THE UNIVERSITY OF NAIROBI
DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

PROJECT REPORT TITLE:
TRACKING OF FREQUENCY HOPPING SPREAD SPECTRUM SIGNALS

PROJECT CODE: PROJECT 014

This project report is submitted in partial fulfilment of the requirement for the award of the degree of Bachelor of Science in Electrical and Electronic Engineering of The University of Nairobi.

Submitted by:
IAN ODHIAMBO OTIENO.............................................F17/1409/2011

Project supervisor:
PROF. VITALICE K ODUOL

Project examiner:
DR. AKUON
DECLARATION OF ORIGINALITY

COLLEGE: Architecture & Engineering
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NAME OF STUDENT: Ian Odhiambo Otieno
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This report has been submitted to the Department of Electrical and Information Engineering, University of Nairobi with my approval as supervisor.

Prof. Vitalice K. Oduol

Date: .....................................................
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ABSTRACT

Frequency Hopping Spread Spectrum communications utilises a pseudo random code to spread the bandwidth of the data being transmitted over a much wider range than is required by the data. Due to the pseudo random nature of the carriers selected for transmission, the spreading and dispreading process must occur simultaneously to recover the transmitted data signal. This requires the receiver have knowledge about the instant the transmitter began transmitting and the propagation delay between the two. However in real world systems, this information is unavailable to the receiver. The project utilises MATLAB version r2016a to demonstrate a method of synchronising the code clock at the receiver with the code clock at the transmitter, this fine alignment process is known as code tracking.
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Chapter One: Introduction

1.1 Project Title and Objectives
PRJ 014: Tracking of Frequency Hopping Spread Spectrum Signals.

The objective of the project is the study of code tracking in frequency hopping spread spectrum communication systems. A description and explanation as to its necessity is required as well. Finally a design and demonstration of a code tracking method for FHSS signals.

1.2 Background
Spread Spectrum communications refers to the technique of taking an information bearing signal of a particular bandwidth and deliberately spreading it out on the frequency domain such that the signal now occupies a much wider bandwidth.

There are three main techniques utilised in Spread Spectrum communications. Direct sequence spread spectrum, frequency hopping spread spectrum, hybrid direct spread frequency hopping. With each utilising a code that is pseudorandom in nature to achieve the spreading.

Each system of spreading the spectrum will require a method of recovering the transmitted signal. This requires the receiver to recover the spreading code timing from the received signal. The acquisition system brings the receiver and transmitter code sequences into coarse alignment while the tracking system

1.3 Scope of the Project
The project concentrates on demonstrating a means of code tracking on FHSS systems. The tracking deals with correction of timing offsets and frequency offsets of the clock running the code generators. Although acquisition is an essential first step before tracking can commence, there is no in depth treatment of acquisition methods. This is because the scope of the project is to design and demonstrate a code tracking method. Subsequently only the simplest acquisition system is utilised.

The tracking systems deployed in DSSS systems are not touched on within the project as they are outside the scope of the project.
Chapter Two: Literature Review

2.1 Spread Spectrum Systems: Classification, Advantages and Characteristics

Spread spectrum systems are classified based on the method used to spread the signal.

2.1.1 Direct Sequence Spread Spectrum

The information signal is used to modulate a bit sequence that is pseudorandom (PN) in nature. This PN sequence has a much higher rate than the information bit sequence. Modulation by the information bit sequence will result in it having a relatively wide bandwidth [1]. Information signal is recovered by multiplying the received signal with a replica of the PN sequence used to spread it. Any interference or jamming introduced in the channel will subsequently be spread by the PN sequence at the receiver. This will lower the power of the interfering signal while recovering the message signal. This system relies on manipulating the power spectral density by spreading and dispersing it across frequencies as well as filtering to suppress interference.

![Figure 1-1 Effect of spreading on signal and noise][1]

2.1.2 Frequency Hopping Spread Spectrum

The information signal is transmitted at multiple carrier frequencies [2]. The most common modulation method is called frequency shift keying (FSK) where distinct frequencies are used to represent the data. The order of the carrier frequencies is made as random as possible through the use of a PN sequence generator. FHSS uses the strategy of avoiding interference by moving (hopping) between multiple carrier frequencies. The carrier frequencies are utilised at different moments in time throughout the period of information transmission as shown in figure 1-2. At each hop, the signal occupies the same bandwidth as the original FSK modulated signal, however, averaged over the time period of operation, the bandwidth of the system is spread over the entire range of the hopping carriers.

![Figure 1-2 Spectral occupancy of a FHSS system][1]
To receive a FHSS signal, at the receiver side, the incoming signal must be multiplied by the locally generated pattern of carrier frequencies (This process is called de-hopping). The original information signal is received utilising filters and various detection schemes. The locally generated pattern of carriers is controlled by a PN sequence generator that is identical to the one used to spread the signal at the transmitter.

2.1.3 Hybrid Direct Spread Frequency Hopping
This scheme utilises a combination of DSSS and FHSS to spread the information signal in the frequency domain [1]. The information signal is first used to modulate a PN sequence (PN₁), this modulated signal is then transmitted at multiple carrier frequencies in an order determined by a second PN sequence (PN₂). The receiver is a combination of the DSSS and FHSS receivers with the received signal first being de-hopped (the spreading due to multiple carriers is nullified using PN₂) and the PN sequence, PN₁, used to recover the information signal from the de-hopped signal.

