary and moving objects in the environment. In 6G cellular systems, basestations will use knowledge of the smart phone's location to improve the connection speed and reliability. By knowing the user equipment location, the basestation can know the wireless channel characteristics to tune the type and direction of transmission to the user equipment. Sonar and ultrasound use acoustic waves to detect location of objects underwater and biological structures in vivo without invasive procedures, respectively, in much the same way that automotive radar and 6G cellular systems use electromagnetic waves. Electromagnetic waves are produced by acceleration of electric charge or transition of electrons between energy levels in atoms [2], whereas acoustic waves are caused by mechanical vibration.

1.1 Chirp Signals

In a chirp signal, as mentioned in Section 3-8 of [3], the principal frequency increases (or decreases) with time. Per the homework #2 solution set [4], chirp signals have a wide variety of applications:

Active sonar systems. The transmitter sends out a "ping" as sound in form of a chirp and then receives sound. The time elapsed between the transmission and reception of the chirp indicates the roundtrip time experienced by the signal after bouncing off an object in the water and returning to the receiver. By receiving sounds in different directions using multiple microphones, the sonar can build a map of the objects in the water.

Bats use chirps for echolocation. Pipestrelle bats use chirps that sweep down from 70 to 45 kHz. [5]

Test & Measurement. When one measures the response of a system to different frequencies, a time-consuming approach is to input a single sinusoid, measure the output, and repeat using many different frequencies. Instead, inputting a chirp can allow the measurement to performed in one take.

4G/5G cellular communication systems periodically send a Zadoff-Chu chirp sequence to synchronize the transmitter and receiver as well as measure the frequency distortion in the electromagnetic propagation from transmitter to receiver (channel estimation). The Zadoff-Chu is a complex-valued chirp signal. [6]

This project will use linear frequency modulated (FM) chirp signals to sweep a range of frequencies linearly with time. A chirp signal is useful in wireless localization for several reasons.

A chirp signal is resilient to many impairments experienced by propagating signals including thermal noise and frequency distortion. Additive thermal noise arises in electronic circuits due to the random motion of electrons due to temperature. Frequency distortion occurs due to multiple transmission paths from the transmitter to receiver in which each path has a different gain and delay. Chirp signals are also resilient to Doppler shifts [7] due to the relative motion between the transmitter and receiver. Chirp signals can be used not only to localize an object, but also estimate its velocity (speed). [8]

1.2 Complex-Valued Signals

Complex-valued chirp signals are used in radar and 4G/5G cellular systems, among others. Since in practice a signal propagating through a medium is real-valued, we can transmit a complex-valued signal by transmitting its real and imaginary components on separate channels through the medium.

In communication systems, the separate channels are called in-phase (I) and quadrature (Q). We can apply amplitude modulation using a cosine to a lowpass signal to generate the in-phase signal, and apply amplitude modulation by a sine to another lowpass signal to generate the quadrature signal. By subtracting the quadrature signal from the in-phase signal, we would have one real-valued signal to transmit and receive. Modulation by the cosine is orthogonal to modulation by sine, and hence, the IQ signals are in separate channels even though they are transmitted together. This is known as Quadrature Amplitude Modulation, which is used in Wi-Fi, cellular, and other communication systems.

Assignment

This project uses wireless signals to estimate the distance to objects. Please complete the following [8]:

- Project #1: Exercise 1.1(a)-(d) and Exercise 1.2(b) [8]
- Project #2: Exercise 2.1(b)-(c) and Exercise 2.3(a) [8]. For Exercise 2.3(a), indicate how you could determine the delay and from the delay, work backwards to find the distance.

Download project descriptions. [8] On pages 4-5 below, Appendix A connects Discrete-Time and Fast Fourier Transforms and Appendix B describes the report format. See [9] for an introduction to radar systems. Please be sure to also see the mini-project #2 hints. For additional optional reading on ways to estimate the direction (angle) to an object, please see [10].

References
[1] B. L. Evans, "Mini-Project #1: Speech Synthesis", EE 313 Linear Systems & Signals, UT Austin, Fall 2021.
[2] T. Ryan, "What causes electromagnetic waves?", Socratic.org, accessed Oct. 24, 2021.
[3] J. H. McClellan, R. W. Schafer & M. A. Yoder, *Signal Processing First*, 2003. Errata. On-line Companion.
[4] B. L. Evans, "Homework #2 Solution Set", EE 313 Linear Systems & Signals, UT Austin, Fall 2021.
[5] R. Mudhar, "Recordings of ultrasonic vocalisations of bats", accessed Oct. 24, 2021.
[6] "Zadoff-Chu Sequence", Wikipedia, accessed Oct. 24, 2021.
[7] "Doppler Effect", Wikipedia, accessed Oct. 24, 2021.
[8] C. S. Burrus, J. H. McClellan, A. W. Oppenheim, T. W. Parks, R. W. Schafer, H. W. Schuessler, "Chapter 10: Applications" (on Canvas), *Computer-Based Exercises for Signal Processing Using Matlab*, 1994. Code.
[9] "Radar Signal Characteristics", Wikipedia, accessed Oct. 24, 2021.
[10] Dina Katabi, "Lab 3: Wireless Localization", MIT 6.888 Wireless Communication Systems, Fall 2013.

