ELEC-H401

Design and Simulation of a DVB-C Transmission Chain

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Introduction

[TODO: CHANGE THE TENSE FROM PRESENT TO PAST]

This project focuses on designing and simulating a Digital Video Broadcasting Cable transmission chain using Matlab. The main goal is to model and analyze the components of a typical modem. The first part of this project includes establishing an optimal communication chain over an ideal Additive White Gaussian Noise channel, mapping the signal into symbols, Nyquist filtering, and evaluating the performance of the system through Bit Error Rate simulations for Quadrature Amplitude Modulation signals. The second part revolves around the design and assessment of time and frequency synchronization algorithms. This encompasses evaluating the impact of synchronization errors such as carrier phase and frequency offset and sample time shift. The algorithms used for this purpose are the Gardner Algorithm for time recovery, and a differential cross-correlator for joint frame and frequency acquisition. Afterwards, their effectiveness is demonstrated through convergence analysis and residual error evaluation (double check). The study also explores phase interpolation techniques to mitigate remaining phase drifts. Finally, the project aims to validate the simulated chain through real-life experimentation on a Hybrid Fiber-Coax setup using Adalm-Pluto hardware, and to compare the simulated performance with experimental observations.

1 Optimal Communication Chain over the Ideal Channel

[TODO: ADD MORE MATH LATER]

1.1 Communication Chain

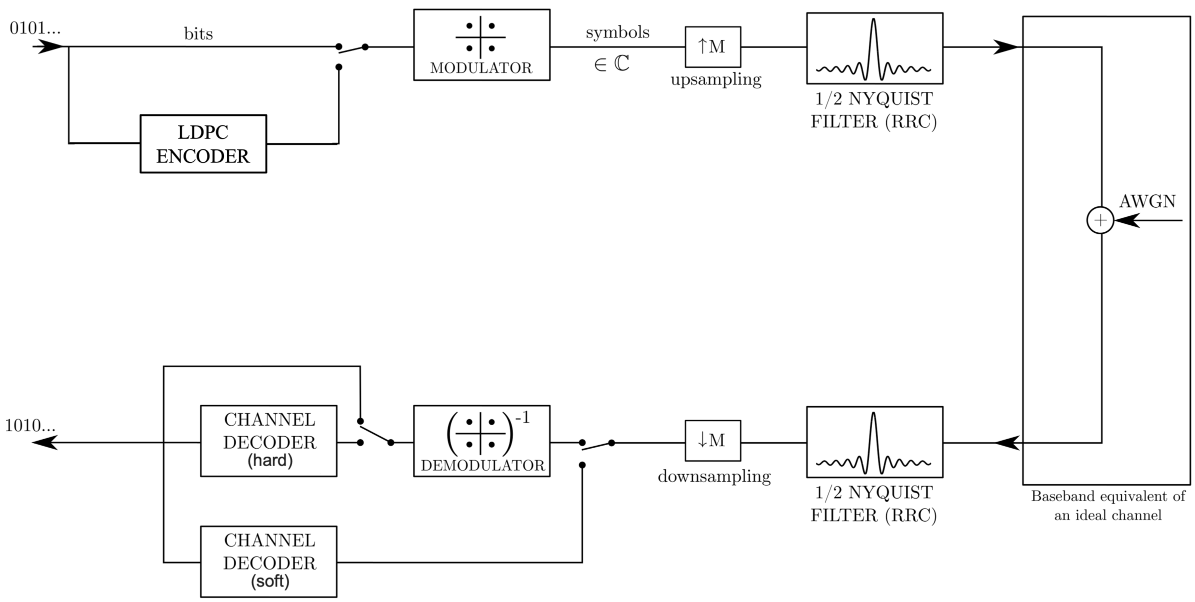

Figure 1: Block diagram of the communication system

The communication chain depicted in Figure 1 models the pipeline of a DVB-C transmitter and receiver at baseband. On the transmitter side, there is a generation of a bit-stream, which is then mapped to complex symbols from a chosen QAM modulation. These symbols are subsequently up-sampled and shaped by a half-root Nyquist filter to limit their bandwidth. On the receiver's side, the signal transmitted is matched-filtered with the same half-root Nyquist filter. The goal of this matched filter is to maximize the signal-to-noise ratio. The output of the matched filter is then down-sampled at the symbols instances, and then demapped to recover an estimate of the bit-stream transmitted.
In this project, the Low Density Parity Check Encoder is not implemented, and the algorithm for symbols mapping and demapping were provided.