2.1.4 Characteristics of Spread Spectrum
The signal must occupy a bandwidth that is much larger than the one necessary to send the information.

Spreading is accomplished by means of a spreading signal (sometimes called code signal). This is a PN sequence that is independent of the information signal.

The receiver recovers the original data via correlation of the received spread signal with a synchronised replica of the spreading signal used to spread the information [2].

In the case of FHSS, a parameter called processing gain is defined as shown in equation (a) [2].

\[
G_p = \frac{W_{\text{hopping}}}{W_{\text{data}}} \ldots (a)
\]

This is the ratio between the bandwidth over which the system hops against the bandwidth of the data signal. It gives a measure of the resistance of the system to noise or jamming.

2.1.5 Uses and Advantages
Spread spectrum techniques were invented for military use as they provide a means of securing information during transmission. The advantages recognised are militaristic in nature, however, they are also useful in civilian environment especially in crowded frequency bands and to limit transmission power to conform to international standards.

This expansion of the bandwidth confers several advantages such as [3]:

1. Preventive measure against interference due to jamming, other users of the channel or interference due to multipath propagation.
2. Concealing a signal by providing a means for transmission at much lower powers.
3. Providing a means for a message to be transmitted only to the intended recipient despite the presence of other listeners.
4. Allows satellites to radiate more total power and stay within flux density limits by spreading signal energy over a wider spectral band. This prevents interference with LOS and terrestrial radio systems [2].

2.2 Historical Background

The historical background of SS communications will concentrate on the invention of FHSS as that is the scope of the project.

FHSS can be said to have originated with Nikola Tesla [4]. On Mar. 17th 1903, he details in US patent 723,188 (Method of Signalling) a system that operates in a similar manner to modern FHSS systems. In the patent he describes a method using two separate signals to make “...exchange of signals or messages reliable and exclusive; but in exceptional instances a greater number may be used and a degree of safety against mutual extraneous interference attained, such as is comparable to that afforded by a combination-lock.” [4]

This patent details a method of using a transmitter and receiver that operate in a predetermined order at two separate frequencies to reduce interference.

The next contributor is a German Physicist and Electrical Engineer known as Jonathan Zenneck who describes FHSS in a section of his book Wireless Telegraphy. [5]

The most famous inventor of FHSS was Hedwig Eva Maria Kiesler, better known as Hedy Lamarr. In US patent No. 2,292,387 (taken in the name of H. K. Markey, Lamarr’s second husband, 11th August 1942) a system is described for radio control of torpedoes [6]. Together with co-inventor George Antheil, Lamarr’s concept was to use frequency hopping to prevent the target from jamming the torpedo controller’s transmissions. The system used 88 carrier frequencies and a mechanical system to synchronise the frequencies. Although the idea wasn’t used during World War II, due to technology limitations, the US navy in 1962 had an improved version installed on their navy ships during the Cuban missile crisis [7].

FHSS technology was utilised in WLAN networks and the standard that controls this is the IEEE 802.11 legacy standard however, modern systems have upgrade to DSSS since this implementation of spread spectrum allows for higher speeds of data transmission [8]. The Bluetooth standard also utilises FHSS to avoid interference in the ISM 2.4GHz band it operates in [9, 10].
2.3 The FHSS System Overview

A generalised block diagram of a FHSS system transmitter is as shown in figure 2-1.

![Figure 2-1 FHSS transmitter](image1)

A generalised block diagram of a FHSS receiver is as shown in figure 2-2.

In the transmitter shown above, the data signal is first modulated using digital modulation techniques. The resulting information signal is used to modulate carrier signals from a fixed set that are chosen in a non-sequential pseudo random order. The most common digital modulation techniques used are FSK and GFSK.

The code generator is the source of the PN sequence and this is used as a control for the frequency synthesiser that generates the carriers. The PN sequence ensures the order of the carrier frequencies appears random. At the output of the mixer, a band-pass filter can be implemented to pass only the sum frequencies and block the difference frequencies.

At the receiver end, the incoming FH signal is mixed with locally generated carriers in the same order as the transmitter carriers, a band-pass filter in this case blocks the sum frequencies and transmits the difference frequencies hence recovering the original information signal. This information signal is then demodulated using the inverse technique.
of the one utilised at the receiver. There will be distortions and non-linearity introduced by the channel and relative movement between transmitter and receiver, this necessitates the synchronization system. This system uses the received signal to control the timing for the clock that runs the PN sequence generator. It’s within this system that the acquisition and tracking methods are concurrently implemented [1].

2.3.1 Digital Modulation at Receiver

The most common technique utilised is call Frequency Shift Keying (FSK). This is a subset of FM modulation. In this scheme digital information is transmitted via discrete frequency changes in the carrier signal. This scheme can be implemented using multiple oscillators or using a single oscillator. The multiple oscillator method produces carrier frequencies that are not continuous in phase.

2.3.1.1 Minimum Shift Keying (MSK)

In this method, the difference between the higher and lower frequency is half the bit-rate of the digital signal. Waveforms represented by 0 and 1 differ by exactly half a carrier period. This criteria allows for the signals to be orthogonal [3].

