Communication Systems

WS2023-2024 Project Design Report

Software Defined Radio (SDR)

Implementation of a Software Defined Radio Receiver

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1 Table of Contents

2 Introduction

This document outlines the procedures and thought process employed in designing a SDR (Software-Defined Radio) receiver, denoted as M6. This receiver is designed to effectively capture signals characterized by diverse specifications and accurately recover the mysteries.

However, decoding Mystery C wasn't perfectly recovered as the presence of ISI played a much larger role hence, making it more difficult in decoding the text completely. All the steps employed in this project was culled from the supplied textbook. (Software Receiver Design Build your Own Digital Communication System in Five Easy Steps)

3 Problem Description:

We are presented with a series of mystery signals exhibiting escalating levels of distortion. Our working hypothesis posits that the received signal comprises of some random noise stemming from intersecting radio waves and assorted impairments. These distortions have been integrated into the transmitter design, a necessity given the impracticality of transmitting analogue signals and the presence of physical impediments like buildings and thermal noise, distortion, etc. The central challenge at the receiver lies in the uncertainty surrounding the carrier amplitude and phase, though we can reasonably assume knowledge of the carrier frequency based on the provided Intermediate frequency used in generating the mystery signals. This report aims to conduct a thorough analysis and propose solutions for rectifying these impairments at the receiver, ultimately enabling the successful decoding of the mystery signals. The following steps were carried out to decode the mystery. First, carrier recovery was performed to calculate the estimate of the frequency and phase. After carrier recovery and down conversion, I applied an algorithm to perform the clock recovery (Timing recovery) to enable us find the optimal sample point for our timing offset tau. Next, I extracted the header by using correlation to the preamble and data. Then, the header was passed through an LMS equalizer (For preamble) and DD for (Data) which in-turn convert the message using quantalph and our decoder reconstructed the messages using pam2letters. Given the non-ideal nature of the radio system, diverse impairments necessitate thorough intervention through various adaptive techniques at specific stages of the receiver design. **Overall concept was drawn exclusively from the supplied textbook.**

4 Mystery Signals Decoding Stages:

4.1 Carrier Recovery

In the initial analysis of mystery Signal A in Figure 1 (bottom), besides the presence of noise, the spectrum doesn't exhibit much visible distortion or interference. Similarly, the time-domain representation indicates the typical envelope variation of a 4-PAM signal. For a sub-Nyquist sampling frequency of $F_s = 700\ KHz$, the center frequency of our modulated mystery A signal should be: $F_c = \left[\left(\frac{1{,}6}{0{,}7}\right) - floor\left(\frac{1{,}6}{0{,}7}\right)\right] * 700 = 200\ KHz$. The mentioned frequency on the spectrum gives us a carrier frequency of: $Fc = 200{,}165\ KHz$. This is a clear indication of frequency offset impairment of $+165\ Hz$ that we should address using phase tracking algorithm (In general, *frequency offset can be time varying value*). the Intermediate Frequency spectrum of Mystery B, when compared to the spectra of Mystery A and the ideal 4-PAM signal, provides the following indications:

- ✓ Mystery B signal has a lower SNR value (*low spectrum amplitude with respect to noise*) than Mystery A signal.
- ✓ An in-band interference is present at about $+20\ KHz$ off the center frequency, $F_c = \left[\left[\left(\frac{1{,}2}{0{,}95}\right) - floor\left(\frac{1{,}2}{0.95}\right)\right] * 950\right] = 250\ KHz$.
- ✓ No other visible impairments on time domain.