1.2 Bit Generation and Symbol Mapping and Demapping

Symbols mapping is the process in which the modulator transforms a sequence of bits into a sequence of complex symbols. This helps improving the spectral efficiency as it allows more bits to be transmitted per symbol over a given bandwidth.
At the receiver end, symbol demapping is performed to convert noisy symbols back into an estimated sequence of bits. This is done through Maximum Likelihood criterion, which aims to selecting the constellation symbol that is closest to the received sample in minimum Euclidean distance.

$$\tilde{\underline{s}}_m^{ML} = \max_{\underline{s}_m}(\ln p(\underline{r}|\underline{s}_m)) = \min_{\underline{s}_m}\left(\sum_{k=1}^{K}(r_k - s_{mk})^2\right) \tag{1}$$

Where:

- $\tilde{\underline{s}}_m^{ML}$ is the estimated symbol using the Maximum Likelihood criterion.
- $\underline{r} = [r_1, r_2, \ldots, r_K]^T$ is the received vector after demodulation
- $\underline{s}_m = [s_{m1}, s_{m2}, \ldots, s_{mK}]^T$ is the vector representing the m-th possible transmitted symbol.
- $p(\underline{r}|\underline{s}_m)$ is the conditional probability of receiving vector $\underline{r}$ given that symbol $\underline{s}_m$ was sent.
- $\sum_{k=1}^{K}(r_k - s_{mk})^2$ represents the squared Euclidean distance between the received vector $\underline{r}$ and the symbol vector $\underline{s}_m$.

1.3 Nyquist Filtering

After mapping the bit-stream into symbols, the sequence of complex symbols $I[n]$ is up-sampled by a factor of $M > 1$, before passing through a pulse shaping filter $g(t)$. The purpose of this filtering is to

1. To limit the bandwidth of the transmitted signal
2. To control the interference between successive symbols

1.3.1 Half-Root Nyquist Filter Design and Matched Filtering

To achieve optimal performance in terms of ISI cancellation and maximizing the SNR at the receiver, a root-raised cosine filter was used. This filter ensures that the overall desired channel response $h(t)$, from the input symbols at the transmitter to the sampled symbols at the receiver, satisfies the Nyquist criterion for zero ISI. This criterion states that the normalized impulse response of the equivalent discrete-time channel $h(kT_{symb})$ is such that

$$h(kT_{symb}) = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases} \tag{2}$$

The filtering is split between a root-raised cosine (RRC) filter $g(t)$ at the transmitter and its matched version $g^*(-t)$ at the receiver. The convolution in the time domain of these two filters, $h(t) = g(t) \otimes g^*(-t)$, forms the overall channel response that satisfies the Nyquist criterion for zero ISI. To design the root-raised cosine filter $g(t)$, the transfer function of the raised cosine filter $H(f)$ was first defined. A square root was then performed on $H(f)$ to find the frequency response of the RRC filter, $G(f) = \sqrt{H(f)}$. Afterwards, an inverse Fourier transform was computed to find its time-domain equivalent $g(t)$.

The frequency response of the raised cosine filter $H(f)$ is almost equivalent to a rectangular window, but with a slope that is less sharp and characterized by a roll-off factor $\beta = 0.2$. Hence the frequency response of an RC filter is given by:

$$H(f)=\begin{cases} T_{symb} & 0\le |f| < \frac{1-\beta}{2T} \\ \frac{T_{symb}}{2}\left(1+\cos\left[\frac{\pi T_{symb}}{\beta}\left(|f|-\frac{1-\beta}{2T}\right)\right]\right) & \frac{1-\beta}{2T}\le |f| \le \frac{1+\beta}{2T} \\ 0 & |f| > \frac{1+\beta}{2T} \end{cases} \tag{3}$$

1.3.2 Filter Properties and Inter Symbol Interference Cancellation

The raised-cosine filter effectively confines the signal energy within a well-defined bandwidth, which is determined by the symbol rate $R_{symb} = 1/T_{symb}$ and the roll-off factor β. The total bandwidth occupied is $B = R_{symb}(1+\beta)/2$. Figure 2 illustrates the frequency response of the raised-cosine filter $H(f)$. It clearly shows a flat passband region, a roll-off region, and a stopband where the response is zero, thus restricting the signal to its allocated spectrum. For the project parameters with a roll-off factor of 0.2, the communication bandwidth is $B = 0.6R_{symb}$

