Digital Communication Systems Simulation of OQPSK

ECE 1473 – Digital Communication

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1 Introduction

There exist many digital modulation schemes that each have their own various complexities and tradeoffs. For any application requiring digital communication, it is most pertinent to understand the constraints of the system before choosing a modulation scheme. In this report, we study the implementation and performance of offset quadrature phase-shift keying (OQPSK). OQPSK is a variation on the simpler scheme quadrature phase-shift keying (QPSK) and the performance of each were directly compared. OQPSK is often seen in applications for satellite communication systems, where the channel causes non-linear distortion. OQPSK has a maximum phase change of 90°–a property we investigate in this report–which is advantageous for such channels[1]. Our simulation results were designed in MATLAB. The simulation includes a full implementation of OQPSK from transmitting an incoming random signal, to adding channel propagation Gaussian noise, to demodulating the noisy signal and recovering the bits. Power spectral density and bit error rates were both calculated to evaluate the performance of OQPSK.

2 Procedures

The simulation of OQPSK modulation can be visualized in the flow chart below. Two channels are generated and modulated with the orthogonal function sine and cosine. The Q-channel is then time shifted by half a bit period. The actual transmitted signal that propagates through the channel is the subtraction of the these two channels. For demodulation, the block diagram is reversed starting with demodulation. OQPSK can be generated using this block diagram when the "Time shift" block is ignored. The simulation environment was MATLAB 2014b distribution.

2.1 Baseband Signaling

The simulation had the following parameters in Table 1.

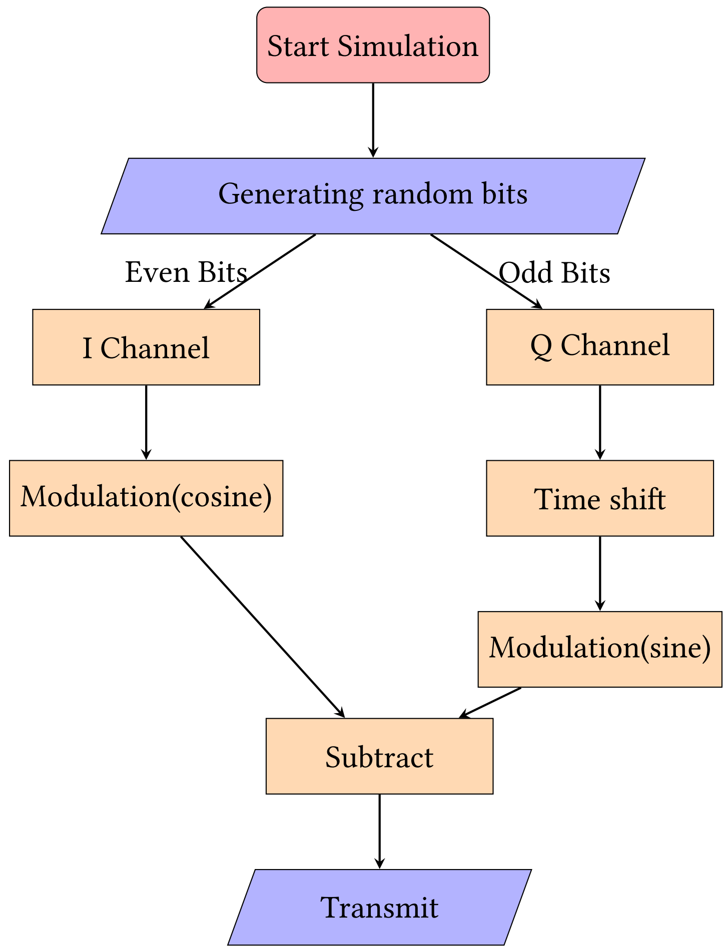

Figure 1: Flow chart for OQPSK modulation

Parameter Names	Values
Bit rate on each channel	500
Pulse length	20 bit times
Root RCRO r	0.5
Samples per bit length	128
Carrier amplitude	1 V
Number of random bits	100
Carrier Frequency	10 KHz
Iterations	200