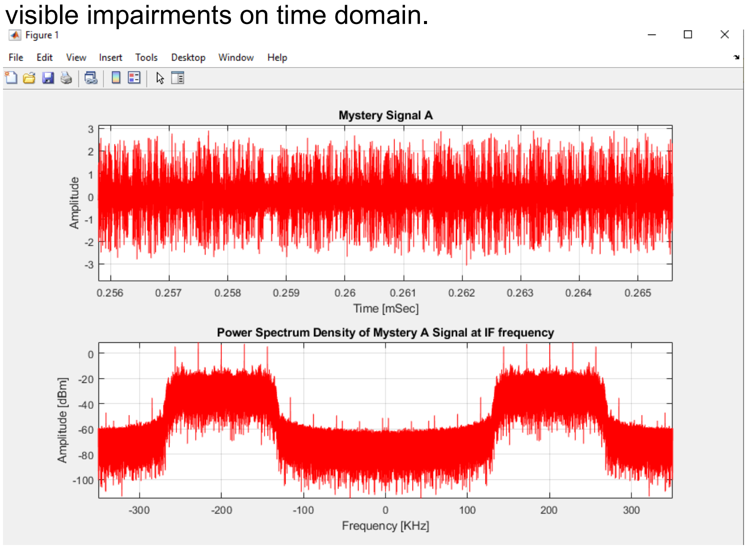

Figure 1: Spectrum of Mystery signal

While the following was observed with Mystery C

- ✓ The presence of frequency selectivity in the signal spectrum. This is a clear indication of presence of Inter-Symbol Interference (ISI).
- ✓ For a sub-Nyquist sampling frequency of $F_s = 819\ KHz$, the center frequency of our modulated mystery C signal should be: $F_c = 819 - \left[\left(\frac{2{,}2}{0{,}819}\right) - floor\left(\frac{2{,}2}{0.819}\right)\right] * 819 = 257\ KHz$. Zooming in to the center frequency $F_c = 257KHz$ of the spectrum of mystery B signal gives as a rough estimation of carrier offset, which is about $-46\ Hz$.

- **COSTAS loop for phase/frequency tracking:**

In this process, I used Costa's Loop which allows us to recover the carrier. The main reason for using Costa's Loop was because it allows us to work directly on the signal without pre-processing. Also, all the tracking loop have the same objective function so when performing carrier recovery using costa's Loop, we are able to track the phase explicitly and also the frequency offset. (G.12) explains further more. I defined the cross function as stated in the book Page. 207 and I used gradient decent to optimize. Fig. 10.9. As seen below, a clean linear curve (*with zero slope for zero frequency-offset or non-zero slope for non-zero frequency offset*) of instantaneous estimated phase $\hat{\theta}(kT_s)$, along with an unavoidable phase ambiguity, serves as an indication of locked COSTAS loop and, consequently, successful phase/frequency tracking in mystery A and B. This indication helped in choosing the right algorithm step size. We can However see that Mystery B curve is a little distorted under the effect of in-band interference tone. i.e. +28KHz of the carrier frequency.

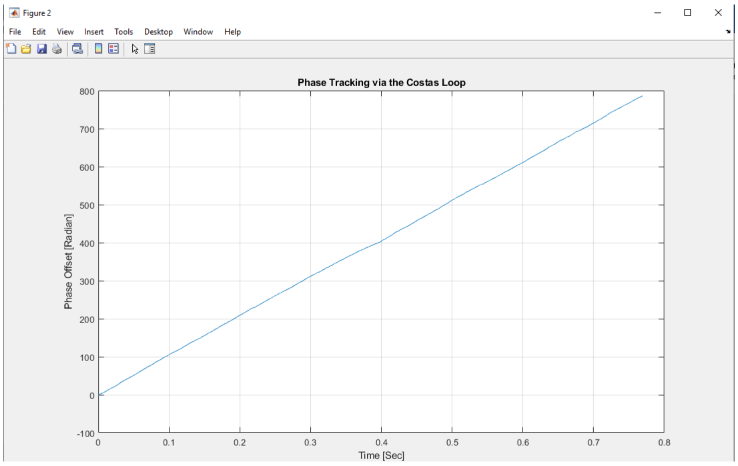

Figure 2: Estimated Instantaneous Phase using COSTAS Loop (Positive Slope)

We can determine the frequency offset at any sample time using the following expression:
Frequency offset $\triangleq \frac{\hat{\theta}(k)-\hat{\theta}(k-1)}{2\pi T_s}\ [Hz]$