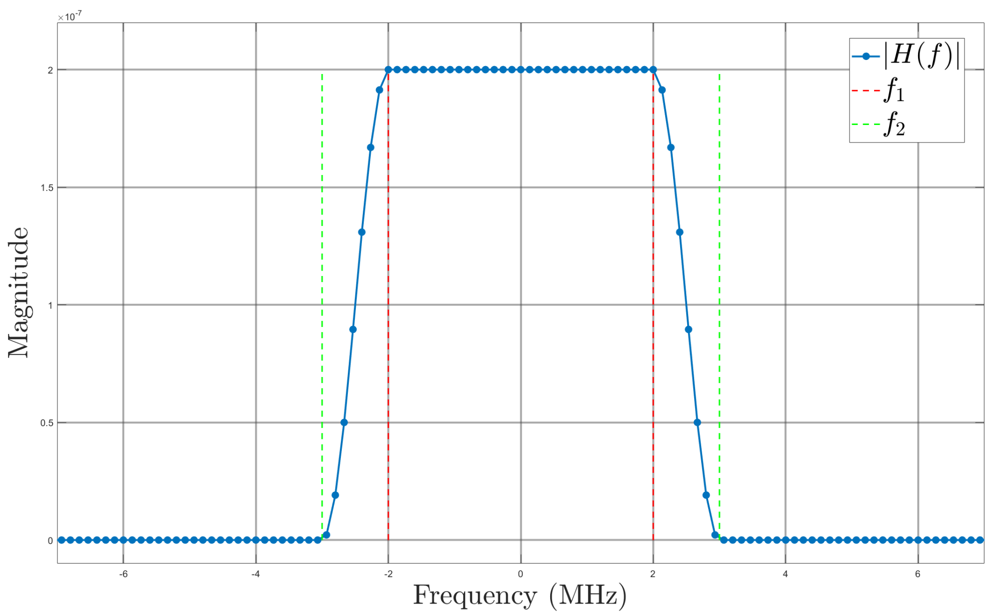

Figure 2: Raised Cosine Filter Frequency Response ($\beta = 0.2$, $taps = 301$, $OSF = 8$)

When the time domain impulse response of the raised-cosine filter is sampled at the symbol rate, it behaves like Dirac's delta pulse.. As shown in Figure 3 by stems representing $h(kT_{sym})$, the normalized RC filter response is unity at $t = 0$ and zero at $t = \pm T_{sym}, \pm 2T_{sym}, \ldots$. This ensures that at the optimal sampling instant for a given symbol, the contributions from all preceding and succeeding symbols are nullified, thus eliminating ISI.

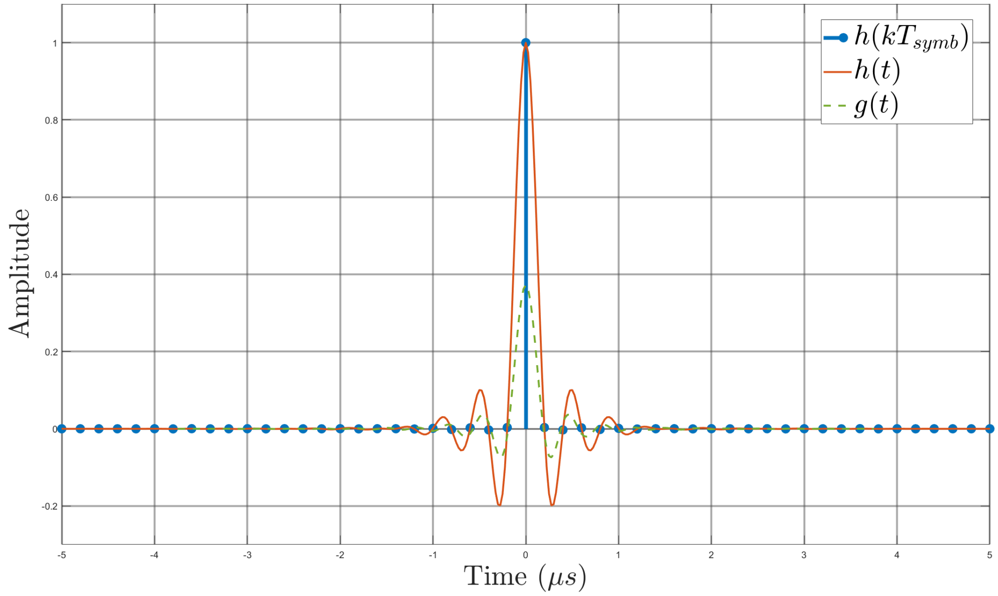

Figure 3: RC and RCC filter Impulse Responses

1.4 Noise Addition and Performance Evaluation

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