A Binary FSK system has signals represented as

\[ s_i(t) = \sqrt{\frac{2E}{T}} \cos(2\pi f_it) \quad i = 1,2 \ldots (1) \]

E is the received energy of the waveform and T is the signalling interval or bit duration. The correlation coefficient is given by

\[ \rho = \frac{1}{E} \int_0^T s_1(t)s_2(t)dt \ldots (2) \]

The two signals are considered orthogonal when

\[ \rho = 0. \]

Applying the correlation coefficient formula to MSK general equation given in equation 1, we have

\[ \rho = \frac{2}{T} \int_0^T \cos(2\pi f_1t) \cos(2\pi f_2t) dt \ldots (3) \]

Given that

\[ \cos(2\pi f_1t) \cos(2\pi f_2t) = \frac{1}{2} \cos(2\pi (f_1 + f_2)t) + \frac{1}{2} \cos(2\pi (f_1 - f_1)t) \ldots (4) \]

We can simplify the correlation integral into equation 5.
\[
\rho = \frac{1}{T} \int_0^T \cos(2\pi(f_1 + f_2)t) \, dt + \frac{1}{T} \int_0^T \cos(2\pi(f_1 - f_2)t) \, dt
\]
\[
= \frac{\sin(2\pi(f_1 + f_2)T)}{2\pi(f_1 + f_2)T} + \frac{\sin(2\pi(f_1 - f_2)T)}{2\pi(f_1 - f_2)T} \quad \ldots (5)
\]

It’s usually the case that the \((f_1 + f_2) \gg (f_1 - f_2)\) due to this the predominant term defining the correlation coefficient is given by equation 6a.

\[
\rho = \frac{\sin(2\pi(f_1 - f_2)T)}{2\pi(f_1 - f_2)T} \quad \ldots (6a)
\]

Orthogonal signalling will occur at multiple values of \((f_1 - f_2)\) as long as the relation of equation 6b holds.

\[
|f_1 - f_2| = \frac{i}{2T} \quad i = 1, 2, \ldots \quad \ldots (6b)
\]

MSK occurs for \(i = 1\). [11]

### 2.3.1.2 Continuous Phase Frequency Shift Keying (CPFSK)

A subset of the FSK method where phase of the modulated transmitted signal is continuous across the multiple frequencies. This is achieved via the use of a single oscillator to generate the multiple carriers. This scheme produces less wideband noise due to mitigating the discontinuity when the frequency of the carrier changes [3].

### 2.3.1.3 Gaussian Frequency Shift Keying (GFSK)

In this method, the digital data pulses are passed through a Gaussian filter (a filter whose impulse response is a Gaussian function or approximates it) to smooth out the transitions and give the resulting output carrier frequency a smooth transition to the next frequency instead of an abrupt one [12]. At the cost of increasing the intersymbol interference, this scheme reduces the sideband power and interference with neighbouring channels.

### 2.3.1.4 Frequency Shift Keying (FSK) and Multiple Frequency Shift Keying (MFSK)

This is a common method used in FHSS systems.

The general analytic expression for FSK modulation is

\[
s_i(t) = \sqrt{\frac{2E}{T}} \cos(\omega_i t + \varphi) \quad \ldots (7)
\]

Where \(0 \leq t \leq T\) and \(i = 1, 2, \ldots, M\) and \(\varphi\) is an arbitrary phase angle

The frequency term has M distinct values, if M=2 the scheme is known as Binary Frequency Shift Keying (BFSK). In practice M is usually a power of 2 i.e. 2, 4, 8, 16 etc. The figure 2-3 shows the waveform changes in a 3FSK scheme.
For orthogonal signalling which ensures maximum detection with a non-coherent receiver, the frequency separation of the tones must obey the relation of equation 8.

$$|f_1 - f_2| = \frac{k}{T} \text{ for } k = 1, 2, ..., N \ldots \ldots (8)$$

This ensures the signals are orthogonal as long as k is an integer [2].

### 2.3.2 Code Generator

This section of the transmitter is what generates the PN sequence that is used to hop the carriers in a seemingly random order. The core of this component is a system that can produce a sequence that:

- passes reasonable tests of randomness
- can be reproduced

In a Transmitted reference (TR) system, the code signal is transmitted independently of the message bearing signal. This means a truly random spreading code can be used since the transmitter receives the code used to spread the signal and will not locally generate it. This system adds the complexity of securing transmission of the code signal to the transmitter without interception or interference.

In a Stored Reference (SR) system, the problem of secure transmission of the spreading code is solved by having the receiver and transmitter independently generate them. The spreading code is now constrained to be deterministic and cannot be random. It uses a pseudo-noise or pseudo random sequence. This PN sequence although deterministic in nature appears truly random to anyone that doesn’t have the means to reproduce it [2].

In probability theory, a binary independent random sequence is known as a Bernoulli sequence. It mimics a coin toss result with “1” corresponding to heads and “0” corresponding to tails. However, this requires too much storage to implement at both the receiver and the transmitter. The solution is to make use of a method that mimics the randomness properties of the Bernoulli sequence. This is done via a long deterministic periodic sequence that can be generated via a simple linear operation [13].
To have the appearance of randomness, a binary sequence should satisfy these properties [2]:

- **Balance Property:** In each period of the sequence, the number of “1” and “0” should differ by at most one digit.
- **Run Property:** A run is a sequence of identical binary digits. We must have half of all the run lengths should be length 1, a quarter of all the run lengths are of length 2, an eighth of all runs should be length 3. This is summarised by saying a fraction $\frac{1}{2^n}$ of all runs are of length $n$ for all finite $n$.
- **Correlation Property:** If a sequence is shifted by any non-zero number of all elements, the resulting sequence will have a number of agreements and disagreements which should differ by at most one count.

