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Improving the Wireless Link Reliability of a Flight Termination System

Garrett McCabe

THE FLORIDA STATE UNIVERSITY

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IMPROVING THE WIRELESS LINK RELIABILITY OF A FLIGHT TERMINATION SYSTEM

By

GARRETT MCCABE

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The members of the supervisory committee were:

Geoffrey Brooks
Professor Directing Thesis

Bruce Harvey
Committee Member

Bing Kwan
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.

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LIST OF ACRONYMS

Eb/N0: bit energy-to-noise power spectral density ratio
AWGN: additive white gaussian noise
BER: bit error rate
BPSK: binary phase shift keying
CDMA: code division multiple access
CPFSK: continuous phase frequency shift keying
CPM: continuous phase modulation
CWI: continuous wave interference
DS/SS: direct-sequence spread spectrum
EFTS: enhanced flight termination system
FDMA: frequency division multiple access
FER: frame error rate
FM: frequency modulation
FTR: flight termination receiver
FTS: flight termination system
GMSK: Gaussian Minimum Shift Keying
IRIG: Inter Rage Instrumentation Group
LOS: line of sight
MSK: minimum shift keying
MSK-SS: minimum shift keying spread spectrum
OFDM: orthogonal frequency division multiplexing
OQPSK: offset quadrature phase shift keying
PAR: peak-to-average power ratio
PN Code: pseudo-noise code
QPSK: quadrature phase shift keying
RF: radio frequency
SIR: signal-to-interference power ratio.
SNIR: signal-to-noise plus interference ratio
SNR: signal-to-noise ratio
TDMA: time division multiple access
UAV: unmanned aerial vehicle

ABSTRACT

A proposed alternative wireless communication technique is developed and compared to the current radio frequency command link in a Flight Termination System. The command link in a Flight Termination System requires a reliable signal in a radio frequency environment that is becoming overcrowded and is susceptible to various sources of interference. The proposed wireless command link implements direct-sequence spread spectrum modulation (DS/SS) to provide additional interference rejection. The DS/SS modulation is paired with minimum shift keying (MSK) which is a spectrally efficient constant envelope digital modulation technique. MSK also benefits from bit error rates that are competitive with other common modulation schemes such as binary phase shift keying in an additive white Gaussian noise wireless channel. The proposed MSK-SS modulation scheme is simulated alongside the current digital modulation scheme, continuous phase frequency shift keying (CPFSK), against narrowband, co-channel and multipath sources of interference to measure its effectiveness of rejecting interference. The MSK-SS system is able to provide bit error rates less than 10^{-6} at 11 dB E_b/N_0, while the CPFSK system requires at least 14 dB E_b/N_0. When subjected to narrowband interference, the MSK-SS scheme benefits from 18 dB of interference rejection to CPFSK. Co-channel interference rejection of MSK-SS is observed to be 12 dB greater than CPFSK. The MSK-SS system is also able to suppress the effects of multipath interference while CPFSK error rates are extremely affected both destructively and constructively. The proposed MSK-SS modulation scheme is able to greatly improve error rates while offering interference rejection with a 99% power bandwidth less than 200 KHz and a minimal impact on the overall acquisition time. This proposed MSK-SS solution could enhance the reliability of the safety critical wireless communication link for a future generation of Flight Termination Systems.

CHAPTER ONE

INTRODUCTION

The development of this thesis began with an examination of how a future generation of a Flight Termination System (FTS) could improve its wireless command link reliability; specifically, when interfering sources are present in the wireless channel. An FTS is required on test vehicles that have the potential to become a hazard to people or property. Used as a tool by the range safety office of a test range, the FTS prevents item under test from departing the controlled area. An FTS is a safety critical device that requires a reliable communication link among its redundant hardware components.

A Radio Frequency (RF) signal transmits through a wireless channel that impairs the receiver's ability to accurately demodulate and decode the intended signal due to channel interference and noise [1]. Multipath delay is also a form of interference; the receiver receives time shifted copies of the transmitted signal due to reflection, diffraction, and scattering of propagating signal [2]. As seen in Fig 1.1, the received signal is a summation of interference and noise, in addition to the transmitted signal.

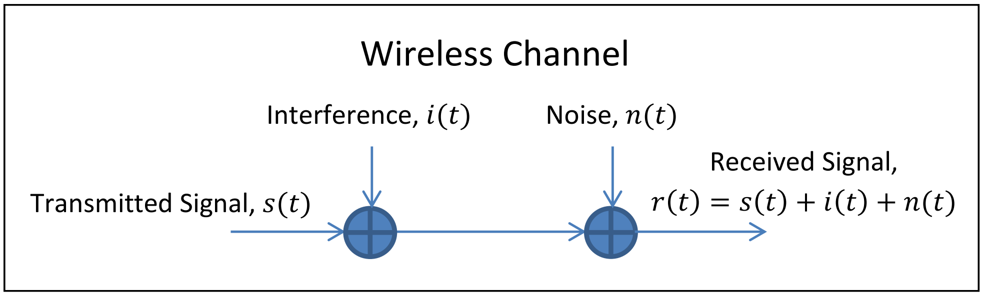

Figure 1.1: A typical wireless channel

In the event that a substantial amount of interference is present, the current FTS wireless command link could lose capture lock on the intended signal and could result in failed operation of the FTS. There are many well-documented techniques that can be used in order to reduce interference inherent in a wireless channel such as Direct-Sequence Spread Spectrum (DS/SS) and Orthogonal Frequency Division Multiplexing (OFDM).

Orthogonal Frequency Division Multiplexing is a multicarrier modulation technique that offers narrowband and multipath interference resistance by using orthogonal frequencies to transmit the symbols [2]. Cyclic prefixes transmitted during a guard interval between the OFDM symbols that are affected by inter-symbol interference are removed, leaving only the OFDM symbols to recover the original message [2].

A disadvantage to using OFDM is that summation of the orthogonal carrier frequencies to create the OFDM symbols can result in a modulated signal with a peak-to-average power ratio (PAR) that is greater than one. The non-constant envelope of an OFDM signal leads to degraded efficiency with non-linear high power amplifiers because the output power must be reduced in order to avoid distortion of the amplified signal [1]. Additionally, as the number of orthogonal carrier frequencies used in OFDM is increased to N, the PAR is increased to a maximum of N [2]. There are techniques that can be used to lower the PAR such as clipping the signal, peak cancellation, and multiple symbol representation; however, these techniques add increased complexity to the system's design and unwanted distortion while not fully reducing the PAR [3] [2].

Previous work rejected spread spectrum modulation for FTS [4]. This was because the proposed implementation was an industry standard Code Division Multiple Access (CDMA) technique that employed non-constant envelope modulation. The non-constant envelope modulated signal required changes to the ground infrastructure because of its incompatibility with non-linear amplifiers and the bandwidth of the system exceeded the target specifications [4].

The problem with amplifying a non-constant envelope signal with high power nonlinear amplifiers is that the output will have fluctuating levels of distortion and spectral regrowth in the side bands as the power level of the input signal varies [5]. Distortion can be avoided by reducing the output level of the amplifier, but this also reduces the efficiency of the amplification system that is expensive to operate and maintain [5]. Using a non-constant input signal allows the nonlinear high power amplifier to operate near 100% efficiency [5].

Spread spectrum modulation has been shown to be an effective method to resist interference gained in a wireless channel in addition to enabling multiple access capability [6]. This thesis recognizes that spread spectrum technology can be used to improve the reliability of the system and offers an implementation that is paired with a digital modulation technique that maintains a constant envelope and is spectrally efficient. Minimum Shift Keying (MSK) modulation was chosen because of its similarity to current FTS digital modulation technique Continuous Phase Shift Keying (CPFSK). Since the bandwidth of a spread spectrum system is directly related to its interference rejection capabilities, it is a fundamental property of spread spectrum that the bandwidth of the signal will be greatly increased [7]. The rapidly decaying side lobes of an MSK signal are also desirable for reducing the bandwidth after spread spectrum is implemented [8] [1].

The proposed Minimum Shift Keying Spread Spectrum (MSK-SS) system is modeled in software and the bit error rates (BER) and frame error rates (FER) are assessed when it is subjected to various types of interference. The bandwidth of the resulting signal and acquisition time associated with the spread code synchronization are also performance metrics. These results are compared to the current FTS digital modulation technique as a baseline in order to validate the thesis.

1.1 Problem Area

Most importantly, CPFSK modulation was chosen for EFTS because of its amiable properties that make it similar to Frequency Modulation (FM) used in the legacy FTS. CPFSK is a continuous phase modulation technique that has a constant envelope signal. This constant envelope signal allows it to have excellent power efficiency and ensures compatibility with the current infrastructure used for the transmission of the signal; in particular, the use of high power amplifiers in the current infrastructure exhibit a non-linear amplification at the transmitter [9].

Amplitude shift keying and phase shift keying modulation techniques do not have a constant envelope signal, and the amplification with a non-linear amplifier would result in a distorted signal with varying power levels throughout the transmission [10].

However, CPFSK and FM have limited interference protection in the form of capture lock on the receiver. In order for an interfering signal to affect the desired signal, the interfering signal must be at a greater power level than the desired signal at the receiver. Although this is mitigated by the use of high power transmitters, a near-far problem can be present since the command link is often used over great distances where the path loss of the desired signal can allow an interfering signal of much lower power to break the capture lock of the receiver.

Since wireless communication is becoming more prevalent in today's society, it is difficult to ensure that the FTS will operate exclusively in its own assigned frequency spectrum. Therefore, a future generation if FTS must offer improvements over the CPFSK modulation in resistance to interfering sources that can originate from either unintentional or intentional emanating sources.

1.2 Premise

Pairing MSK modulation with DS/SS should improve error rates over the current CPFSK modulation scheme in a wireless channel afflicted by interference. Testing this thesis with computer simulations will demonstrate the interference resistance abilities, showing that the MSK-SS modulation scheme will improve the FTS's command link reliability.

1.3 Scope

The scope of this thesis is restricted to comparing the proposed modulation scheme to the current CPFSK digital modulation in RF environments that are subjected to increased interference. The testing of this thesis is limited to software simulation using MATLAB to construct the models needed to perform the tests. Since the designs of the CPFSK demodulator/detector for current Enhanced Flight Termination System (EFTS) receivers are deemed proprietary by their respective manufacturers, the modeling of the CPFSK receiver will be built as a coherent correlation demodulator. The design and implementation of carrier frequency and phase tracking is outside of the scope of this document, since similar conventional techniques for tracking the carrier can be applied to both CPFSK and DS/SS.

1.4 Document Summary

The organization of this document is structured to enable the reader to understand the problem and background information used in formulating this thesis. This chapter provides an introduction to the limitations of the current CPFSK system in terms of interference rejection and a proposed replacement modulation scheme. Background information on FTS, spread spectrum, and related work regarding FTS with spread spectrum is contained in Chapter 2. The proposed MSK-SS modulation scheme is detailed in Chapter 3, with simulations comparing MSK-SS to CPFSK in Chapter 4. Final conclusions and future work are presented in the final chapter.

CHAPTER TWO

BACKGROUND

This chapter is dedicated to providing the background information on the topics and technologies discussed within this thesis. Section 2.1 describes the usage and operation of a Flight Termination System. Section 2.2 provides the foundation and theory for direct-sequence spread spectrum systems. Section 2.3 demonstrates the effectiveness of direct-sequence spread spectrum resisting continuous wave interference as a proof of concept. Specifics about CPFSK and MSK are described in Section 2.4. Section 2.5 details the previous work involving spread spectrum with Flight Termination Systems.

2.1 Flight Termination Systems

Flight Termination Systems are embedded in test vehicles operated on Department of Defense test ranges that have the ability to exit the terrestrial boundary of the designated testing site. Test vehicles such as guided munitions, unmanned aerial vehicles (UAV), and remotely piloted target drones are equipped with FTS's to ensure that the flight of the test vehicle will be terminated if the safety of people or property is threatened. The operation of FTS's are standardized and governed by the Range Safety Group of the Range Commanders Council [9].