Table 1: Simulation Parameters

100 bits were generated randomly using the randn function in MATLAB. The function generates a pseudo-random Gaussian distribution with variance one. To generate a random bipolar bit sequence, each bit was then assigned to either +1 or -1 based on the sign of the output. This generated binary bit sequences that had equal distributions of 1's and 0's. Because of the nature of the OQPSK modulation, even bits(a_i) are assigned to I channel and odd bits(a_q) to Q channel. Due the noise from the channel and in order to avoid inter-symbol interference, a Root-Raised-Cosine pulse was used to generate the raw signals for both channels according to the formula $s(t) = \sum_n a_n h(t - nT_b)$. The root-raised-cosine-roll-off pulse follows the equation where T_b and r is bit period and roll-off factor respectively:

$$h(t) = \begin{cases} 1 - r + \frac{4r}{\pi} & t = 0 \\ \frac{r}{\sqrt{2}}\left[\left(1+\frac{2}{\pi}\right)\sin\left(\frac{\pi}{4r}\right) + \left(1-\frac{2}{\pi}\right)\cos\left(\frac{\pi}{4r}\right)\right] & t = \pm\frac{T_b}{4r} \\ \frac{\sin\left[\pi Rt(1-r)\right] + 4Rrt\cos\left[\pi Rt(1+r)\right]}{\pi Rt\left[1-(4Rrt)^2\right]} & \text{otherwise,} \end{cases}$$

Figure 2: Root-raised-cosine-roll-off pulse

2.2 Digital Modulation

Both channels were than mixed with respective carriers. The I channel was mixed with $A_c cos(f_c t)$ and Q channel with $A_c sine(f_c t)$. The output on Q channel was delayed by half a bit period. The delay was implemented by extending the time vector and filling the first half bit period with zeros. In addition, extra caution was taken to make sure that both channel outputs have the same number of samples. By subtracting Q channel output from I channel, the OQPSK was generated. The modulation follows equation where $f_c and A_c$ is the carrier frequency and amplitude:

For I channel: $s(t) = A_c m(t) Re\{e^{jf_c t}\} = A_c m(t) cos(f_c t)$

For Q channel: $s(t) = A_c m(t) Im\{e^{jf_c t}\} = A_c m(t) sin(f_c t)$

2.3 Channel Modeling

The transmitting channel was modeled using an additive white Gaussian noise. The noise was generated using the randn() MATLAB function with a scaling factor as standard deviation of the noise. It was then added to the transmitted signal. 50 different noise variances were tested ranging from 2.0187 to 1011.7.

2.4 Demodulation and Optimal Detection

The constellation map for OQPSK is seen in Figure 3. Only 90° phase shifts are possible since only one bit can change at a time.

Demodulation was performed separately for I and Q channels. Two product detectors, $cos(f_c t)$ and $sin(f_c t)$ were used to decode two channels. Then, a root-raised-cosine match filter was used to eliminate the high frequency components in order to recover only the baseband signal. The match filter was the same as the pulse used in baseband signaling.

Both channels were than sampled at an integer multiple of bit period, with an offset of half of the bit period on Q channel, since it was shifted before the modulation process. The sampled values were normalized to -1 or +1 and compared to the original bit values.

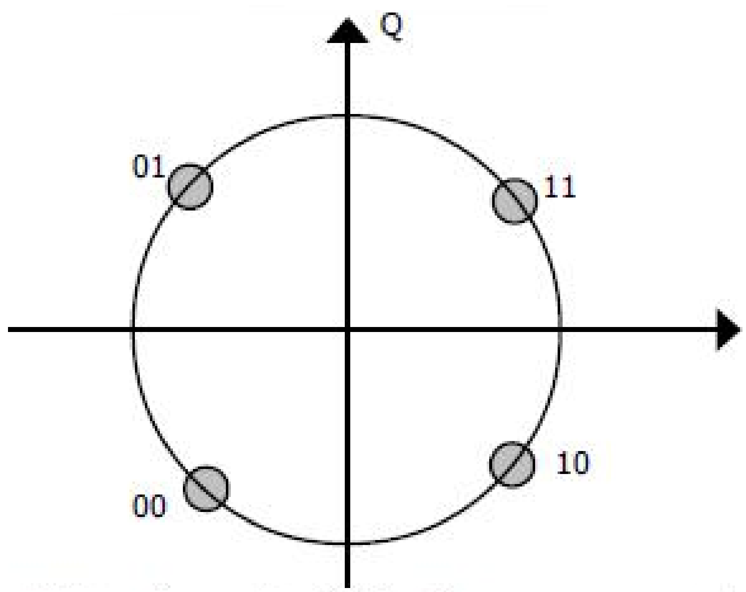

Figure 3: Constellation map for OQPSK[3]. Q-channel is represented by the y-axis and the I-channel is represented on the x-axis.