### 2.3.2.1 Maximal Length Linear Shift Register Sequences

Consider the four stage shift register shown below. The clock pulse which drives it is not shown.

![Four stage LFSR](image)

At each pulse the register contents are shifted to the right, furthermore the contents of L3 and L4 go through a modulo-2 addition before being fed back to L1. The flip-flops in the shift registers are commonly D flip-flops. The output is defined as the contents of L4 at each clock cycle. If the initial state of the register is L1L2L3L4 = 1000 then the contents of the registers will follow the pattern: 1000-0100-0010-1100-0110-1011-1101-1110-1111-0111-0011-0001-1000. This means the period of the sequence is 15 clock cycles. This particular type of sequence is called a maximal length sequence and it will have a period as given in equation 9.

$$ p = 2^q - 1 \ldots (9) $$

Where $p$ is the number of clock cycles and $q$ is the number of flip-flops in the register (register length). The output of L4 is 000100110101111. This sequence obeys the 3 properties for a PN sequence given above.

For the content of the Linear Feedback Shift Register (LFSR) to be considered a PN sequence, it must be a maximal length sequence [2]. The input bit is driven by the XOR of some bits of the overall shift register value. The bit positions that affect the next state are called taps. The connection of the taps in a LFSR are defined by a feedback polynomial.
In the feedback polynomial the 1 corresponds to input of the first bit. The powers of the terms represent the tapped bits counting from the left, the first and last bits are always connected as an input and output tap respectively. The coefficients of the feedback polynomial are either 1 or 0 dependent on whether there is a tap connection or no tap connection. The feedback polynomial of the figure 2-4 is given by equation 10.

\[ P(x) = x^4 + x^3 + 1 \ldots \ldots \quad (10) \]

There are two ways of providing feedback, either external or internal feedback. Even if the registers are given the same initial values (called a seed) the external and internal feedback connections will produce separate sequences. For the case of feedback polynomial given in equation 11.

\[ P(x) = x^3 + x^2 + 1 \ldots \ldots \quad (11) \]

The differing connections are shown by figure 2-5.

The two LFSR shown in figure 2-5 will produce sequences of length 7 but of different order.

The degree of the feedback polynomial is equivalent to the number of stages of the feedback polynomial. A maximal length sequence is only produced if the feedback polynomial is primitive.

There exists a list of primitive polynomials and one is provided in Appendix A. Following the list, it can be observed that the feedback polynomials all share some common characteristics:

- Even number of taps
- The set of all taps are relatively prime

These conditions are not sufficient to classify a polynomial as primitive but all primitive polynomials obey the above conditions.

The only state not allowed is the state of all the bits being 0 as this will trap the register in a state of all the bits being set to 0.
2.3.3 Frequency Synthesizer
This is the component that produces the carriers used to hop the carrier signals. It’s an electronic system that produces a range of frequencies from a single origin (reference) frequency. The reference frequency must be spectrally pure and very stable. Sources that satisfy this condition are piezoelectric crystals [1].

There are three basic types of frequency synthesizers:

1. Direct Synthesis
2. Indirect Synthesis
3. Direct Digital Synthesis

2.3.3.1 Direct Synthesis
This utilises frequency multipliers, dividers and electronic switches to produce the desired frequencies. The advantages lie in their ability to give high frequencies as well as their fine resolution, the main disadvantage is that the cost of hardware is large and providing phase continuity between the frequencies produced is close to impossible.

The standard approach of implementing this scheme is known as Double-Mix-Divide (DMD) and is illustrated in figure 2-6.

![Figure 2-6 Double Mix Divide frequency synthesizer [1]](image)

The reference signal is changed through the use of mixers, dividers and summing through the band pass filters.
2.3.3.2 Indirect Synthesis
This method utilises a voltage controlled oscillator, feedback loops and a reference that is phase locked to the output. It produces continuous phase outputs but is slower in switching speed between the produced frequencies. A single loop indirect frequency synthesiser is shown in figure 2-7.

The generated frequency $f_o$ is obtained from the reference frequency $f_{ref}$. The Phase frequency detector outputs a signal that is proportional to the difference between the two input periodic signals input to it. The LPF enhances the spectral purity, reduces phase noise and provides the necessary voltage to drive the VCO (voltage controlled oscillator). The VCO produces a frequency that is controlled by its input voltage. The divider scales the output frequency by $N$ [14].

$$f_{ref} = \frac{f_o}{N} \Rightarrow f_o = N f_{ref} \ldots (12)$$

The frequency resolution is $f_{ref}$. Channel spacing that is small requires small $f_{ref}$ and large $N$ [14]. The lower the bandwidth of the loop filter, the less the phase noise, the higher the bandwidth of the loop filter the faster the switching time [1].
2.3.3.3 Direct Digital Synthesis

This scheme of frequency synthesis uses stored values of a sine wave sampled at a very high rate to produce analog versions of the sine wave at a specified frequency.

As the phase advances around a circle, this is equivalent to an advancement in the waveform. Successive additions of phase will advance the waveform forward an equivalent number of advancements [15].