The basic components of an FTS are the antenna, Flight Termination Receiver (FTR), FTS battery, and an independent method of termination to render the test vehicle unable to continue flight. The antenna is used in conjunction with the FTR in order to receive a one-way command link from the ground station to decode commands such as arming and terminating the test vehicle. Upon a successful decoded terminate signal by the FTR, the flight of the test vehicle is terminated by means of a drag door deploying, parachute, or an explosive device. All of these components are doubled to operate parallel to each other to make up the FTS that is redundant with no single point failure. The FTS is also completely independent of the control systems of the test vehicle to ensure the system can operate reliably in the event the test vehicle loses power [9]. A simplified block diagram of an FTS is shown in Fig 2.1.

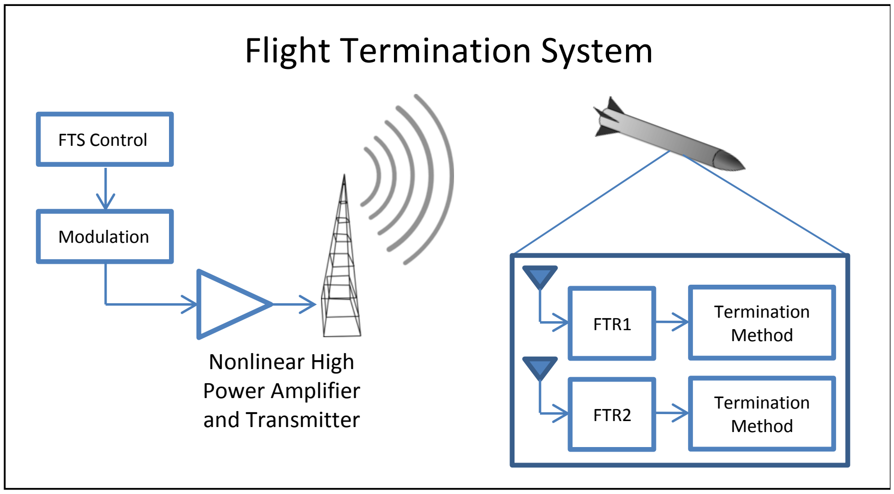

Figure 2.1: Block diagram of an FTS

Although the command link in an FTS is one-way, the status of the FTR and its monitor outputs are typically embedded in the telemetry stream of the test vehicle, so that the status of the FTS can be monitored at all times. The command link signal originates from the ground transmitters that usually output several kilowatts of power [4]. This allows the test vehicle to operate over extremely large distances usually on the order of hundreds of miles.

The current command link operates with a frequency modulated (FM) signal by modulating Inter Range Instrumentation Group (IRIG) tones that are transmitted in sequence in order to issue various commands to the FTS. This “legacy” FTS technique has been the standard for the past couple of decades and is currently in use at the majority of DOD test ranges.

A “next generation” FTS has been developed using robust digital modulation technology and has improved security features over the legacy FTS. This next generation FTS, referred to as Enhanced Flight Termination System (EFTS), uses Continuous Phase Frequency Shift Keying (CPFSK) modulation [4]. The decision to use CPFSK as the digital modulation scheme was driven mostly by its similarity to the legacy FTS FM system. Many of the design specifications were carried over from the legacy FTS, such as the bandwidth and frequency deviation. The frequency deviation for the EFTS modulation scheme is 60 KHz, which is equivalent to two tones being transmitted over the legacy FTS system at 30 KHz per tone [4]. The maximum bandwidth requirement of 360 KHz at -60 dB is copied directly from the legacy FTS standard [9]. However, during the previous evaluation of using spread spectrum, there was consideration in relaxing the bandwidth to 360 KHz at -20dB if needed [4].

2.2 Direct-Sequence Spread Spectrum Technology

The concept of spreading transmitted wireless energy over a larger bandwidth than what is minimally required to transmit the original signal is known as spread spectrum. This is performed with an extra layer of modulation at the transmitter [6]. Desirable qualities of a spread spectrum system include interference and fading suppression, message privacy, and multiple access capability [6].

There are three types of spread spectrum modulation techniques. Direct-sequence modulated systems use a digital code sequence that has a bit rate much higher than the information signal bandwidth. This digital code is used to modulate the carrier. Frequency-hopping modulated systems use a digital code sequence to shift the carrier frequency. The pattern in which the carrier frequency is shifted is determined by the code sequence. Pulsed-FM modulated systems, also known as “chirp” modulation, sweep the carrier frequency over a given pulse time interval to create a wideband signal [7]. The most applied method of spread spectrum digital communications is direct-sequence modulation because of its design simplicity over the other types [7].

2.2.1 Direct-Sequence Modulation

To create a direct-sequence spread spectrum modulated signal, a narrowband information signal is spread over a wide frequency band by modulating the information by a wideband encoding signal, also called a spreading code [7]. A common example of spread spectrum modulation is conventional frequency modulation, where a deviation ratio greater than one is used. The high modulation index results in the modulated signal having a much wider bandwidth than the original information being transmitted [7]. Other common names for direct-sequence modulated systems are “direct spread” and “pseudo-noise” systems [7].

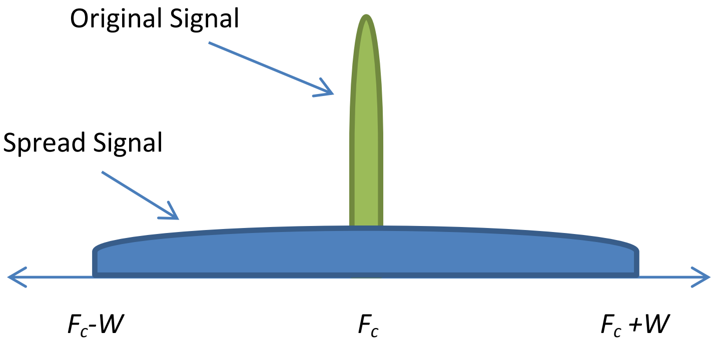

Figure 2.2: Bandwidth of a spread signal

Before carrier modulation, the spreading waveform is mixed with data, or an information waveform, to create the direct-sequence spread spectrum signal. This can be represented by the following expression: $s(t) = Ad(t)p(t)\cos(2\pi f_c t + \theta)$, where A is the signal amplitude, $d(t)$ is the data, and $p(t)$ is the spreading waveform [4]. The spreading waveform, which is a digital sequence, is NRZ encoded and mapped according to $0 \rightarrow -1$ and $1 \rightarrow 1$. Assuming that both the received waveform and the spreading waveform are synchronized in the receiver, the original waveform can be recovered by multiplying the signal against the spreading waveform again. The multiplication yields the following despread signal: $s_1(t) = p(t)s(t) = Ad(t)\cos(2\pi f_c t + \theta)$. The modulated data can then be extracted from the despread signal [6].

Since the narrowband information signal is being spread over the larger bandwidth of the spreading waveform, the transmitted signal can often have power levels below the noise floor. This has the unique ability of allowing the transmitted signal to be harder to detect and intercepted in a hostile environment. The transmitted signal can only then be despread if the correct spreading code is known. This process known as despreading reduces the bandwidth of the signal back to the original signal before spreading, and any interference energy gained by the wireless channel is spread over the bandwidth of the spreading waveform [6]. The interference rejection capability of the system can be approximated by the relationship W/B where W is the bandwidth of the spreading waveform and B is the bandwidth of the information waveform [6]. Direct-sequence systems provide a form of message privacy since the data cannot be decoded without the spreading sequence [6].

The bandwidth requirement of a spread spectrum signal can be calculated by the following formula derived from Shannon's channel capacity: $W = \frac{N}{S} * \frac{C}{1.44}$ [7]. From this equation the bandwidth of a spread spectrum signal, W, can be calculated given a noise-to-signal ratio, N/S, and an information rate, C. Spread spectrum modulation can then be used as a tool to increase the bandwidth of the signal to maintain a low information-error rate for any given noise-to-signal ratio [7].

2.2.2 Spread Spectrum with Multiple Users

Direct-sequence spread spectrum has a unique ability to mix many user signals that are operating on the same carrier frequency. Since each user can be assigned their own spreading code, this allows the signals to be combined together within the same frequency spectrum. During the despreading process, the other users' signals will be spread as noise across the bandwidth of the spreading code.

Code division multiple access is a wireless technology that uses direct-sequence spread spectrum to allow multiple users to share the same frequency spectrum. Using both orthogonal and non-orthogonal spreading codes increases the systems robustness against fading and interference [11]. A CDMA system allows many users to share the same spectrum given that each user has their own spreading code. For this reason it is important that the spreading codes used have a cross correlation that is nearly zero. A CDMA wireless network is only an effective multiple-access framework if the spreading codes are mutually orthogonal to minimize the interference between users [11]. Both Walsh and pseudo-noise codes are used in CDMA systems.

Another advantage of implementing a CDMA system in a multi-use environment is the frequency reuse. Other cellular network technologies such as time division multiple access (TDMA) and frequency division multiple access (FDMA) require that adjacent cells use different carrier frequencies to minimize interference. Because CDMA cellular systems use spread spectrum techniques, the system can be described as having a universal frequency reuse. All adjacent cells can operate on the same carrier frequency because interference rejection is part of the despreading processes [11]. Frequency planning is not required between cells and the capacity of the system can be maximized by allowing for a greater bandwidth.

2.2.3 Creating the Spreading Codes

Codes are used to protect against interference, reduce noise, and offer a form of privacy. These important properties of spread spectrum systems are attractive qualities of many communication systems [12]. There are several types of code sequences that can be used as spreading codes. Two types of spreading codes are implemented in spread spectrum systems, orthogonal and non-orthogonal. Walsh codes are a type of orthogonal codes; when two are multiplied together, they result in zero. Pseudo-noise codes, or PN codes, are a type of non-orthogonal codes that appear to be a random sequence, though they have properties that allow them to be used as effective spreading codes.

Two other qualities worth mentioning in choosing a spreading code are the autocorrelation and cross-correlation properties of the code. Autocorrelation is defined as the similarity a signal has with a time-shifted copy of itself [7]. When the autocorrelation of a particular spreading code nears a delta function, it is least likely that the receiver will incorrectly synchronize the signal in the acquisition process. Cross-correlation is defined as the measure of similarity between a signal and another signal [7]. A desirable output to the cross-correlation of various spreading codes is zero in spread spectrum application.

Walsh codes are used as an effective spreading code because each of the rows produced from the Hadamard matrix are mutually orthogonal to each other [7]. This is an important quality for spreading codes because the cross-correlation will also be zero. However, this is only true in a synchronous spread spectrum system. These codes are not desirable for an asynchronous system, where numerous coded messages may not arrive at the receiver in sync. The first CDMA digital system known as cdmaOne, or IS-95, used Walsh codes of length 64 in the system [11]. Walsh codes are always of length 2^n and are generated recursively by the Hadamard matrix. The Hadamard matrix follows the following format:

$$H_{2^n} = \begin{bmatrix} H_{2^{n-1}} & H_{2^{n-1}} \\ H_{2^{n-1}} & \overline{H_{2^{n-1}}} \end{bmatrix}$$

The other commonly used type of spreading codes in spread spectrum systems are pseudo-noise codes. Though these codes appear to be a random sequence, they are deterministically generated sequences and their properties are desirable for spread spectrum systems [3]. A common type of PN code used is the Gold code. Gold code sequences are desired for communication systems since they can produce a large number of codes that have well-defined correlation characteristics.