2.5 Visualization of signals and spectra

The spectrum of the transmitted signal(without noise) was generated using FFT() and FFT-SHIFT() functions in MATLAB. The magnitude of the of the power spectrum density was normalized by dividing by $N * d_t$ (FFT length and sampling time). The theoretical PSD was plotted using two shifted copies of the Raised-Cosine-Rolloff spectrum at the carrier frequency. Many trails were ran and the averaged PSD was plotted against the theoretical PSD.Both PSDs were plotted in normal scale and logarithmic scale. The ideal PSD follows equation where $|F(f)|$, T_s

and A is the spectrum for Raised-cosine-roll-off pulse , symbol period and a constant of $\sqrt{2}$:

$$P(f) = \frac{|F(f)|^2}{T_s} A^2 A_c^2$$

The null bandwidth of the OQPSK signal using RRCRO pulses can be verified using equation where r is the roll-off factor and R is the symbol rate (bit rate in each channel):

$$B = \frac{r+1}{2} R$$

This is where weather the design specs in terms of power intensity regulated by FFC would be met or not can be known. The results section will discuss how the parameters used in this simulation met specs. The total normalized in-band power was calculated using equation where $|F(f)|^2$ is the simulated PSD :

$$\sum |F(f)|^2 df$$

2.6 Bit Error Rate Calculation

An important performance metric for digital modulation schemes is called the bit error rate (BER). BER determines the probability of a scheme resulting in a error due a certain signal-to-noise ratio (SNR). The theoretical BER for QPSK and OQPSK (polar) assuming ideal transmitter and receiver is

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

where E_b is the energy of the transmitted signal per bit period and N_0 is the variance of the noise. The energy per bit was calculated using equation

$$\sum (h_i(t - nT_b) cos(f_c(t - nT_b)))^2 dt) + \sum (h_q(t - nT_b) sin(f_c(t - nT_b)))^2 dt)$$

where dt is the time interval between each sample and h is the pulse used in the baseband signal. The bit energy is the summation of both channel outputs after modulation process.

E_b/N_0 was selected to cover from -15dB to 7dB of the x-axis of the BER plot. The noise variance was calculated as $N_0 f_s/2$ when the noise was bandlimited to $f_s/2$. The area under the noise PSD is the same thing as variance. The idea Bit Error Rate plot was generated using qfunc() in MATLAB with $\sqrt{2 * e_b/N_0}$ as an argument.

The bit error increased whenever there was a mismatch of sampled values with the original bit patterns. The threshold was set to be zero because the signal was polar.

For our simulation, we generated SNR ratios between -15dB and 5dB and applied the noise to our simulation. For each noise variance, 50 trials at 100 bits each were simulated.

3 Results

3.1 Baseband Signaling

Figure 4 shows the beginning waveforms of the simulation. Ten random bipolar bits were generated and grouped into even and odd bits. The effects of the RRCRO pulses used for each bit can be seen in the generated Q and I-channels. The bit sequence for the Q-channel is (-1,-1,-1,1,1) and the I-channel sequence is (-1, 1, 1, 1, 1). It can be seen that the waveforms follow the appropriate pattern for their respective bit sequences. At the bit sample times, both channels have values that are near -1 or 1 but not exact.