The sine table stores the amplitude of a phase value. At each phase value, the sine table is used to give the output of its equivalent amplitude. The faster the phase value increments, as controlled by the phase accumulator, the faster the values are output from the sine table and the higher the frequency of the produced waveform. The DAC (Digital to Analog Converter) converts the sampled values of the sine wave to the analog waveform. The Lowpass filter eliminates the unwanted high frequency components resulting from DAC. The output obtained is a sine wave of arbitrary frequency defined by the phase accumulator which can in turn be controlled by a code word [14].

2.3.4 Mixers

These are components that multiply the 2FSK signal with the carrier signals to perform the hopping (at transmitter) and de-hopping (at the receiver). The mixer at the transmitter performs the task of spreading the spectrum. This is done by multiplying the two waveforms producing sum and difference frequencies that span a much wider bandwidth than the original message signal.

The mixer at the receiver end multiplies the incoming signal with a locally generated hop set to recover the original 2FSK signal used to modulate the data digitally. The useful signals for recovering are the sum frequencies originating from the transmitter.
2.3.5 Bandpass Filter
This filter selects the difference frequencies from the mixer operation preceding it allowing the recovery of the original signal that is to be demodulated to recover the digital signal.

At the transmitter end we have

\[ s_i(t) = \sqrt{\frac{2E}{T}} \cos(\omega_i t) i = 1,2 \ldots \ldots (13) \]

In this case the assumption is \( \varphi = 0 \) for 2FSK modulation. The hop set carriers are given by

\[ s_k(t) = \sqrt{\frac{2E}{T}} \cos(\omega_k t) k = 1,2, \ldots N \ldots (14) \]

Where \( N \) is the number of carrier frequencies used to hop the signal and assuming

\[ \omega_k \gg \omega_i \ldots (15) \]

At the transmitter, the mixer operation produces waveforms of sum and difference frequency and the sum frequencies are transmitted.

\[ \omega_{\text{transmit}} = (\omega_i + \omega_k) \ldots (16) \]

At the receiver end, the incoming frequencies are multiplied by the same hop set to recover the original data modulated signal. The Bandpass filter only selects the difference frequencies.

\[ \omega_{\text{receive}1} = (\omega_{\text{transmit}} + \omega_k) \text{ and } \omega_{\text{receive}2} = (\omega_{\text{transmit}} - \omega_k) \]

\[ \omega_{\text{receive}} = (\omega_i + \omega_k - \omega_k) = \omega_i \ldots (17) \]

The signal is now de-hopped and can move on to demodulation to recover the digital signal from the received waveform.

2.3.6 Demodulation
The most common configuration of FHSS system is the FSK/FHSS system. Due to uncertainties of phase introduced by the channel, the most common scheme of demodulating the FSK signal is to use non-coherent demodulation where receiver has no prior knowledge of the phase of the received waveform. This requires the detector be configured as an energy detector. There are two main methods, Quadrature receiver and Envelope detection [2].
2.3.6.1 Quadrature Receiver

The diagram of a quadrature receiver is shown in figure 2-10, it relies on the frequencies being detected being orthogonal to each other.

The reference signals for detecting the signals are 90° out of phase with each other. The upper branch detects a waveform of frequency $\omega_1$ and the lower detects a waveform of frequency $\omega_2$.

The correlation operation is used to compare how similar the waveforms are to the reference generated signal at the receiver. The squaring operation removes the negative components from the correlation.

If the received signal is of the form given in equation 18, where $n(t)$ is noise added by the channel.

$$ r(t) = \cos \omega_1 t + n(t) \ldots (18) $$

The top branch of the receiver will yield maximum output and output of lower branch will be near zero due to orthogonality of the signals. The same will apply if received signal is of the form

$$ r(t) = \cos \omega_2 t + n(t) \ldots (19) $$

in this case the lower branch will yield the maximum output and upper branch will have a near-zero output. The decision stage will give an output of a bit 1 or bit 0 dependant on which arm yields the highest magnitude signal.

![Figure 2-10 Quadrature Receiver for non-coherent demodulation of FSK](image-url)
The Q channel is necessary due to possible phase shift introduced by the channel such as the case given by equation 20.

\[ r(t) = \cos(\omega_1 t + \varphi) \ldots (20) \]

in which case it will partially correlate with the I channel and partially correlate with the Q channel at the detection frequency of the branch [2].

### 2.3.6.2 Envelope Detectors

This approach utilises Bandpass filters centred at the frequency \( \omega_1 \) and with a bandwidth \( W_i = \frac{1}{T} \) where \( T \) is the duration of the symbol. These filters are followed by envelope detectors.

The detectors extract the signal envelopes and this operation makes no use of the phase information of the signal. The decision stage gives a binary 0 or binary 1 output dependent on which output of the envelope detector is maximum [2].

![Bandpass filter based non-coherent demodulation scheme for MFSK](image)

*Figure 2-11 Bandpass filter based non-coherent demodulation scheme for MFSK [2]*
2.3.7 Synchronization System
This system handles the twin tasks of acquiring and tracking the incoming waveforms.

Since the hop set used to spread the signal is pseudorandom in nature, the acquisition task primarily handles bringing the receiver in sync with the transmitter such that the spreading and dispersing operations happen in step for continuous data transmission.

The tracking stage follows the acquisition stage and ensures that over the duration of communication the transmitter and receiver remain in sync.

The acquisition and tracking stages primarily aim to solve the problems of uncertainty of propagation delay between transmitter and receiver, carrier frequency offset, relative clock instabilities and the Doppler Effect (due to relative velocity between transmitter and receiver).