Gold code sequences are generated by performing the modulo-2 addition of the outputs of two maximum length shift registers [12]. This shift register is a linear feedback shift register which produces code sequences called m-sequences. Maximal linear code sequences, or m-sequences, generated from the maximum length shift register are often used for general communications because they offer equal or better performance than other codes [12]. The maximal sequence code is thus named for the longest code sequence that can be generated for a shift register of a given length. The length of the code can be found by the following formula: $2^n - 1$ chips where n is the length of the shift register [12]. The feedback connections, or taps, required for maximal codes have been documented in Dixon [7] [12]. Changing the initial mask of the shift register will produce the same periodic code sequence, but it will be time-shifted [11].

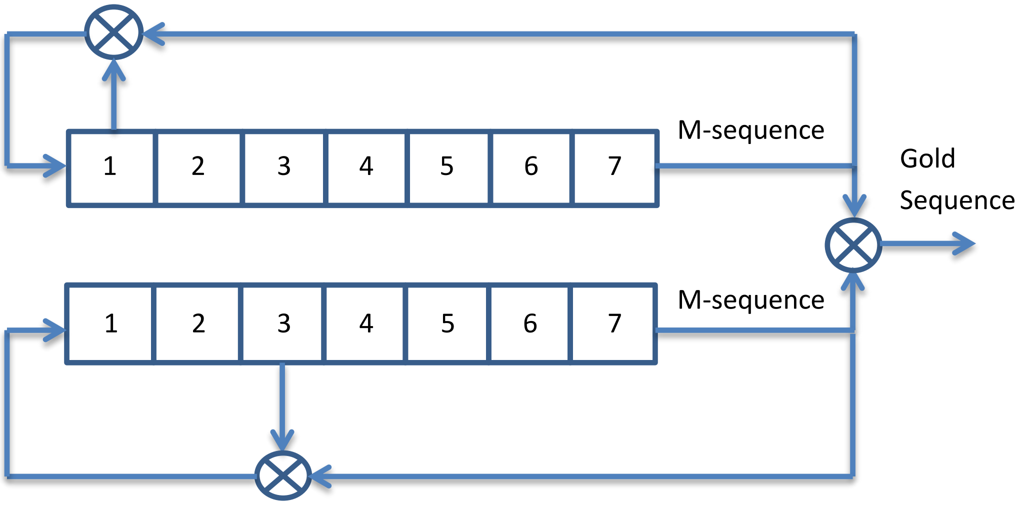

Figure 2.3: Gold code sequence generator

Figure 2.3 depicts a Gold code sequence generator. The feedback taps on the shift registers are one and seven for the upper shift register and three and seven for the lower shift register. The outputs of these shift registers are modulo-2 summed together to generate the Gold code sequence. Additional Gold codes can be created by varying the initial register contents of one of the m-sequence generators. Using any combination of two shift registers with n stages will produce $2^n - 1$ possible gold code sequences of the same length.

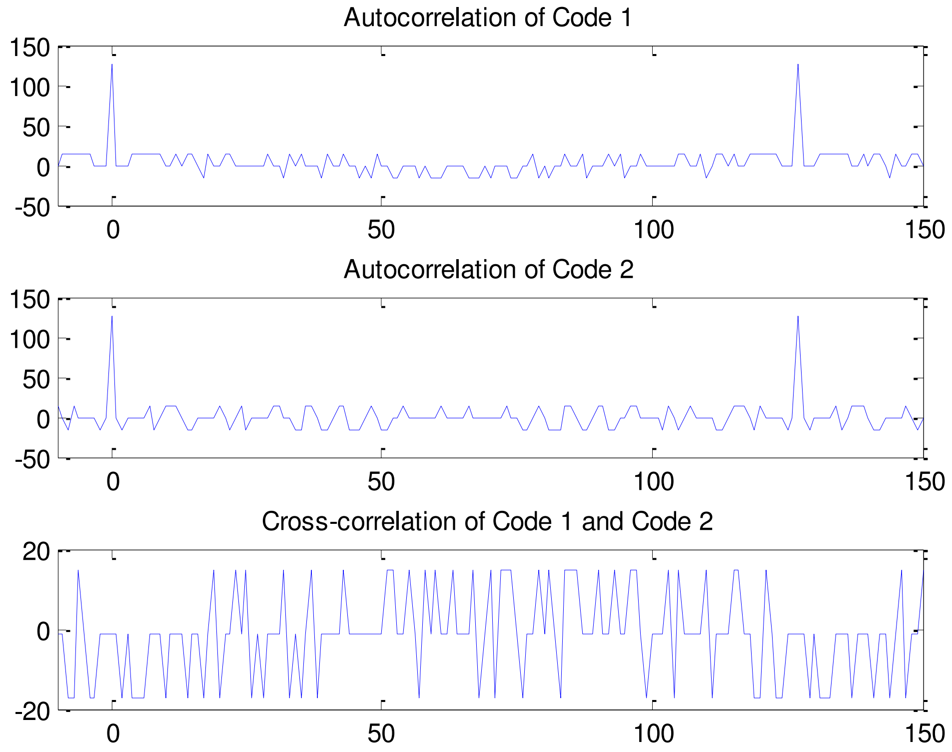

Figure 2.4: Autocorrelation and cross-correlation plots of two 127 chip long Gold codes

As seen in Fig 2.4, the circular autocorrelation and cross-correlation plots of Gold codes make them very desirable to use as spreading codes. The autocorrelation functions have distinct peaks at a zero time shift and at each multiple of the code length. The magnitude of the peak corresponds to length of the code, since there are no mismatches. This distinguishable peak is important to the synchronization of the local spreading code in the receiver. The low cross-correlation allows it to be distinguishable in a multi-user environment.

The significant use of maximal code sequences in spread spectrum systems is evidence that their properties are desirable for use as a spreading code. The statistical distributions of ones and zeros are always the same throughout the length of the code; if a code is modulo-2 added with the phase shift of itself, it will result in another phase-shifted replica of itself, and the number of ones in a code will always be one more than the number of zeros in a maximal code sequence [12].

2.2.4 Processing Gain

One of the most important characteristics of a direct-sequence spread spectrum system is the processing gain, G. The processing gain is a function of the bandwidth of the transmitted spread spectrum signal and the information rate of the original signal with the formula: $G = \frac{BW_{RF}}{R_{info}}$ [7]. Alternatively, the processing gain can also be expressed as the number of chips per bit of information with the following equation: $G = \frac{T_s}{T_c} = \frac{W}{B}$, where T_s is the baseband signal bit time, T_c is the chip time, W is the bandwidth of the spreading code, and B is the bandwidth of the baseband signal [6]. The processing gain is a significant metric for DS/SS systems because it provides a measurement to the interference rejection capability of the system [6]. However, the tradeoff of having a large processing gain for interference rejection means that the bandwidth of the transmitted signal will be very large.

2.2.5 Code Synchronization

The benefits of implementing a spread spectrum system can only be realized if the receiver accurately detects and synchronizes its local spreading code to the received waveform. In most spread spectrum applications, this can be accomplished by transmitting a known prefix before the message. The code synchronization is typically done in two stages – acquisition and tracking [13]. This process is aided by the peaks in the autocorrelation function of the spreading code. The code acquisition can typically synchronize the code to within a fraction of a chip by comparing the autocorrelation value to a set threshold [13]. Lowering the threshold may increase the amount of false alarms, while raising the threshold may lower the probability of detection. Code synchronization is further refined by a tracking loop that continuously maintains the correct code synchronization [1].

Incorrect code synchronization reduces the energy per chip, E_c, which also affects the energy per bit, E_b. Initially, the local spreading code, $p_l(t)$ has an offset of $NT_c$from the spreading code in the received signal, $p(t)$, where N can take the value from zero to the length of the spreading code. The local spreading code, $p(t + NT_c)$, is multiplied to the received signal, $p(t)$, before being integrated over the spreading code period, T_{sc}. This results in an autocorrelation, $\mathcal{R}(NT_c) = \int_0^{T_{sc}} p(t)p(t + NT_c)dt$, a function that is used to minimize the offset in the local copy of the spreading code. In the figure below, the autocorrelation function is shown as the offset between the received spreading code and the local spreading code is varied between -10 and 10 chips. An optimum threshold that minimizes the probability of false alarms and maximizes the probability of detection is a value equidistant between the two highest peaks of the autocorrelation function. From the figure below, it can be seen that this threshold intersects the autocorrelation function at $\pm\frac{T_c}{2}$. As long as the initial acquisition can detect the offset within one-half of a chip, significant BER degradation can be avoided from incorrect synchronization.

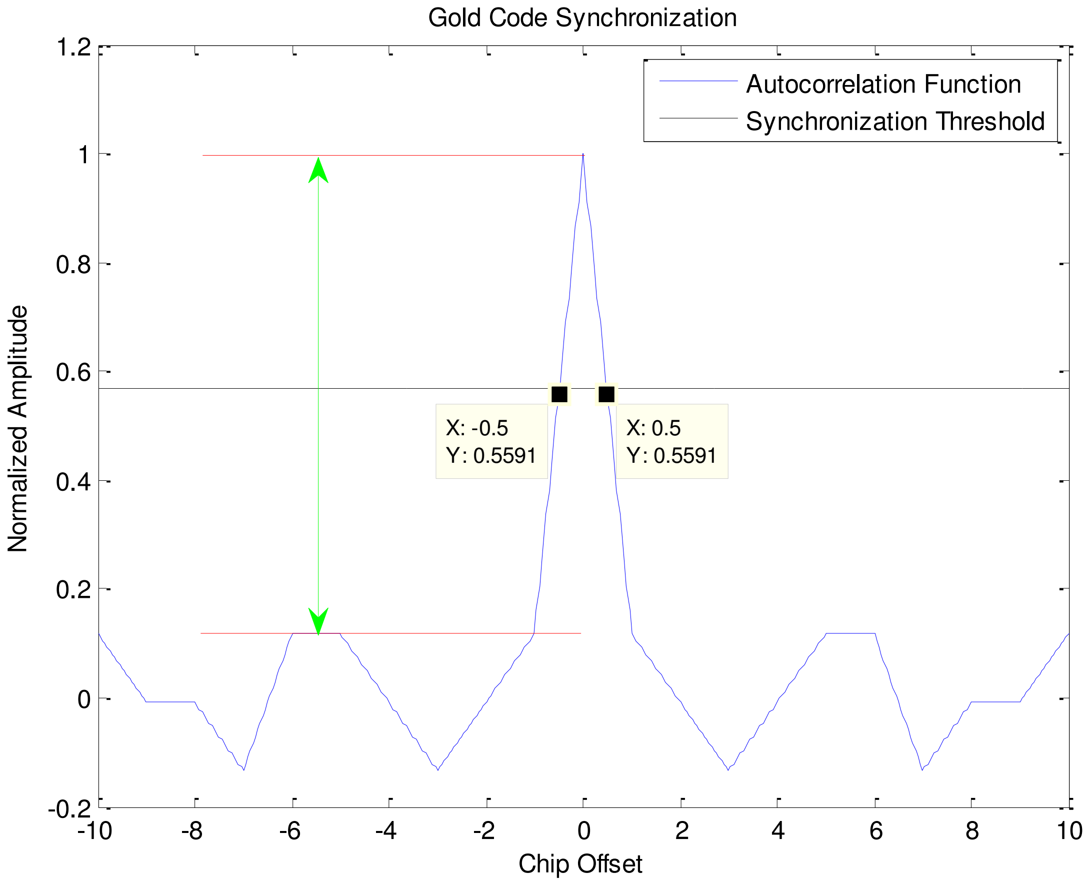

Figure 2.5: Gold Code synchronization with threshold

2.3 A Demonstration of a DS/SS System's Ability to Resist Interference

In this section, it is seen how direct-sequence spread spectrum can be used to reject continuous wave interference at the carrier frequency of a binary phase shift keying (BPSK) modulated signal. This demonstration provided a proof of concept before continuing with the development of the thesis.