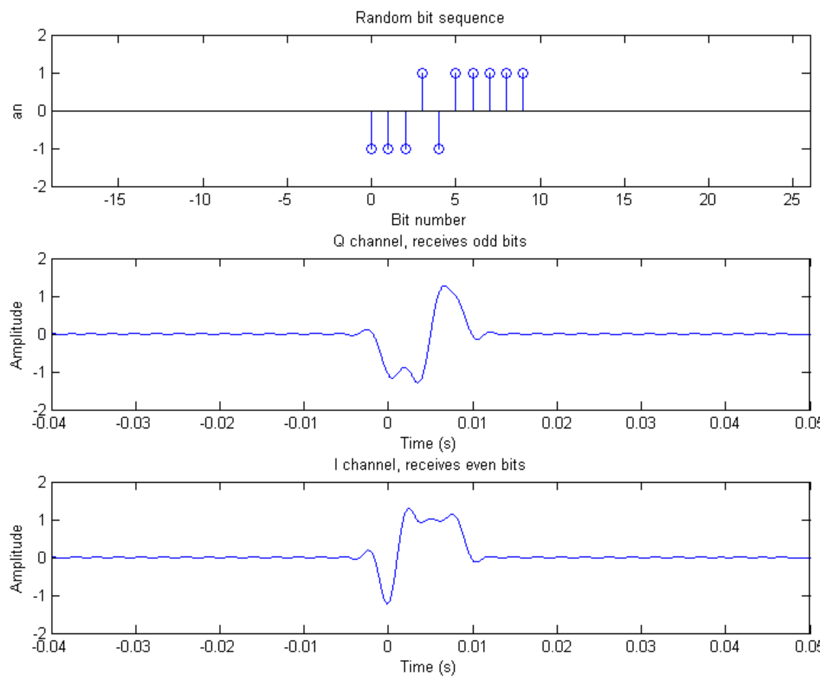

Figure 4: Random bit sequence generated using bipolar levels (top). Q channel generated using RRCRO pulses before time shift, receives odd bits starting with the first (middle). I channel generated using RRCRO pulses, receives even bits (bottom).

3.2 Digital Modulation

Time shifting the Q-channel and modulation for both channels are displayed in Figure 5. Due to the much higher frequency of the carrier signal than the bit rate, we expect to see lots of oscillations. An outline of both channels was also plotted on the envelope for the modulated signals to verify correct functionality. In the Q-channel plot, at time $t = 0$ seconds, the waveform is still very near zero. This indicates that the Q-channel has properly been time shifted since the first bit should now appear at $t = T_b/2$.

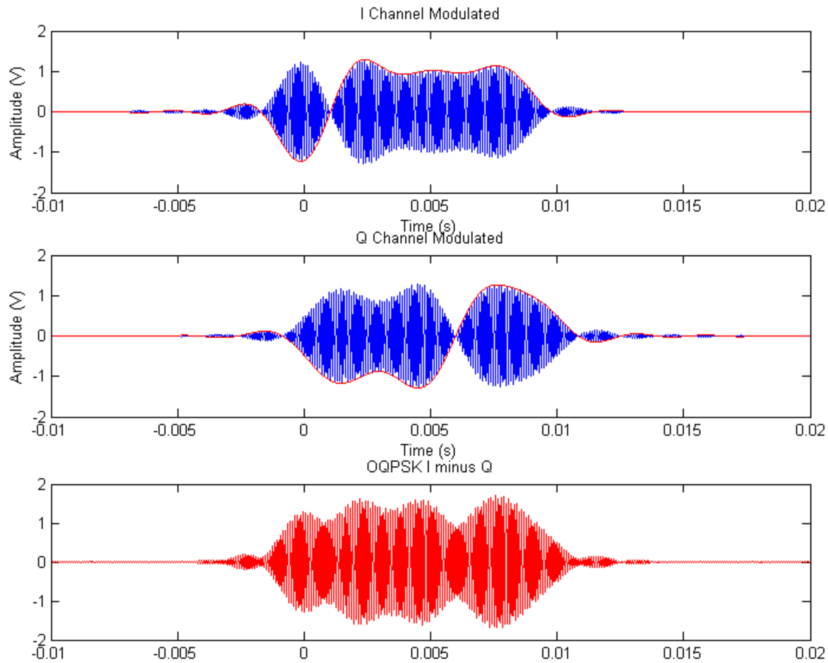

Figure 5: I channel modulated with carrier 10kHz (top). Q channel shifted by half a bit period and modulated with carrier 10kHz (middle). OQPSK TX signal, I channel subtracted by Q channel (bottom).

3.3 Optimal Detection

Figure 6 shows the output of the receiver after the signal was filtered optimally using the matched filter. In this instance, no noise was applied to signal so we expect perfect reconstruction. In both the I and Q-channels, values sampled at the bit times equal the expected bit exactly. For the non-ideal case, Figure 7 shows the output of the matched filter when noise with variance 5 was added to the signal. The plot on the top shows the transmitted signal, which looks vastly different than the transmitted signal without noise in Figure 6. Even still, both channels are able to recover the correct bits after matched filtering. Slight deviations from the the exact bit value were observed, but for this instance there were no bit errors.