The acquisition system handles the correction for uncertainty in propagation delay between transmitter and receiver which in turn controls the timing of the clock driving the PN generator. The tracking subsystem often concentrates on compensation for carrier frequency offsets, Doppler Effect correction and clock timing instabilities [2].

The carrier frequency offset between the transmitter and receiver is corrected for on the receiver side. Implementation requires a means of detecting transmitter frequency and adjust the local oscillator frequency to match [3].

2.4 Acquisition Schemes
There are several methods used to achieve initial sync with the transmitter in the acquisition stage. They are primarily divided into two categories:

1. Parallel Search
2. Serial Search

The examination of these methods requires further characterisation of a FHSS system for ease of explanation in subsequent sections.

The hop set refers to the set of frequencies used by the FHSS system to spread the signal. The dwell time refers to how much time the FHSS system spends transmitting on a single carrier. A chip refers to the shortest uninterrupted waveform in the FHSS system [1].

In a Slow Frequency Hopping System (SFH) within a single hop of the carrier, there are several data symbols, in such a case, the chip of the system is equivalent to the data symbol. In a Fast Frequency Hopping System (FFH) there are multiple carriers used during transmission of a data symbol. There are multiple hops per transmission of a data symbol. In this case the chip duration corresponds to the dwell time [1].
2.4.1 Parallel Search

![Block diagram of the parallel search acquisition method](image)

The parallel search method searches through all of the frequency hopping carriers simultaneously. It is built to wait until it detects that the incoming signal is in the correct hopping pattern before declaring that acquisition has been achieved.

The pattern of the hopping in the hop set is known to the receiver. A bank of filters are tuned to the frequencies of the hop set. These frequencies are envelope detected and added with appropriate delays (corresponding to carrier dwell time) between them. The result of the test on the hop set is compared to a threshold and acquisition is declared if the value obtained exceeds the threshold.

The subsequent stages of tracking and demodulation are then enabled after acquisition has been declared [2].

This scheme has two main advantages [2]:

1. The acquisition time is improved due to checking for multiple carriers at the same time.
2. There is a lower probability of false alarms where acquisition is erroneously declared.

The main disadvantages of the scheme:

1. If the hop set has a large number of carriers the hardware cost of the filters becomes prohibitively large.
2. There is greater complexity in implementation since the results of the matched filters are compared sequentially instead of simultaneously.
3. The implementation for systems with large hop sets is harder to conserve space on the circuit due to large number of components.
2.4.2 Serial Search

This implementation minimises cost and complexity of a fully parallel search acquisition scheme.

A single matched filter or correlator is used to sequentially test for detection of signal within the hop set. The block diagram implementation is illustrated below.

![Block diagram of serial search acquisition scheme](image)

Figure 2-13 Block diagram illustration of serial search acquisition scheme [2]

The acquisition system tests for the correct hopping pattern by waiting on a known frequency for a set period of time. In the diagram above the Bandpass filter followed by the square-law detector and integrator function as an energy detector. If the signal is de-hopped correctly, the input to the correlator will exceed the threshold and acquisition is declared to have occurred. The hopping pattern is known and the PN code generator is initialised to allow the transmitter to de-hop the signal by mixing it with the frequency hopper output [2].

There is a possibility of a false alarm occurring. This primarily occurs due to noise resulting in acquisition being erroneously declared due to temporary exceeding of the threshold. The effect of false alarm is mitigated by having the serial search system continually monitor for the presence of the incoming signal. Hence it’s only when the threshold is continually maintained for a set period of time that acquisition is declared to have occurred [3].

The main advantage of serial search implementation is the reduced hardware and implementation cost. The main disadvantage of serial search is that it is time consuming in operation.

Say a FHSS system has a hop set of M carriers. If the dwell time of the carrier is $\lambda$ seconds, in the worst case scenario [2], the acquisition time is given by equation 21.

$$t_{acquisition} = M \lambda \quad (21)$$
2.5 Tracking Scheme

The tracking system performs the task of bringing the frequency hopping at the receiver into fine alignment with the transmitter hopping pattern as well as correcting for Doppler frequency offsets.

The tracking systems can be classified as coherent or non-coherent. The classification is made based on whether the carrier frequency and phase are known exactly. In most cases the carrier phase and frequency are not known exactly and hence the implementation utilised is the non-coherent tracking loop.

The implementation utilised for FHSS signals is an adaptation of the Earl-Late gate tracking loop.

The block diagram of the tracking loop is illustrated in figure 2-14.

The waveforms for the receiver timing lagging behind the transmitter timing are shown below in figure 2-15

The waveforms for the receiver timing leading the transmitter timing are shown in figure 2-16.

The timing offset in both cases is denoted by $t_0$. The carriers used in the hopping pattern are denoted by $F_n$ for $n = 1, 2, ..., 6$. 

![Figure 2-14 Early-Late Gate adaptation for code tracking FHSS systems [3]](image)

![Figure 2-15 Timing illustration and waveforms for lagging receiver](image)
The tracking loop assumes that the acquisition system has brought the receiver and transmitter pattern within a timing error of less than the chip interval i.e. the timing offset, \( t_o \), is small. The Bandpass filter is tuned to a single intermediate frequency with a bandwidth of the order of \( \frac{1}{T_{ci}} \), where \( T_{ci} \) is the chip interval. The output of the Bandpass filter is envelope detected to produce the signal detection waveform that is used to show presence or absence of a signal during transmission. This signal detection waveform is multiplied by VCC waveform to produce the three level signal of the tracking waveform.