4.2 Downconversion

Using the instantaneous phase estimation $\hat{\theta}(kT_s)$, from the previous step, down conversion can be realized without any risk of signal amplitude fading, due to phase difference.
For any type of modulation, the components can be derived from the received signal $r(kT_s)$ as follow:

$$x(kT_s) = LPF\{r(KT_s) * \cos[2\pi F_c kT_s + \hat{\theta}(kT_s)]\}$$
$$y(kT_s) = LPF\{r(KT_s) * \sin[2\pi F_c kT_s + \hat{\theta}(kT_s)]\}$$

The cut-off frequency of the low-pass filter must be chosen to preserve the maximum amount of signal power to avoid signal distortion. The following figure.3 illustrates the baseband spectrum after coherent down conversion. In Mystery C, we use AGC to get our reference point. If there is not AGC and the signal has low SNR, the point will be close hence, making it far from the reference point. In short, AGC helps sample reference point in the actual position. (-1, -3, +1, +3) It also helps to adjust the amplitude to a constant value

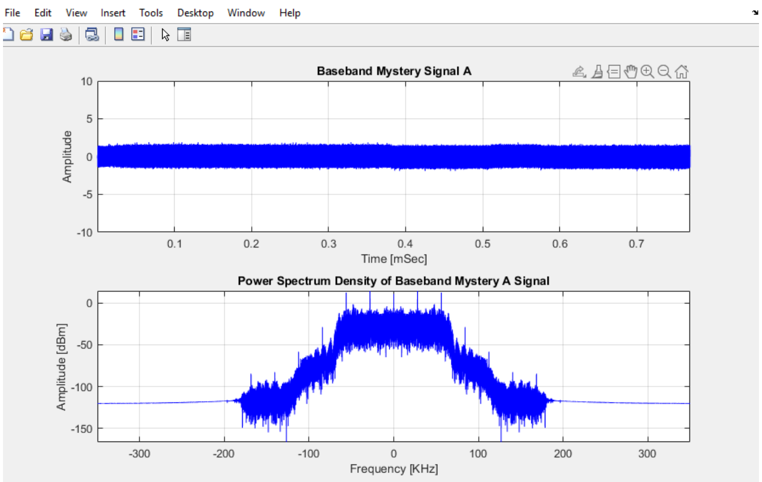

Figure 3: Baseband of Mystery A, B C signal spectrum

Also, in order not to have a wrong constellation, I performed up-sampling and down-sampling which will allow us to get the correct number of samples per symbols

4.3 Matched Filter and Timing / Clock Recovery

After down conversion, we first perform matched filtering to maximize SNR and reduce inter-symbols interference due to the transmitter's root-raised cosine filter. Due to the noise value, we convolved the mystery signal with matched filter. Afterward, the timing recovery algorithm utilizes the output of the down-conversion as its input. Recognizing that the received signal has a square root raised cosine shape, we include the necessary parameters in the square root raised cosine (SRRC). Figure 4 (top plot) illustrates the good performance of the power-maximization algorithm. The reason for using this method is because maximizing output power helps mitigate the impact of interference and noise on the received signal. It also helps in reducing the likelihood of bit errors in the received data. At the beginning of the curve below, we can observe the transient time-window necessary for convergence of the timing recovery algorithm. This time window depends on the adopted μ factor. A high μ factor value implies fast convergence but, on the other hand, a low SNR recovered constellation, and vice versa. The offset estimate in figure 4 (bottom plot) indicates the difference between the nominal and actual clock periods.