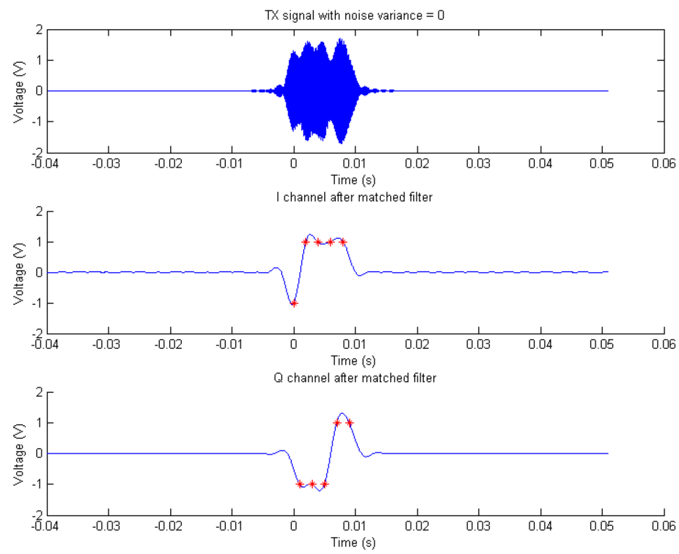

Figure 6: I-channel after matched filtering (top). Q-channel after matched filtering (bottom).

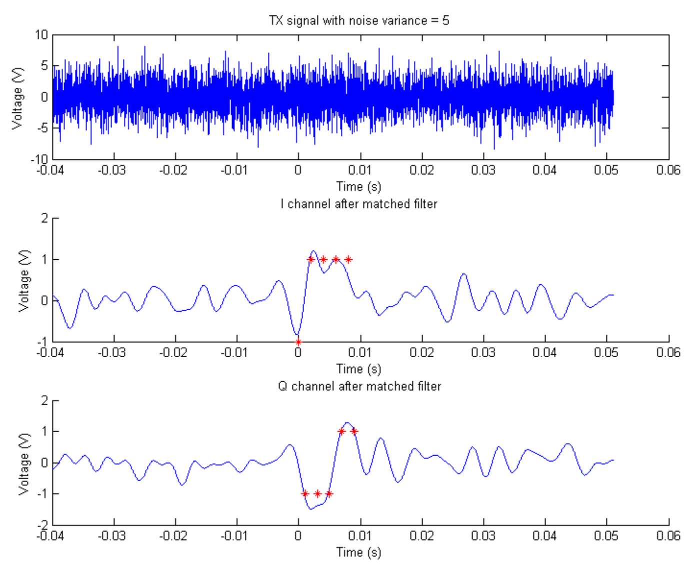

Figure 7: TX signal with channel modeling noise (top). I-channel after matched filtering (middle). Q-channel after matched filtering (bottom).

3.4 Power Spectral Density

The power spectral density calculated in the simulation and plotted theoretically are shown in Figure 8. Theoretically, the PSD should equal zero outside the bandwidth. The absolute bandwidth measured was around 750Hz when using -80dB as a reference. In the simulated waveform, sidelobes are present and diminish the further they are away from the passband. Figure 9 shows the PSD zoomed in. The passband has a level of -50dB, the highest PSD above 5kHz away from the passband is -120dB, and the highest PSD above 8kHz is -130dB. The total in band power was calculated to be 0.2755W by summing the area under the curve after 50 iterations of averaging inside the effective bandwidth from 9625Hz to 10375Hz. It is shown in Figure 10