The situation in which the receiver lags the transmitter results in the tracking waveform being more positive than the VCC waveform. A Lowpass filter is used to extract the mean of this waveform which will be positive and this positive signal drives the VCC to increase its frequency and hence speed up the receiver hop transitions allowing it to catch up with the transmitter.

The case for the transmitter hopping pattern lagging the receiver hopping pattern results in the tracking waveform being more negative than the VCC signal. The mean of this tracking waveform is used to drive the VCC which will increase transition time allowing transmitter hopping pattern to catch-up to the receiver hopping pattern until synchronisation is achieved [3, 16].

This method is an adaptation of the early-late gate method because the signal used to adjust the VCC is only 0 when there is no timing offset between the transmitter and receiver hopping patterns while both clocks retain a stable equivalent frequency. The loop ensures early transition and late transitions are corrected for to maintain optimum synchronism between the transmitter and receiver of the FHSS system. As the loop returns the value of the timing offset tends to zero. The loop also corrects for frequency mismatches between the oscillators driving the PN sequence generators.
Chapter Three: Design

3 Simulation Model Construction

The tracking system is implemented using MATLAB r2016a version in Simulink. The complete model overview is shown in figure 3-1.

Figure 3-1 System Block diagram overview
3.1 Transmitter
This subsystem contains the Binary data input, 2FSK modulator, the PN generator and the hopping carriers. The Transmitter subsystem is shown below.

3.1.1 Bernoulli Binary Generator
This block is used to provide the digital data input. It is set to a rate of 1kbps and the 1 and 0 are equally likely to occur.

3.1.2 2FSK_mod
This block implements the 2FSK modulation scheme utilising a set of two oscillators as shown below.

The separation frequency is 2 kHz which obeys the orthogonality condition. A binary 0 is represented by 10 kHz and a binary 1 is represented by 12 kHz.

3.1.3 transmit_mix
This block carries out the mixing operation and it’s implemented using the MATLAB product block.
3.1.4 transmitter_clock
This subsystem contains the clock that drives the PN generator for the transmitter. This subsystem contains the voltage controlled clock (VCC) that runs at 500Hz meaning the system transmits two symbols per hop and is hence a SFH system.

3.1.5 Transmitter PN Generator
This subsystem contains the flip flops required to implement the pseudo noise sequence. The implementation is done using JK flip flops interconnected to behave as D flip flops. The feedback polynomial is $x^3 + x^2 + 1$ and the initial seed is 100. The resulting sequence is a maximal length sequence of period 7. The implementation is a 3 stage LFSR.

The bit to integer converter is used by the next Transmitter Carrier Generator subsystem to generate the hop set.

3.1.6 Transmitter Carrier Generator
This subsystem generates the hop set. The hopping carriers range from 100 kHz to 700 kHz in steps of 100 kHz which is an integer multiple of the 2FSK frequency separation and the input bit rate.
3.1.7 transmit_delay
This block is a delay block that performs the job of timing correction to correct for the PN generator being positive edge triggered. Its value is set to 1 to have minimal effect on the timing of the signal.

3.2 Channel
The channel is modelled as an AWGN which is an additive white Gaussian noise channel. This models the channel as having corrupting noise being added to the signal in the process of transmission.

3.3 Receiver
The Receiver subsystem overview is shown below in figure 3-6.

![Figure 3-6 the receiver subsystem](image)

3.3.1 receive_mix
This block utilises the MATLAB product block to model the de-hopping operation by multiplication by the locally generated hop set.

3.3.2 Receiver Carrier Generator
This subsystem contains the locally generated hop set and is identical to the transmitter carrier generator (figure 3-5).

3.3.3 Receiver PN Generator
This subsystem generates the maximal length PN sequence and its construction is identical to the PN generator at the transmitter (figure 3-4).

3.3.4 sorting_error_fix
This MATLAB block uses a delay of 1 integration period to force the acquisition and tracking systems to activate after signal is received. The primary purpose of the block is to prevent ambiguous execution errors occurring in the model.
3.3.5 receiver_clock
The clock that controls the PN generator for the transmitter. This subsystem is constructed as shown below in figure 3-7.

![Diagram of receiver_clock subsystem](image)

**Figure 3-7 receiver clock**
The receiver_delay block models the effect of timing offsets in the receiver clock. It has an offset timing resolution of 0.6667μs. The enable block allows the execution of the clock to be dependent on an external input signal. The VCC_wave output is used in the tracking system.

3.3.6 Noncoherent 2FSK Receiver
This subsystem performs the task of recovering the original binary information sequence from the received symbols of waveforms of 10 kHz and 12 kHz.

![Diagram of Noncoherent 2FSK demodulator](image)

**Figure 3-8 Non-coherent 2FSK demodulator**
This receiver doesn’t utilise any phase information from the incoming signal and hence its noncoherent. The conditional switch functions as the decision algorithm to output a binary 1 or 0 dependent on the which arm has the larger output. The integration period of the integrate and dump filter is set to the symbol period which is equivalent to the input data bit rate. The comparison between the two arms is performed by the Subtract1 block.
3.3.7 **Integrate_Dump_signal_detection**

This subsystem performs the serial search operation of the receiver as well as enabling the tracking subsystem and receiver clock subsystems.