2.3.1 Introduction

The application of direct-sequence spread spectrum (DS/SS) in wireless communication systems has been driven by the susceptibility of noise and interference on a wireless channel.

The interference rejection capabilities of a DS/SS system are inherited by the fundamental design of the modulation scheme. A spreading sequence is used to spread the transmitted signal's energy over the bandwidth of the spreading waveform. Upon recovering the signal at the receiver, any interference is spread while the desired signal is despread. This demonstration is intended to provide experimental results on the interference rejection capabilities of DS/SS.

2.3.2 Simulation Details

For this demonstration, a BPSK signal with DS/SS will be compared to a BPSK signal without DS/SS. These signals will be subjected to the same simulated wireless channels. LabView software by National Instruments will be used to model the transmitter, wireless channel, and the receiver. The performance metric used to analyze the results will be the bit error rate (BER). The BER will be computed by calculating the error between the received bit stream and the known transmitted bit stream. In order to study the effectiveness of the DS/SS system exclusively, it will be assumed that the receiver has synchronized the spreading code to the received signal. The following figures depict how the transmitter and receiver will be implemented in LabView.

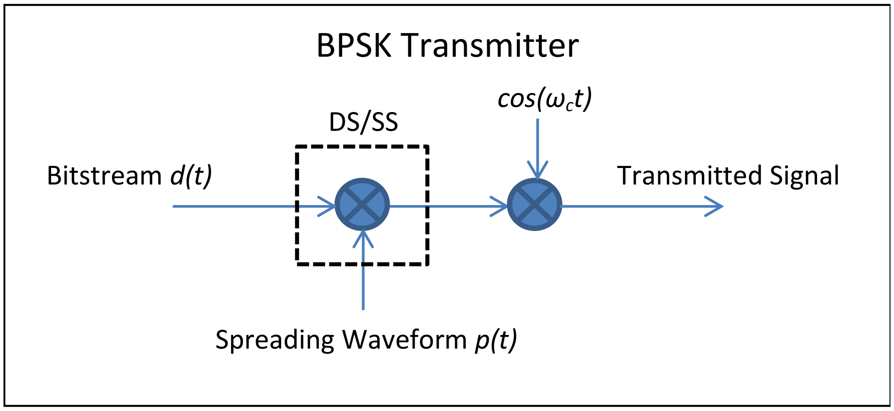

Figure 2.6: BPSK transmitter block diagram

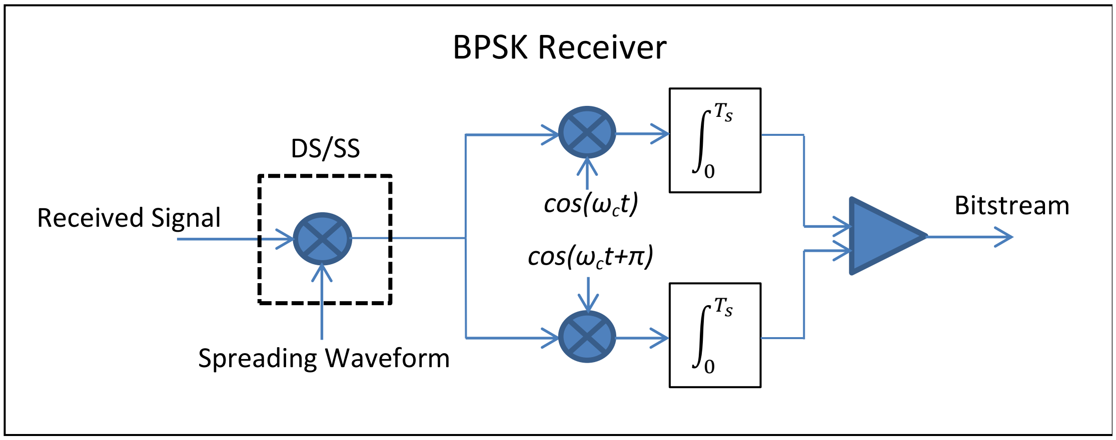

Figure 2.7: BPSK receiver block diagram

2.3.3 AWGN Simulation

The first simulation provided a baseline to validate the modeled systems in LabView in a wireless channel with additive white Gaussian noise (AWGN). The BER was measured by varying the bit energy-to-noise power spectral density ratio (E_b/N_0) over -3 dB to 8 dB for a BPSK signal with and without DS/SS. These results were then compared to the theoretical BER for a BPSK system. The theoretical BER of a BPSK signal in an AWGN channel can be calculated from the following formula: $P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right)$. Other parameters of the simulation were the following: bit rate of 200 bps, carrier frequency of 15 KHz, sampling frequency of 40 KHz, chip rate of 5 kcps, and a simulation time of 500 s.

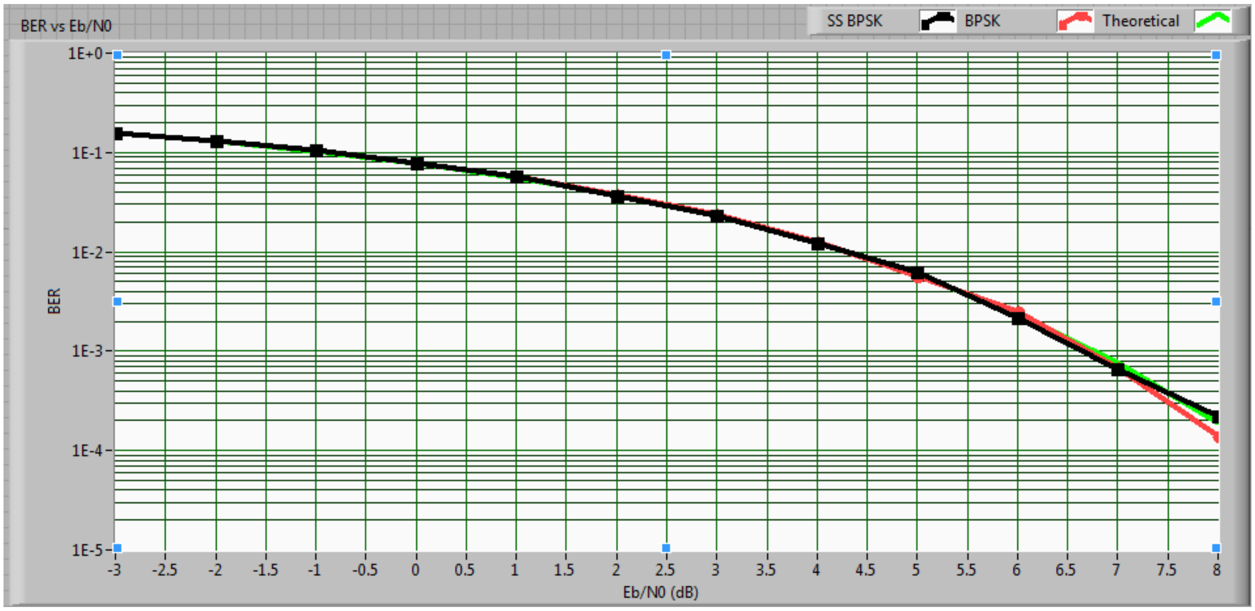

Figure 2.8: AWGN simulation results

From the results shown in Fig 2.8, it can be seen that the BER of the BPSK system with and without DS/SS are perfectly aligned with the theoretical calculations. These results are as expected since a DS/SS system provides no benefit in a wireless channel with only AWGN. Since AWGN is present at all frequencies, spreading the noise is ineffective in the DS/SS system. The slight divergence of the results at the higher Eb/N0 range is attributed to the sample size. Due to the limited computing resources, the simulation was limited to 500 seconds because of the vast amount of processing time needed to perform the simulation. Although these results were as expected, this simulation was useful to validate the LabView model.

2.3.4 AWGN with CWI Simulation

For this simulation, the BER was measured in an AWGN channel with continuous wave interference (CWI) at the carrier frequency for a BPSK system with and without DS/SS. This processing gain (G) was further varied in this simulation to demonstrate the relationship of the processing gain to the interference rejection capability. The processing gain was set to 5 and 25 by running the simulation with a chip rate of 1kcps and 5 kcps, respectively. The E_b/N_0 ratio was held at 8 dB which yielded a signal-to-noise ratio (SNR) of 5 dB. This is calculated from the following equation: $\frac{E_b}{N_0} * \left(\frac{R_b}{W}\right) = \frac{S}{N}$. In this simulation, the signal to noise plus interference (SNIR) metric was varied over -4 dB to 5 dB. The following equation shows the relationship between the SNR and the SNIR: $\frac{S}{N} = \frac{S}{N+I},\ when\ I = 0$. Other parameters of the simulation were the following: bit rate of 200 bps, carrier frequency of 15 KHz, sampling frequency of 40 KHz, and a simulation time of 500 s.

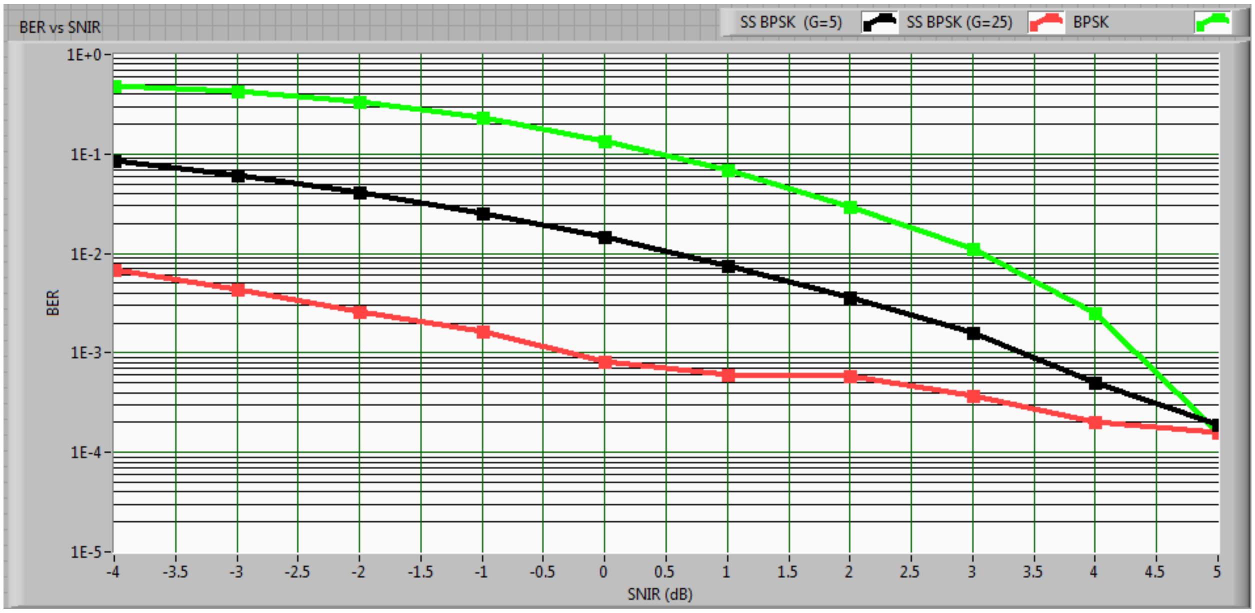

Figure 2.9: AWGN with CWI simulation results

When CWI is added to the wireless channel, it can be seen from Fig 2.9 the BER is improved by an order of magnitude when the processing gain is 5 and further by another order of magnitude when the processing gain is 25. From this simulation, DS/SS clearly improves BER when by spreading the energy of the CWI while recovering the original signal. Similarly to the previous simulation, the precision of the data points are slightly skewed by the limited sample size.

2.3.5 Conclusions

The simulations performed demonstrate the use of DS/SS as an effective technique to combat interference. Although DS/SS provided no benefit in a wireless channel affected purely with AWGN, the validation provided from the first simulation increased the confidence in the results obtained from the second simulation with the added CWI. Performing the simulation with CWI lead to the conclusion that implementing a DS/SS system can resist interference; increasing the processing gain can further improve the interference resistance at the expense of increasing bandwidth.