Appendix A: **Connections Between the Discrete-Time and Fast Fourier Transforms**

Discrete-Time Fourier Transform (DTFT). The Discrete-Time Fourier Transform $X_{freq}(\omega)$ computes the frequency content in a discrete-time domain signal $x[n]$:

$$X_{freq}(\omega) = \sum_{n=-\infty}^{\infty} x[n]\, e^{-j\,\omega\,n}$$

An *infinite* number of coefficients could be needed to exactly represent $x(t)$.

Discrete-Time Fourier Series. A discrete-time periodic signal $x[n]$ with period N samples is composed of a constant term plus frequency components at integer multiples (harmonic) of a fundamental frequency of $2\pi/N$ rad/sample which is equivalent to f_s/N in Hz. Fourier series analysis computes the constant term $X[0]$ plus the magnitude and phase of each frequency term $X[k]$ for $k = 0, 1, \ldots, N\text{-}1$.

$$x[n] = \frac{1}{N}\sum_{k=0}^{N-1} X[k]\, e^{j\left(k\frac{2\pi}{N}\right)n} \quad \text{where} \quad X[0] = \sum_{n=0}^{N-1} x[n] \quad \text{and} \quad X[k] = \sum_{n=0}^{N-1} x[n]\, e^{-j\left(k\frac{2\pi}{N}\right)n}$$

A *finite* number of Fourier series coefficients would always be needed to exactly represent $x[n]$.

Discrete Fourier Transform (DFT). The Discrete Fourier Transform (DFT) applies the Discrete-Time Fourier Series to a finite-length signal (or portion of a signal) to create a sampled version of the Discrete-Time Fourier Transform (DTFT):

$$X[k] = \sum_{n=0}^{N-1} x[n]\, e^{-j\left(\frac{2\pi}{N}k\right)n} = X_{freq}\left(\frac{2\pi}{N}k\right) \quad \text{for } k = 0, 1, \ldots, N-1$$

The DFT samples in both time and frequency. The DFT takes a vector of N discrete-time samples and produces a complex-valued vector of N frequency components.

Fast Fourier Transform (FFT) is a fast algorithm to compute the N discrete-time Fourier transform coefficients $X[k]$ from the N samples of a discrete-time signal $x[n]$. As with the continuous-time Fourier series, the discrete-time Fourier series assumes that the N samples of $x[n]$ represents the fundamental period of an infinitely long signal in the time domain. Unlike the continuous-time Fourier series, the discrete-time Fourier series always has a finite number of terms, N. One of the reasons for this is due to the Sampling Theorem, which says that the sampling rate $f_s > 2 f_{max}$ where f_{max} is the highest frequency of interest and hence $f_{max} < \frac{1}{2} f_s$. Sampling only captures continuous-time frequencies $(-\frac{1}{2} f_s, \frac{1}{2} f_s)$ whereas continuous-time signals have frequencies. You can think of the discrete-time Fourier series as computing the Fourier series coefficients for frequency components from $-\frac{1}{2} f_s$ to $-\frac{1}{2} f_s$, which is a finite number because $f_s > 0$.

How fast is the FFT? The FFT to compute $X[k]$ above requires $2M \log_2 M$ real-valued multiplications and additions and $4M$ words of memory instead of the $4 M^2$ and $M^2 + 4M$, respectively, for the direct matrix-vector implementation of the discrete-time Fourier series. A direct matrix-vector multiplication to compute $X[k]$ would create a complex-valued $N \times N$ matrix of the term $\exp(-j\,(2\pi/N)\,kn)$ for $k = 0, 1, \ldots, N\text{-}1$ in one dimension and $n = 0, 1, \ldots, N\text{-}1$ in the other, form a column vector of $x[0], x[1], \ldots, x[N\text{-}1]$, and multiply the matrix and vector to find the column vector of $X[0], X[1], \ldots, X[N\text{-}1]$.

Appendix B: **Report Format for Mini-Project #2**

Please write a self-contained narrative report. The audience is the other students in the class. The report should provide references to the textbook and other sources as needed. Please refer to the hints above, which apply to homework assignments and mini-project reports, as well as the following additional guidelines for the mini-project:

1. Introduction -- explain in your own words and with appropriate references the larger topic of project. Build on your experiences so far in the class. You can also use ideas from the Introduction section in the lab assignment. Probably half of a page for this section.
2. Overview -- explain in your own words and with appropriate references the general idea of the topic of mini-project, including mathematical models. You can also use ideas from other sections in the lab assignment. Not more than a page for this section.
3. Project #1 -- provide the MATLAB code and answers to the questions in that part.
4. Project #2 -- Exercise 2.1 (except part (a)) and Exercise 2.2 -- provide the MATLAB code and answers to the questions in those exercises.
5. Conclusion -- draw conclusions from your work and explanations in the earlier sections. Probably half of a page for this section.