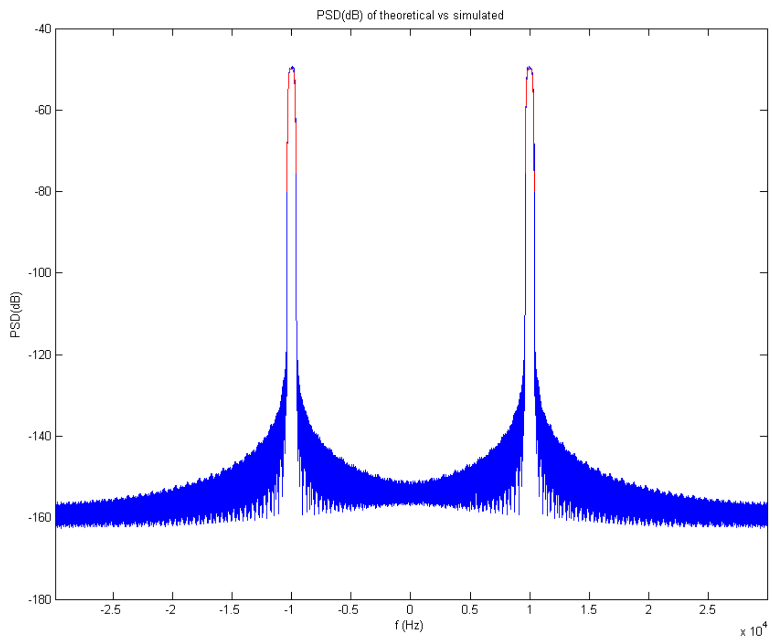

Figure 8: Theoretical against simulated PSD for modulated signal.

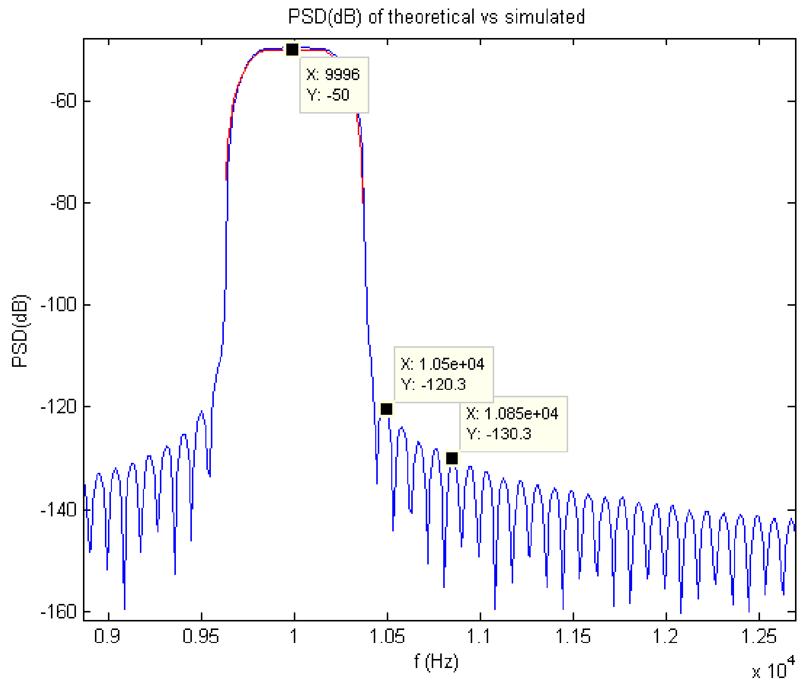

Figure 9: Theoretical against simulated PSD for modulated signal.