2.4 Continuous Phase Modulation Techniques

Modulation techniques that do not have any discontinuities in phase over time are characterized as having a continuous phase. Minimum Shift Keying (MSK) modulation is type of Continuous Phase Modulation (CPM) that is also spectrally efficient and a constant envelope signal [14] [15]. Because of these qualities, MSK is employed in many communication systems that have constraints on the type of modulation technique because of the use of nonlinear channels such as traveling wave tube high power amplifiers [14]. Due to the gradual phase transitions of MSK, the side lobes decay faster than other common modulation types and it yields a higher spectral efficiency than Quadrature Phase Shift keying (QPSK) and Offset Quadrature Phase Shift Keying (OQPSK) [1]. The side lobe decay can be seen in Fig 2.10 as compared to a QPSK and BPSK signal.

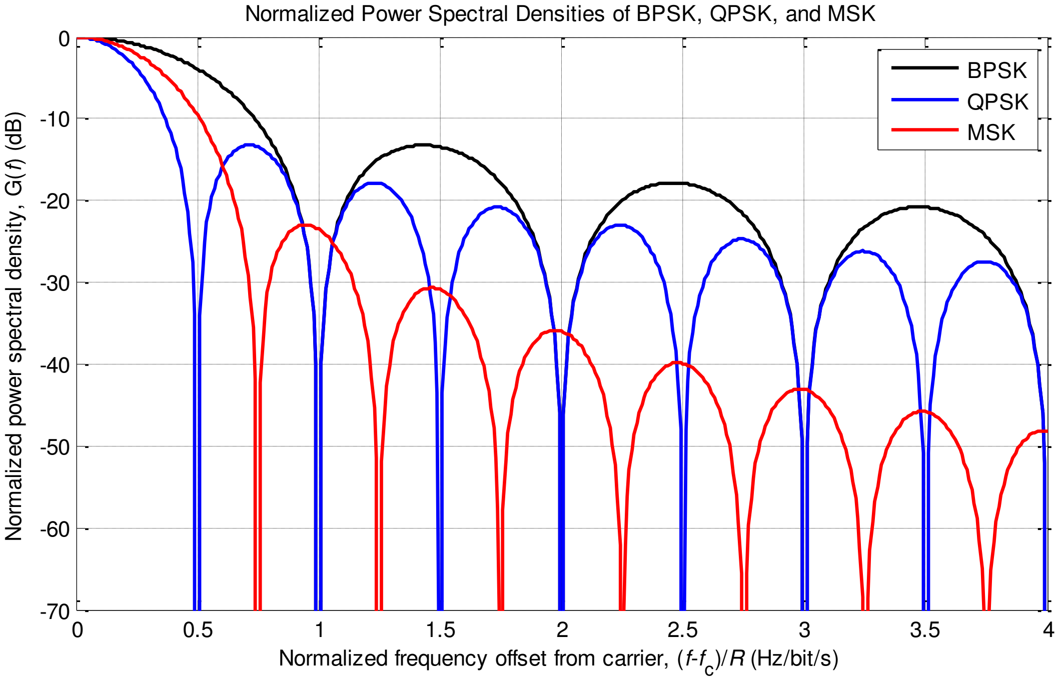

Figure 2.10: Normalized PSD of BPSK, QPSK, and MSK

MSK modulation can be described as a special case of either OQPSK or Continuous Phase Frequency Shift Keying (CPFSK) [1]. A CPFSK waveform can be expressed as $s_{CPFSK}(t) = \cos[2\pi f_c t + d_k 2\pi f_d t + \theta_k]$, where $\theta_k = \left[\theta_{k-1} + \frac{k\pi}{2}(d_{k-1} - d_k)\right] mod\ 2\pi$, d_k is the kth NRZ encoded data bit, f_d is the peak frequency deviation, and f_c is the carrier frequency [1]. Since the modulation index can be defined as $h = 2f_d T_b$ or $h = \frac{1}{2}$ for MSK, substituting this in the CPFSK waveform expression yields the MSK waveform expression: $s_{MSK}(t) = \cos\left[2\pi f_c t + \frac{d_k \pi t}{2T_b} + \theta_k\right]$ [15].

MSK can also be expressed as OQPSK when the baseband data has sinusoidal weighting. The half sine wave is offset one data bit period between the in-phase and quadrature components. Using the trigonometric identities $\sin(x \pm y) = \sin(x)\cos(y) \pm cos(x)\sin(y)$ and $\cos(x \pm y) = \cos(x)\cos(y) \mp \sin(x)\sin(y)$, the MSK waveform can be expanded to the form:

$s_{MSK}(t) = A\left[\alpha_n cos\left(\frac{\pi t}{2T_b}\right)\cos(2\pi f_c t) + \beta_n \sin\left(\frac{\pi t}{2T_b}\right)\sin(2\pi f_c t)\right]$, where α_n and β_n are the $2k$ and $2k + 1$ bits of the NRZ encoded data stream with a period of $2T_b$ [16].

The figures below show block diagrams of how the MSK transmitter and receiver can be built in MATLAB.

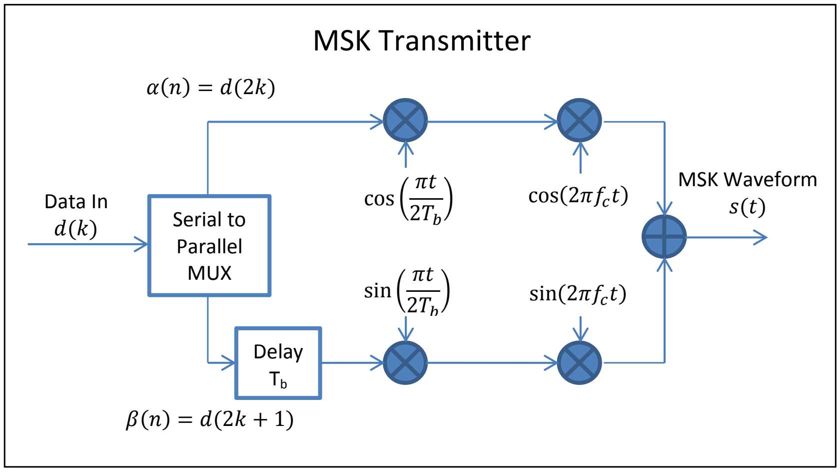

Figure 2.11: MSK transmitter block diagram

The figure above shows how the MSK transmitter can be modeled as an OQPSK quadrature system with baseband pulse shaping of cos $\left(\frac{\pi t}{2T_b}\right)$ and sin $\left(\frac{\pi t}{2T_b}\right)$. After modulating the basis functions, the two quadrature legs are summed together to create a continuous phase waveform [17].

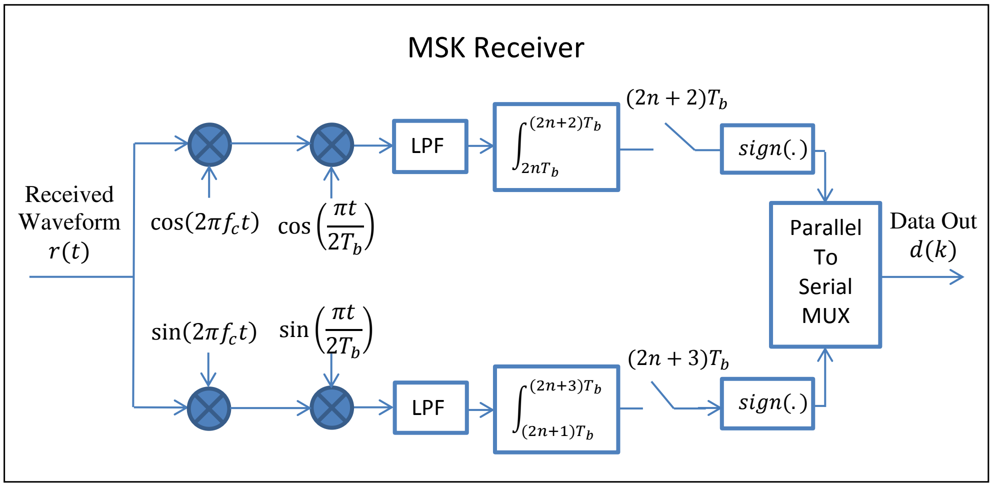

Figure 2.12: MSK receiver block diagram

The figure above shows a coherent MSK receiver modeled as an OQPSK system [17] [18]. The rate of n is equal to $2k$ since the bit period of each quadrature leg has a duration of $2T_b$. The detected symbols are parallel to serial multiplexed at a rate of $1/T_b$ in order to recover the transmitted data sequence.

2.5 Related Work

In 2001, the use of spread spectrum to meet the EFTS objectives was independently investigated by CMC Electronics Cincinnati and Interstate Electronics [4].The two studies were tasked with three areas of focus. The first area of focus was to meet the 360 KHz at -60 dB bandwidth requirement, and then further relaxed bandwidth requirements of 360 KHz at -20 dB and 1 MHz at -20 dB. The second area of focus was the ability of the proposed system to operate in the dynamics and environment that an employed FTS would be subjected to; in particular, the phase noise induced on the system. The last area of focus would be to comment on the proposed solution's ability to resist interference when given different interference threats. Although the results of the vendors' studies are published, the full, detailed reports are deemed proprietary and are not available to the public.

Both CMC and IEC chose a variant of Code Division Multiple Access (CDMA) over a frequency hopping implementation of spread spectrum in order to ensure the bandwidth is kept at a minimum. A direct-sequence spread spectrum system is executed by using a spreading code in order to spread the energy of the transmitted signal over a larger bandwidth than required.

The proposed design by CMC resembles an industry standard approach to CDMA. This solution depends on the cross-correlation properties of the PN spreading codes to provide isolation between PN codes and allow for continuous transmissions of more than one transmitter for redundancy. Using a Binary Phase Shift Keying modulated signal with a 500 Kcps spreading code rate, CMC was able to meet the EFTS design requirements with a 2.6 MHz bandwidth. The acquisition time of the system also varied between 305 ms and 920 ms.

The approach proposed by IEC differs from the CMC proposal in that it uses spreading codes with a desirable auto-correlation property instead of depending on the cross-correlation of PN spreading codes. This change improved the near/far resistance and decreased the bandwidth of the proposed design. This method also requires the transmissions to occur sequentially; also, no two transmitters can operate at the same time. The decrease in bandwidth means that the design was able to meet the 360 KHz at -60 dB bandwidth requirement, but this was at the expense of a lengthened worst case acquisition time of 1.28 seconds.

Although both of these studies reported an undesirable solution for EFTS at the time, it provided ground work for future research in implementing a spread spectrum technology in a next generation FTS. The decision to use a non-constant envelope modulated signal, such as BPSK, also required changes to the current ground transmitter infrastructure. Future research should consider design alternatives, such as using a constant envelope transmitted signal in order to alleviate these issues.

CHAPTER THREE

IMPROVING A FLIGHT TERMINATION SYSTEM'S INTERFERENCE RESISTANCE

A proposed alternative wireless communication technique for the FTS command link must have constant envelope or near constant envelope to maintain compatibility with the current ground transmitter infrastructure and improve on the current interference rejection offered by FM and CPFSK. Minimum Shift Keying (MSK) is a special case of CPFSK modulation that has a modulation index equal to one half [5]. Because of its small modulation index, it is highly spectrally efficient and its side lobes decay rapidly [14]. It also has characteristics inherited from CPFSK in that it is a constant envelope signal with continuous phase and can be non-coherently detected to reduce the effect of phase noise induced in the system because of the unique FTS RF environment. The details on MSK modulation can be found in Section 2.4.