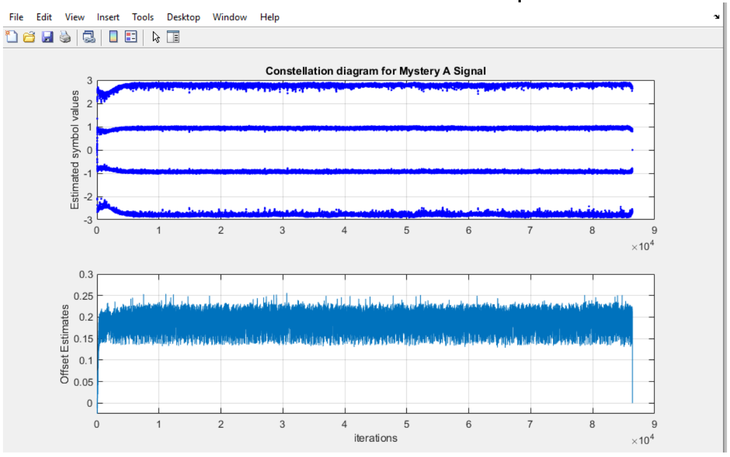

Figure 4: Symbols of Mystery A, B, C after timing recovery

4.4 Equalizer

Equalization is used to remove multipath echoes and other interferers. Here, I adopted a two-stage equalization procedure. Which was also stated in the Software receiver design book First, I used the Least Mean Squared equalizer (Time invariant system) because we have a given preamble, hence, we use this part of the equalizer to train the given preamble while the coefficient is updated. As for data, I used decision directed and the reason for using this approach was because data we receive was unstable. The presence of noise was evident in Mystery C.

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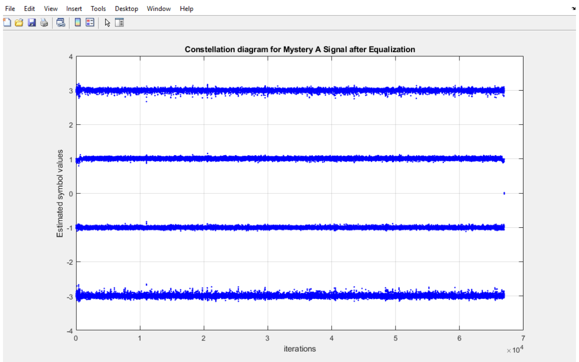

Figure 5: After equalizer was performed on the 3 symbols

4.5 Quantization and Decoding (With Frame Synchronization)

For all frame-based transmission, determining the starting point of each frame is necessary for correct information decoding. Utilizing the known 4-PAM sequence associated with the periodic message "0x0 This is the Frame Header 1y1" as a preamble of 125 4-PAM symbols, we can effectively achieve frame synchronization using correlation. For Mystery B signal, even with a lower SNR compared to Mystery A signal, the synchronization operation still works properly since the maximum value of the correlation function is clearly distinguishable.

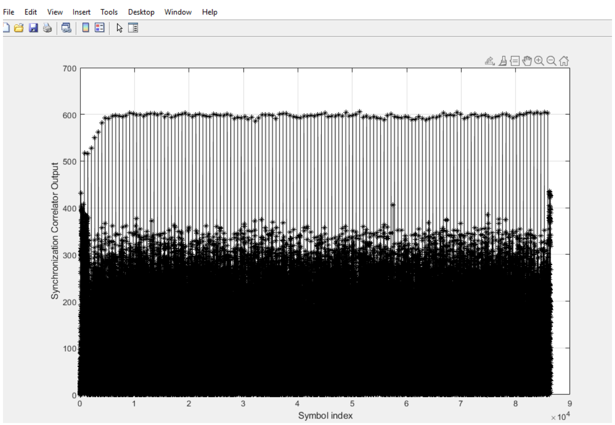

Figure 6: Result of correlator for frame synchronization.

4.6 Conclusion about decoding the Mystery signals

We can conclude that the Mystery A signal has a high SNR value (low constellation error) due to the absence/low interference and distortion. Mystery B signal having a lower SNR than Mystery A signal and the presence of in-band interference tone, we are able to retrieve the information message using standard processing. Unexpectedly COSTAS loop effectively reduces in-band interference tone. Even with the presence of severe ISI, Mystery C signal can still be retrieved using standard processing. AGC and equalization perform well to compensate for time-varying SNR conditions. I believe the equalizer if well-tuned can help with the complete decoding of the Mystery C which is evident in the output.

Reference:

Software Receiver Design (C.Richard Johnson, 2011)