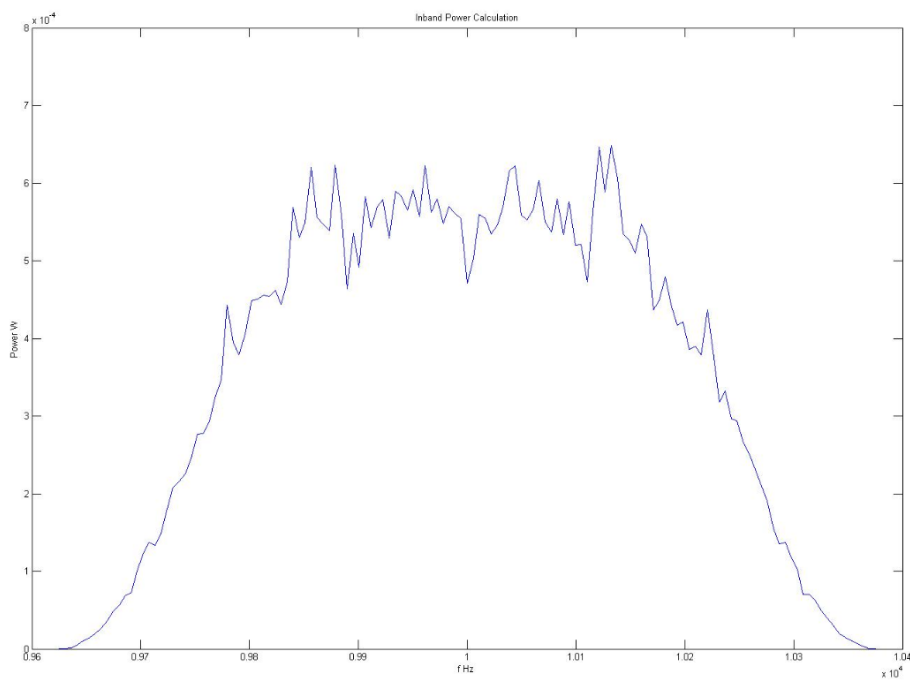

Figure 10: Inband power calculation

3.5 Bit Error Rate

The theoretical BER for an optimal receiver is plotted against the simulated BER in Figure 11. At low SNR values, both curves match and approach asymptotically towards a 50% BER. At higher SNR values, both simulated and theoretical match but begin to deviate near 7dB SNR.

Figure 12 shows the Shannon capacity for SNR values used in the simulation. At around -11dB, the maximum bit rate goes below 1000 bits/sec, which is the maximum bit rate our simulation achieves.