Direct-sequence spread spectrum (DS/SS) methods offer superior narrow-band interference rejection by spreading the energy of the transmitted signal across a wider bandwidth [2]. The details on DS/SS can be found in Section 2.2, and a demonstration of a DS/SS system's ability to resist interference is detailed in Section 2.3. Since the spreading of the energy is performed with a pseudo-random spreading code, several test vehicles can be addressed by assigning different pseudo-random spreading codes to each test vehicle. Pairing DS/SS with a constant envelope or near-constant envelope modulation technique such as MSK can maximize compatibility requirements with the current transmitter infrastructure.

3.1 MSK-SS Design

The proposed alternative modulation scheme to CPFSK is the Minimum Shift Keying-Spread Spectrum (MSK-SS) system. Two important parameters of a DS/SS system are the spreading code length and the chip rate. Increasing the chip rate in turn increases the bandwidth of the system and the processing gain, while decreasing the time needed for synchronization. Increasing the length of the spreading code provides higher peaks in the autocorrelation function of the code, but increases synchronization time.

Short Gold codes with a length of 127 chips are chosen to be used as the spreading code. The use of Gold codes ensures that an adequate number of spreading codes are available for use and the cross-correlation properties of the codes allow for asynchronous multiple access capability. This will minimize co-channel interference in the event an intentional or unintentional FTS command transmission intended for another test vehicle has reduced effects on the desired transmission.

Choosing a low chip rate for the spreading code is also essential in reducing the overall bandwidth of the MSK-SS system. A chip rate of 144 Kcps and a data rate of 2.88 Kbps yield a processing gain of 17 dB [4]. This chip rate is still low enough to keep the bandwidth to a minimum and still high enough to offer significant interference rejection capabilities.

The MSK-SS signal can be represented by the following equation: $s_{MSKSS}(t) = A\left[\alpha(t)p(t)cos\left(\frac{\pi t}{2T_c}\right)\cos(2\pi f_c t) + \beta(t+T_c)p(t+T_c)\sin\left(\frac{\pi t}{2T_c}\right)\sin(2\pi f_c t)\right]$, where α and β are the two serial to parallel multiplexed data signals from the message $d(t)$, $p(t)$ is the spreading waveform, T_c is the chip time, f_c is the carrier frequency, and A is the signal amplitude. Each quadrature leg is modulated with the spreading waveform at a rate of $\frac{1}{2T_c}$. Once the two components are summed together, the MSK-SS waveform has an effective chip rate of $1/T_c$ because of the offset between the two quadrature components.

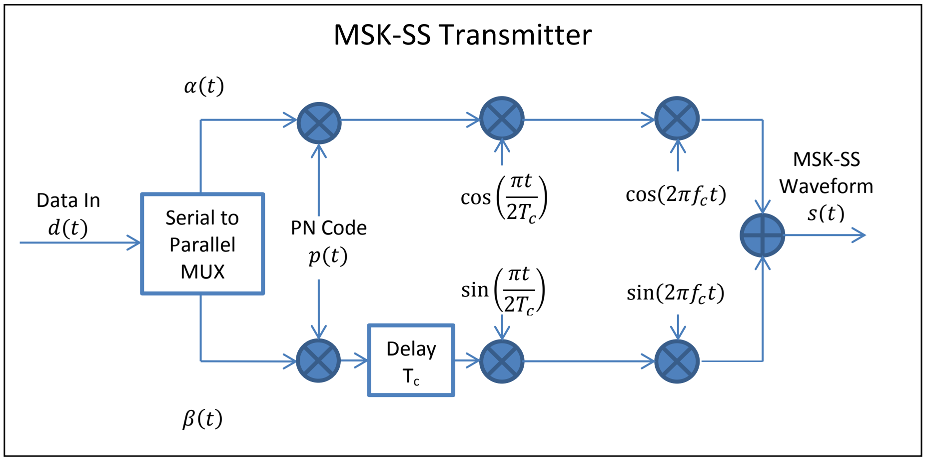

Figure 3.1: MSK-SS transmitter block diagram

The MSK-SS transmitter block diagram shown in Fig 3.1 resembles a QPSK transmitter with the addition of baseband pulse shaping and a delay to offset the quadrature components. Because of this representation, each quadrature leg is chipped at half the chip rate for a period of $2T_c$, and the offset delay is equal to T_c.

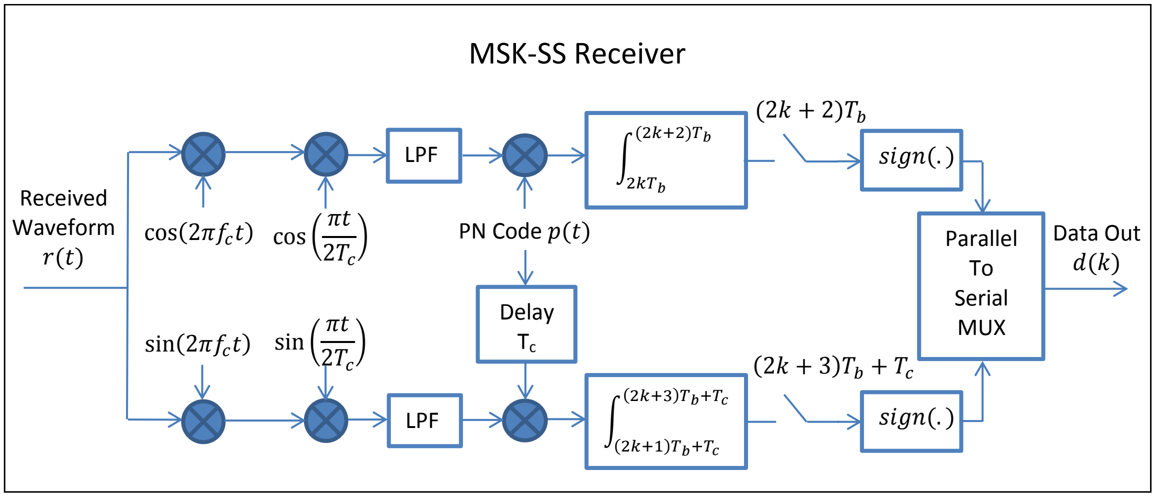

Figure 3.2: MSK-SS receiver block diagram

In the MSK-SS receiver shown in Fig 3.2, the despreading is performed after the down conversion from the carrier frequency and the baseband pulses. A 2nd order Butterworth low pass filter with the cutoff frequency set to the carrier frequency, removes the image frequencies as a result from the down conversion. The correlators integrate their input over $2T_b$ before being sampled and hard decision detected. A parallel to serial multiplexor creates the recovered bit stream.

3.2 MSK-SS Acquisition Time

With the implementation of DS/SS, the acquisition time of the FTS is increased in order to synchronize the local spreading code to the received signal. Each quadrature leg can be synchronized in parallel with the transmission of a preamble before every message that is known at the receiver. Assuming a high $\frac{E_b}{N_0}$ ratio, synchronization takes a maximum time of one spreading code period. The preamble needs to transmit a minimum of $\frac{2LT_c}{T_b}$ bits, where L is the length of the spreading code, T_b is the bit time, and T_c is the chip time.

For the proposed MSK-SS system, a minimum of six bits are needed in the preamble. This yields a maximum synchronization time of less than 2.1 ms. The preamble size can be increased in the event of severe noise to ensure the correlation peak is detected; however, this increases the maximum synchronization time by 347 μs for every additional bit in the preamble.

3.3 MSK-SS Bandwidth

Due to the definition of a DS/SS system, the bandwidth is greatly increased. Designing a DS/SS with a large processing gain increases the bandwidth by an equivalent factor. The chip rate for the proposed system is chosen to maintain a tradeoff between the interference rejection and the resulting bandwidth of the MSK-SS system.

The 99% power bandwidth of a MSK modulation scheme can be approximated by $B_{99\%} \approx 1.2R_b$ [17]. Substituting in the chiprate, the bandwidth is $1.2 * 144\ Kcps = 172.8\ KHz$.

This can be verified from the normalized singled sided power spectral density of the MSK-SS system in Fig 3.3. The 99% power bandwidth, or -20 dB, is measured to be $86.12\ KHz * 2 = 172.24\ KHz$.

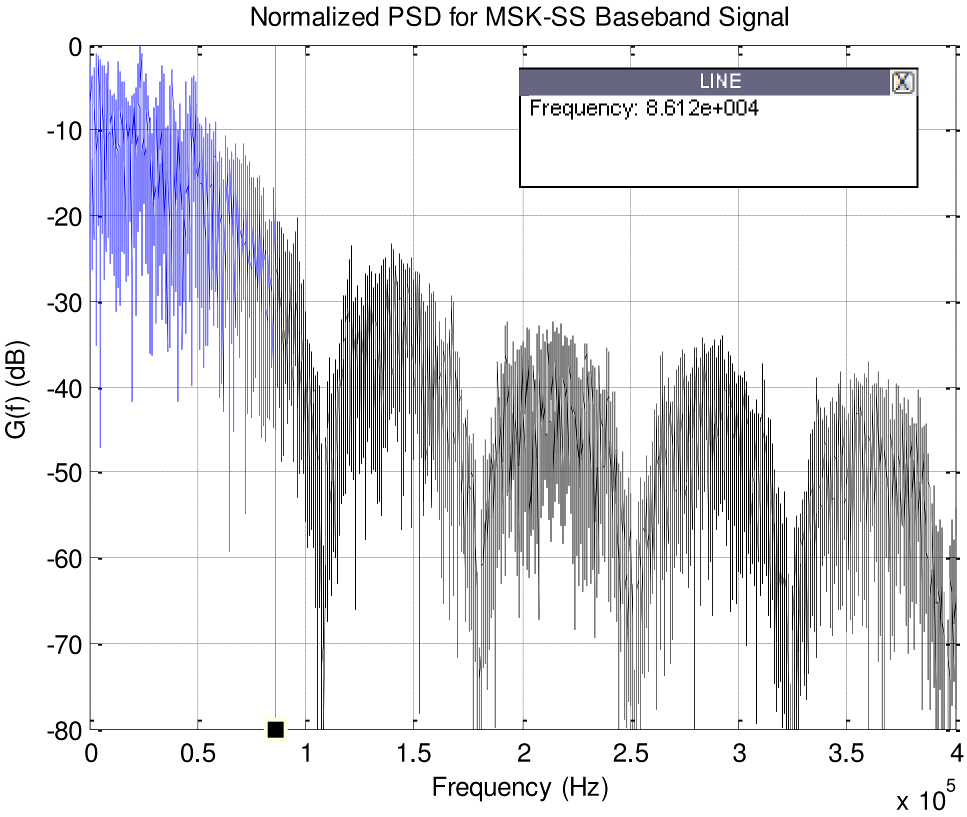

Figure 3.3: MSK-SS baseband normalized power spectral density

CHAPTER FOUR

SIMULATIONS

In order to test this thesis, the proposed MSK-SS system is modeled and simulated using MATLAB software. The performance of the system when subjected to various forms of interference such as continuous wave, co-channel, and multipath is used to validate this thesis against the performance of the CPFSK system when subjected to the same conditions.

Each modulation scheme being simulated will modulate a 64-bit long frame. This is the frame length as documented in the current EFTS standard [4]. This frame of randomly generated bits is subjected to a wireless channel before being demodulated and detected. The simulation is iterated to obtain a large sample size to ensure accurate error rates. The primary performance metrics for assessing the performance are the bit error rate (BER) and the frame error rate (FER). The BER is calculated by comparing the detected bits to the transmitted bits. Typical wireless communication systems implement a form of error correction to correct at least one bit error in a frame. These simulations are performed assuming no error correction. If at least one bit in a frame is erroneously detected, then the entire frame is counted as an error. Carrier phase and the spreading code is also assumed to be synchronized with the receiver.

For the CPFSK system, the data rate is 2.88 Kbps and the frequency deviation is ± 60 KHz. These parameters are taken from EFTS specification [4]. The MSK-SS system is also simulated at a data rate of 2.88 Kbps and a chip rate of 144 Kcps.