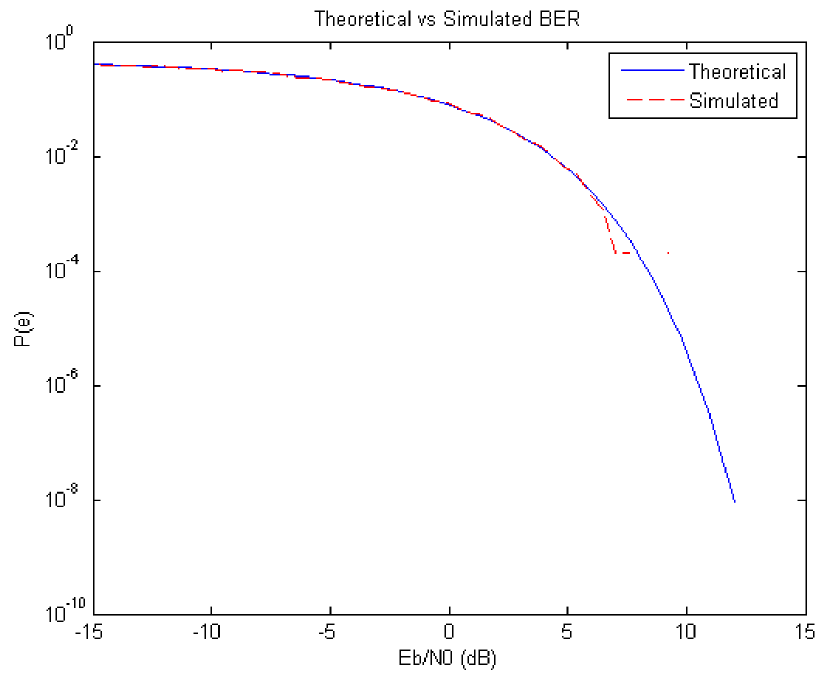

Figure 11: Theoretical against simulated BER results for various SNR values

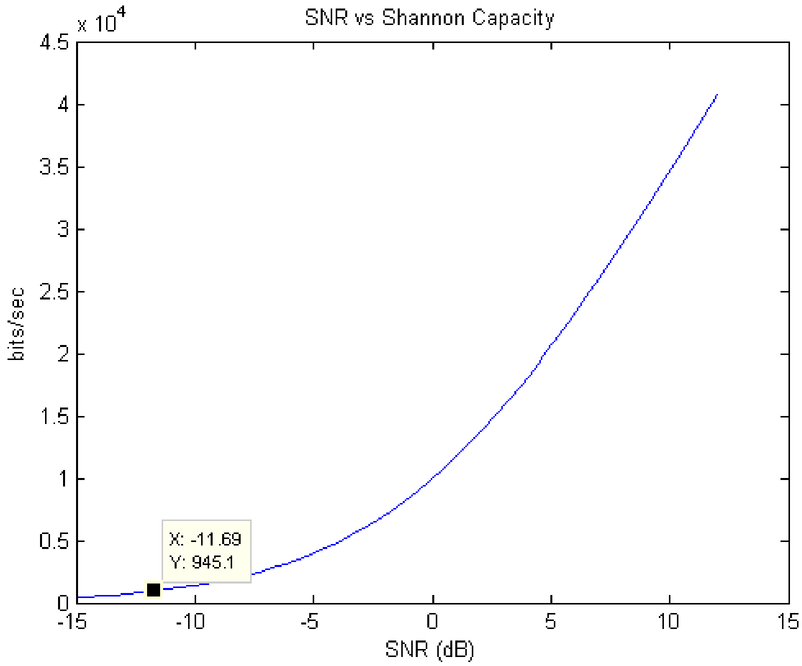

Figure 12: Maximum Shannon capacity bit rate against various SNR values

4 Discussion

During baseband signaling, small errors in the I and Q-channels at bit times were noticed because a small value of Kt was used. This resulted in a RRCRO pulse that was severely truncated and therefore led to errors in the baseband signal. Practically, these small deviations are virtually nonexistent when considering the amount of noise that will be added through channel modeling. In addition, the number of samples per bit should be carefully chosen so that there is no aliasing when a 10kHz carrier was used.

In the optimal detection section when no noise was added, ideally the sampled values at integer multiple of bit times should be exactly 1 or -1 after normalization. This is due to the fact that a root-raised-cosine-roll-off pulse was used which does not cause intersymbol interference. However, at some random instances, the magnitude of sampled values are not exactly 1. This could be a result of truncation of the RCRO pulse as described above, or rounding errors. Despite this, Figure 6 shows the correct decoded bits as in Figure 4.

The sidelobes present in the simulated PSD do not exist in the theoretical PSD. This is due to two reasons, one being the truncation of the RCRO pulse and the other being this was a discrete simulation. This simulation had a sampling rate 64kHz, and thus aliasing will occur for frequencies higher than 32kHz. Another consequence of being a discrete simulation is that the calculation of the PSD itself is only an approximation as we cannot generate a signal period extending to infinity. Upon inspection of the passband, we found from our measurements that we met the modulation requirements. For frequencies above 5kHz, we exceedingly met the requirement to be at least -40dB below the passband by 70dB. However, we barely met the requirement for frequencies above 8kHz to be at least -80dB below.

In addition, the bit rate used in the simulation was defined as bit rate for each channel. Therefore, the simulated PSD should use the same bit period in the calculation was

The root-raised-cosine-roll-off pulse used in this simulation was tested extensively with different roll-off factors to make sure there is no divided by zero rounding errors within a certain precision which will cause blips in the modulating signal. With lower roll-off values, the PSD of both the theoretical and simulated widened in the passband and vice versa with higher roll-off values.

In the BER graph for Figure 11, we were able to match our theoretical results for low SNR values. For higher SNR values, some deviations were seen but this is expected. Our simulation only generates 50 trials at 100 bits for each noise variance. With these parameters, the lowest non-zero BER we can detect is .02%. More trials with more bits will generate a simulated BER that matches closer BER to theoretical.

BER and the bit rate for QPSK and OQPSK are the same[CITE BOOK], so it is important to distinguish why one would use OQPSK over QPSK. OQPSK eliminates a simultaneous transition in both the Q and I-channels, since the channels are offset in time. In QPSK, both bits can switch which causes a 180° phase shift. In QPSK, only 90° phase shifts are possible. 180° phase shifts can hover around 0V and cause a low amplitude envelope. This is undesirable for synchronizing with the carrier signal, so at the compromise of complicating the transmitter and receiver circuitry, OQPSK removes any 180° phase shifts.

5 Conclusion

A full simulation modeling the transmitter channel, and receiver using OQPSK modulation was implemented in Matlab. The BER and PSD were calculated both through simulation through many trials and theoretically through the expected equation. Both methods matched taking into regard the discrete limitations of the simulation. Our simulation had a modest goal of achieving a bit rate of 1kbits/sec, but even with this, the system could sustain heavy amounts of noise–around -11dB SNR–and still be able to achieve this bit rate as given by Shannon's Theorem. In addition, our design met specifications for a minimum and maximum power within a passband, and maximum power outside the passband. Such requirements are similar to FCC regulations. The OQPSK has advantage over QPSK in that it's envelope doesn't go to zero and has less amplitude variation. This prevents a PLL circuit from losing lock on to the carrier signal when the amplitude is very small. However, the transmitter and receiver are more complicated because the extra time delay that was introduced during modulation.

References

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