4.1 AWGN Channel

The first simulation performed is the performance of CPFSK and MSK-SS in an additive white Gaussian noise (AWGN) wireless channel. This simulation does not account for any kind of interference, but instead the noise accumulated in the signal due to natural sources [1]. The white Gaussian noise is added to the transmitted signal to calculate the error rates at 5 to 15 dB E_b/N_0 in 1 dB steps.

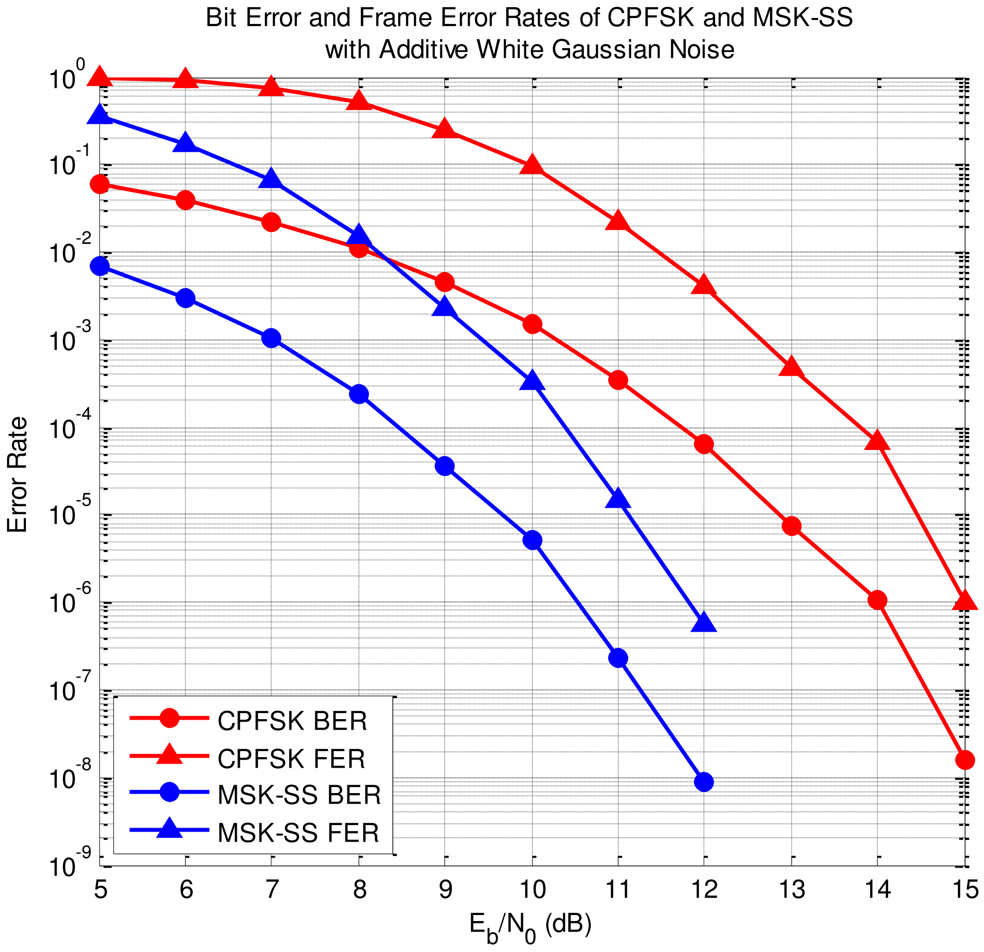

Figure 4.1: Error rates of CPFSK and MSK-SS with AWGN

As seen in Fig 4.1, the error rates are improved with MSK-SS over CPFSK in an AWGN channel. However, this is not due to applying spread spectrum, but to the inherent characteristic of MSK. Since MSK can be implemented as an Offset-Quadrature Phase Shift Keying modulation scheme with sinusoidal weighting, the demodulation can be performed by integrating over twice the bit period yielding error rates with a 3 dB improvement over an optimal FSK demodulated system. The MSK-SS system has bit error rates less than 10^{-6} at 11 dB E_b/N_0

while the CPFSK requires an E_b/N_0 greater than 14 dB. After 12 dB E_b/N_0 of the MSK-SS simulation, the error rates are zero because of the limited sample size.

4.2 Narrowband Interference

This simulation shows how random interferers can affect a CPFSK, while the MSK-SS spreads the interfering energy over the bandwidth of the spreading code. To simulate narrowband interference on a wireless channel, a continuous wave interferer is summed to the desired signal. During each iteration of the simulation, the carrier frequency of the interferer is defined by a random value uniformly distributed over the bandwidth of the transmitted signal. The phase of the interferer is also chosen by a uniform random value from 0 to 2π. The interferer's signal power is varied while holding the desired signal's power constant. The degree of freedom is the signal-to-interference power ratio (SIR), and it is varied from -30 to 30 dB in 2 dB steps. Noise is also added to the wireless channel at an 11 dB E_b/N_0 ratio for CPFSK and MSK-SS.

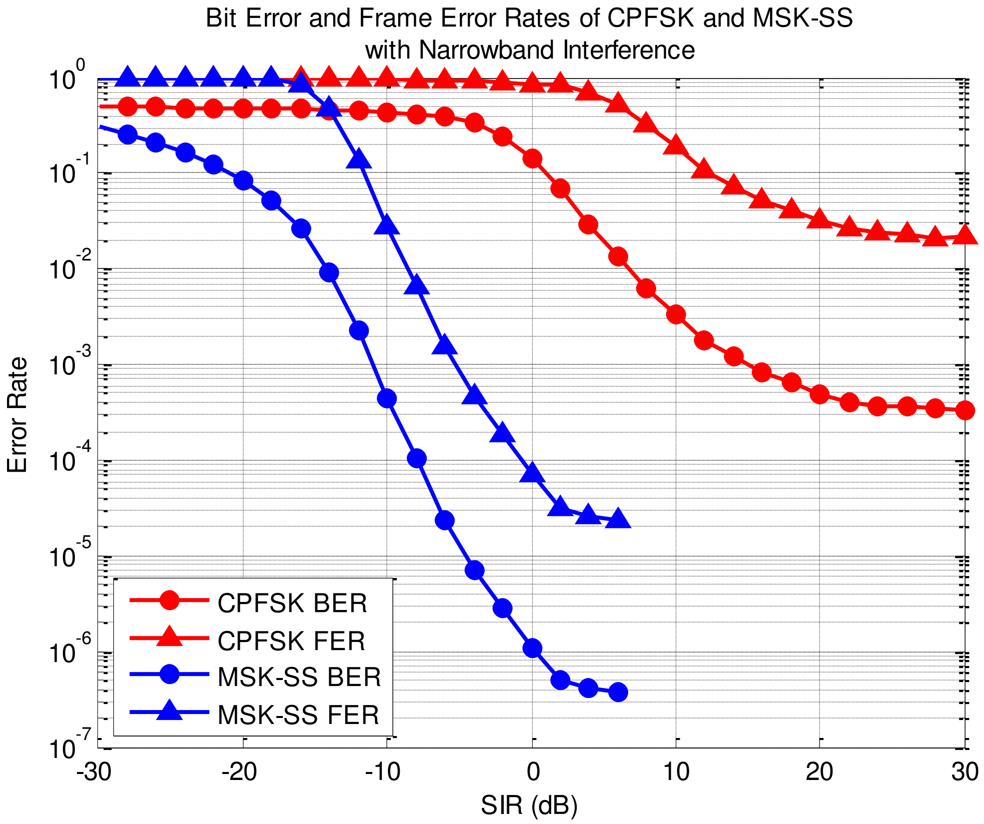

Figure 4.2: Error rates of CPFSK and MSK-SS with narrowband interference

In this simulation, it can be seen how effective the MSK-SS system is against narrowband interference. The error rates for the CPFSK system do not show significant change until the SIR is greater than 0 dB. This shows how an interfering source with a signal power greater than the desired signal can greatly affect the signal reliability of the CPFSK system, while the MSK-SS system is able to resist interference and offer improved error rates at the same E_b/N_0 ratio. The MSK-SS system begins to saturate at 4 dB SIR with a BER less than 10^{-6}, while the CPFSK doesn't begin to saturate until 22 dB SIR with a BER less than 10^{-3}. This difference of 18 dB can be explained by the processing gain of DS/SS in the MSK-SS modulation scheme.

4.3 Co-channel Interference

Co-channel interference is typically caused by more than one transmitter operating on the same frequency. In this case of an FTS, the co-channel interferer is assumed to be a second test range operating an independent FTS. A single test range can control several test vehicles operating at once by time-multiplexing the transmissions, but this does not guarantee that another test range will not interfere with the desired command link. Although these conflicts can be avoided by frequency scheduling with nearby test ranges, the increased demand for testing weapon systems and UAV's can result in relaxed scheduling in the future.

This simulation is performed by generating two signals with differing random message frames, where one is the desired and the other the interferer. The interferer is randomly time-shifted before being summed to the desired signal. For the MSK-SS simulation, the interferer is also assigned a different Gold code from the desired signal. The degree of freedom in this simulation is the signal-to-interference power ratio (SIR), and it is varied from -30 to 30 dB in 2 dB steps. Noise is also added to the wireless channel at an 11 dB E_b/N_0 ratio for CPFSK and MSK-SS.

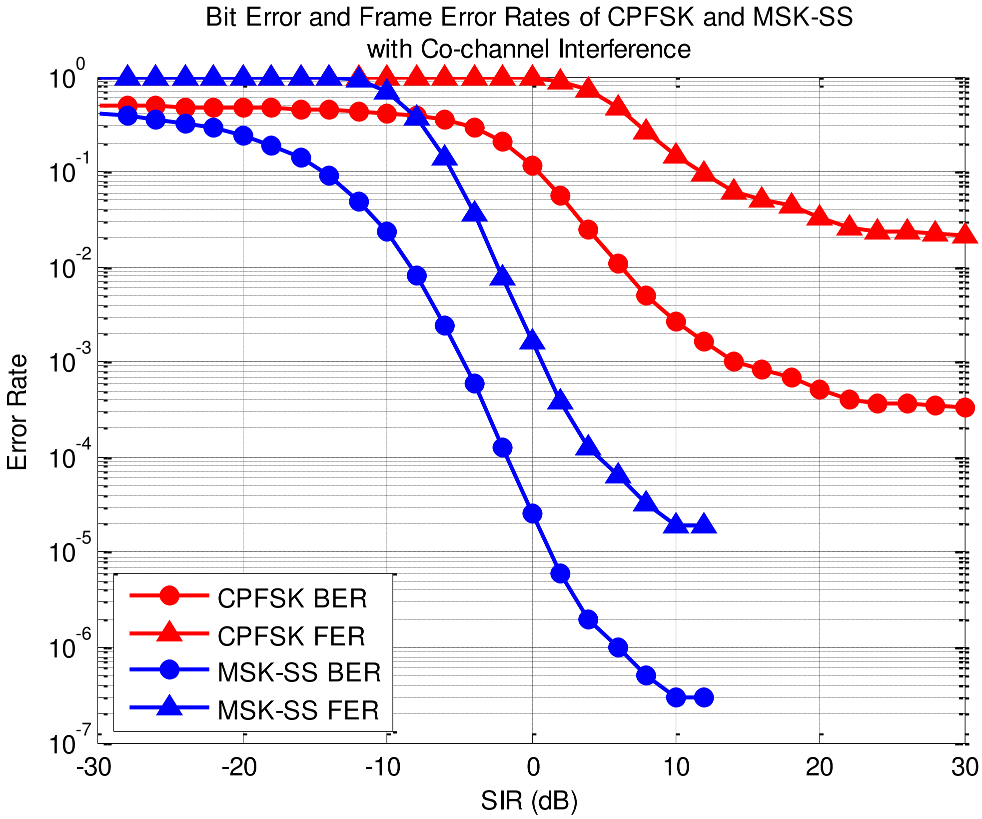

Figure 4.3: Error rates of CPFSK and MSK-SS with co-channel interference

As seen in Fig 4.3, the error rates of the MSK-SS system are still improved over the CPFSK system; however, the larger bandwidth of the interferer reduces the effectiveness of the MSK-SS scheme. Saturation is reached at 10 dB SIR with a BER less than 10^{-6} and at 22 dB SIR with a BER less than 10^{-3} for the MSK-SS and CPFSK systems, respectively.

4.4 Multipath Interference

This simulation shows how effective the MSK-SS system is at suppressing multipath interference that can cause inter-symbol interference. To perform this simulation, a copy of the transmitted signal was delayed from one chip time to one tenth of a bit time. This simulation only represents a 2-path channel that consists of a line of sight (LOS) component and a non-LOS component. Typically, the non-LOS will have greater attenuation over the LOS component because of the additional path loss caused by reflection, diffraction, and scattering of the signal. For this simulation, the non-LOS component is held at equal signal power to the LOS component in order to induce a maximum amount of inter-symbol interference. Noise is also added to the wireless channel at an 8 dB E_b/N_0 ratio for CPFSK and MSK-SS.

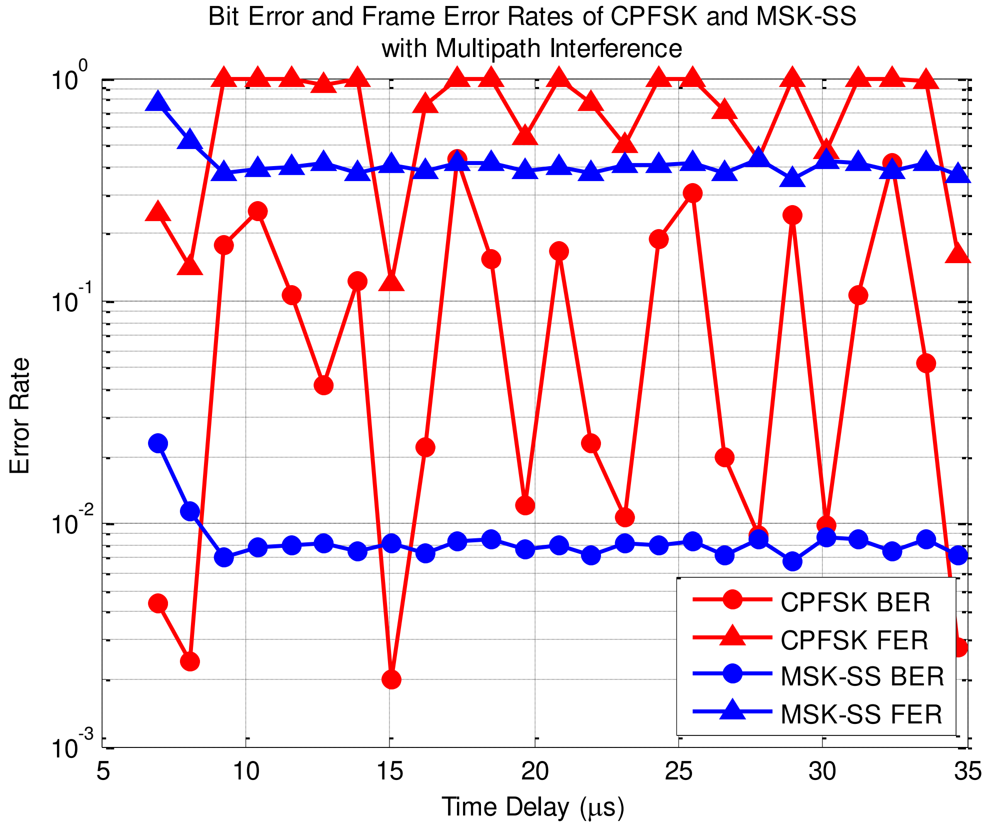

Figure 4.4: Error rates of CPFSK and MSK-SS with multipath interference

The CPFSK system is drastically affected by constructive and deconstructive interference. The MSK-SS is able to reduce the variance of the error rates over varying time delays. However, this benefit is limited to the chip rate; the multipath delay is spread as an interfering signal when the delay is greater than more than one chip duration [19]. The MSK-SS system offers no protection for multipath delays that are of less than one chip duration. If the chip rate was to be increased, the spread spectrum system would offer protection at shorter delays.

4.5 Synchronization Error

Since it is not practical to expect that the spreading code will be 100% synchronized at all times, this simulation is intended to demonstrate how the error rates are increased with a slightly unsynchronized code. This simulation is performed by shifting the local copy of the spreading code at the receiver before the signal is despread. Noise is also added to the wireless channel at an 8 dB E_b/N_0 ratio.

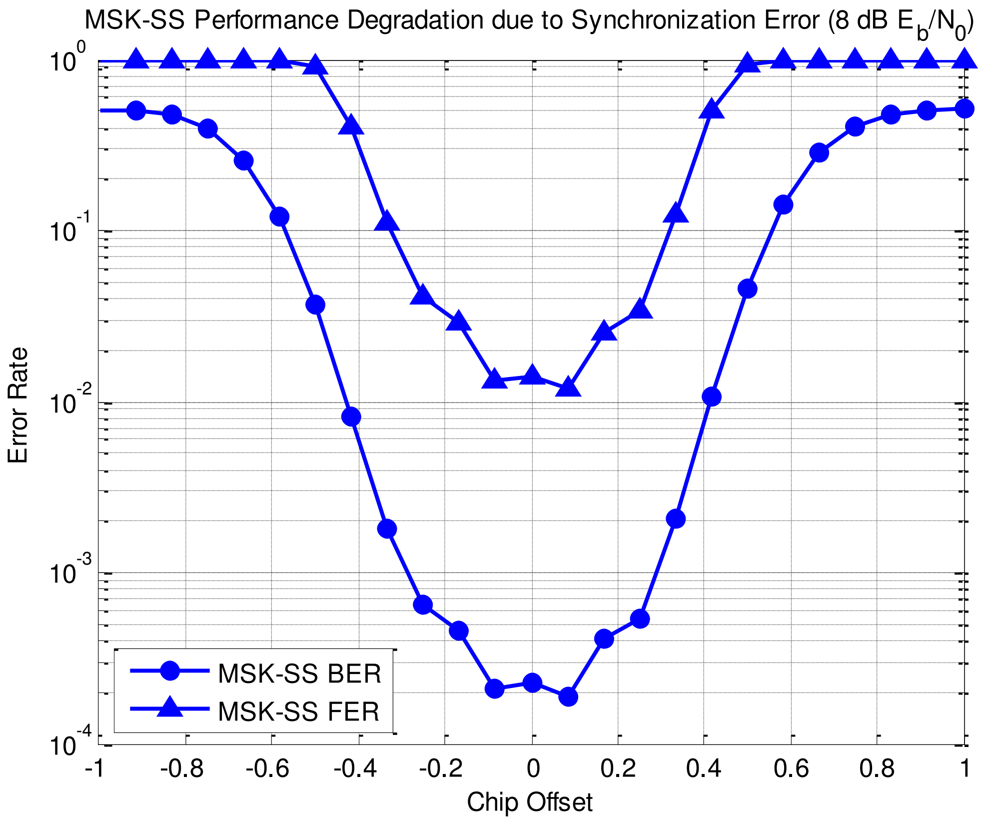

Figure 4.5: Error rates of MSK-SS with synchronization error

As seen in the figure above, error rates increase as the spreading code becomes unsynchronized. Spreading code acquisition can easily synchronize a code to within one half a chip [13]. As long as the continuous code tracking is able to keep the spreading code synchronized to within a ±10% offset error of one chip, the system is able to maintain error rates.

CHAPTER FIVE

CONCLUSIONS

This chapter summarizes the results from each of the simulations to provide an assessment on replacing CPFSK with the proposed MSK-SS modulation scheme. Considerations for future work are also discussed to expand on additional improvements to the FTS.

5.1 Conclusions from Results

In this thesis, an alternative communication link for a Flight Termination System was proposed to offer improved error rates in wireless channels plagued with interference while maintaining compatibility with the high power amplifiers currently in use. Pairing the constant envelope modulation scheme, MSK, with direct-sequence spread spectrum offered a realizable solution to interference rejection.

At 11 dB E_b/N_0, the MSK-SS modulation scheme was able to provide bit error rates less than 10^{-6} while the CPFSK system required an E_b/N_0 ratio greater than 14 dB. The MSK-SS system proved to be most effective against narrowband interference. The MSK-SS system was able to reject 18 dB of narrowband interference power over the CPFSK system. The spread spectrum system became less affective with wideband interference in the co-channel interference simulation; however, the MSK-SS system was still able to provide 12 dB of interference rejection. The MSK-SS was also shown to reduce the effects of inter-symbol interference caused by multipath interference.

While spread spectrum has been shown to improve the error rates over CPFSK, there are several tradeoffs to implementing a spread spectrum system related to bandwidth, acquisition time, and synchronization.

The increased bandwidth of the MSK-SS signal is less than 200 KHz at -20dB. In order to meet the EFTS specification, the signal must have a bandwidth less than 360 KHz at -60 dB.

However, since this requirement was carried over from the legacy FTS using FM, suggestions have been made towards opening up the requirement to 360 KHz at -20 dB. In this case, the bandwidth is acceptable.

Acquisition time is also slightly delayed due to the overhead of accurately acquiring the correct timing of the spreading code. Due to the desirable autocorrelation properties of the Gold codes, acquisition can take place within one period of the spreading waveform assuming a high E_b/N_0 ratio. With a preamble of six bits in length, the total duration is less than 2.1 ms. This added overhead does not have a significant impact on the maximum acquisition time of 100 ms for the FTS.

Since the synchronization of a spreading code is rarely perfect in a real system, it is important to consider the error rate degradation if the spreading code isn't 100% synchronized. As long as the spreading code is synchronized to within a ±10% offset of one chip, the system is able to maintain error rates with negligible effect.

For a future generation FTS that operates in an RF environment affected by severe interference, a MSK-SS approach to the command link offers a considerable alternative to the current CPFSK modulation scheme in order to improve the reliability of the FTS.

5.2 Future Work

While this thesis presents a direct-sequence spread spectrum application for FTS with a constant envelope, other interference suppression techniques could be further evaluated. Further research and analysis can be performed in the interest of reducing the peak-to-average power ratio of an OFDM signal in order to prevent distortion when used in conjunction with nonlinear amplifiers. Compatibility with the nonlinear high power amplifiers is a requirement for FTS in order to maintain compatibility with the current ground transmitter infrastructure, and any future modulation scheme should be able to operate at high efficiency with the high power amplifiers.

The reduction of the overall bandwidth of the MSK-SS can be investigated, for example, by implementing a Gaussian Minimum Shift Keying (GMSK) modulation scheme. Applying a

Gaussian low-pass filter to the data bit stream suppresses the side lobes further than the MSK modulation scheme.

If the proposed MSK-SS modulation scheme is to be developed into a prototype FTR for a next generation FTS, it is important that the hardware is subjected to the same acceptance criteria as the EFTS receiver. The hardware can be tested by generating the MSK-SS signal in the lab, along with various interfering sources to gather empirical data to support the performance of the proposed modulation scheme in this document.

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BIOGRAPHICAL SKETCH

Garrett Michael McCabe received his Bachelor of Science degree in Electrical Engineering from the University of West Florida in the spring of 2010. He was admitted to graduate school at Florida State University in the fall of 2011, where he is pursuing a Master of Science degree in Electrical Engineering. His professional career began in 2010 as a civil servant for the United States Air Force where he is currently serving as an electronics engineer for the 96th Test Wing at Eglin Air Force Base.