The integrate and dump filters are utilised as matched filter energy detectors to detect the presence of successfully dehopped signal. Once the signal level crosses the preset threshold, this subsystem enables the receiver clock and the tracking subsystem. The system waits on one of the channels for the signal to be detected indicating the received signal has been dehopped, The transmitter has knowledge of the hopping carriers and the hopping sequence and simply initiates the clock to start following the hopping pattern.

3.3.8 **Tracker**

This subsystem implements the tracking operation. It is modelled as and enabled block that is dependent on the signal being acquired first before initiating the tracking of the signal to correct for timing offset. The block diagram of the subsystem is shown below.

The Lowpass filter is used to extract the mean of the tracking signal which is used to control the frequency of the VCC in the receiver clock subsystem.
3.3.8.1 Matched_filter_energy_detector
This is a subsystem within the Tracker that is used to detect the timing errors between the receiver and transmitter clocks. It has a higher sensitivity than the signal detector used to serial search the incoming signal during acquisition.

The energy detector detects misalignment between the received hopping pattern and the locally generated hopping pattern.
Chapter Four: Results and Analysis

4.1 Modulation and Spreading

The modulation method used to convert the digital input to 2 distinct frequencies utilised a pair of oscillators and the spectrum of the 2FSK signal is shown in figure 4-1.

The two peaks of 10 kHz and 12 kHz correspond to binary 0 and 1 respectively.

The result of the signal being spread out is shown by the spectrogram below (figure 4-2).

Figure 4-1 Spectrum of 2FSK modulated binary input

Figure 4-2 Spectrogram showing spectral occupancy of carriers
The dark line segments indicate the frequency is being utilised to transmit data over the channel. The range of carriers is from 100 kHz to 700 kHz.

4.2 Transmission over the Channel

The AWGN channel is utilised to demonstrate that the system designed is successfully transmitting data and receiving. The figure 4-3 shows the results with the AWGN channel set to a signal to noise ratio of 10. The received binary output is only valid while the Acquisition subsystem output is at 1. The period preceding this is utilised by the serial search subsystem to acquire the signal. A graph of the BER (bit error rate) against time shows that the system acquires the signal initially by waiting at the pre-set frequency and then initiates the process of hopping by enabling the clock that drives the PN generator. This is shown in figure 4-4.

![Transmitted Binary Input](image1)

![Received Binary Data](image2)

![Acquisition Subsystem Output](image3)

*Figure 4-4 transmitted binary, received binary and acquisition subsystem output.*

![Graph of BER over time](image4)

*Figure 4-3 BER change over time*
The acquisition subsystem demonstrates that the receiver is not required to wait at a predetermined seed with the transmitter and start hopping simultaneously to transmit data.

This solves the problem of uncertainty of timing inherent in spread spectrum systems as the receiver hopping timing is recovered from the transmitter. The acquisition time is directly related to the relative timing difference between the seed at the receiver and the current PN code the transmitter is broadcasting on.

### 4.3 Tracking Subsystem

The acquisition system brings the transmitter and receiver PN code sequences into course alignment. The tracking subsystem initiates the process of achieving fine alignment of the PN sequences. This is shown by figure 4-5.

![Figure 4-5 Receiver PN sequence leading transmitter, alignment improvement highlighted by reference lines](image)

In the figure 4-5, the PN sequence for the receiver is ahead of the sequence for the transmitter, hence the receiver hops to the next frequency carrier earlier than the transmitter. The transmitter and receiver clocks are also seen to be out of alignment. As the system runs, the timing offset is reduced as shown by the orange lines on the figure.

From the theoretical analysis, if the transmitter PN sequence lags behind the receiver PN sequence than a negative control voltage is expected at the VCC to slow down the receiver clock and allow the transmitter clock to catch up. As the code clock is brought into
alignment, the control voltage of the VCC will tend towards 0V. This process is shown by the
figure 4-6.

From figure 4-7, the receiver hopping pattern is delayed behind the transmitter hopping
pattern. The theoretical expectation is that the VCC will speed up its transitions to allow the
receiver clock to catch up with the transmitter clock. As soon as alignment is achieved, the
VCC control voltage tends to 0V. This process is shown by figure 4-8.
The tracking speed is controlled by the VCC sensitivity and the bandwidth of the Lowpass filter that produces the mean signal. The higher the VCC sensitivity, the greater the correction the tracking signal can apply and hence the faster the response of the tracking system.

Figure 4-9 and 4-10 shows the behaviour of the tracking system with a frequency offset of 10Hz between the transmitter and receiver code clocks.

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**Figure 4-8** Tracking signals with receiver hopping pattern lagging transmitter hopping pattern

**Figure 4-9** Tracking control voltage with transmitter +10Hz ahead of receiver
The VCC oscillator that controls the timing of the VCC clock for the PN code generator has a sensitivity of 40Hz/V. The expected value of tracking signal that would lead to a frequency correction of ±10Hz is ±0.25V. These values are shown in figures 4-9 and 4-10.
Chapter Five: Conclusion and Recommendations

5.1 Conclusion
The objectives of the project were achieved. FHSS systems were studied and the importance of code tracking was demonstrated. The importance of an acquisition system was also demonstrated.

The system allows the receiver to adjust its clock frequency to match up the locally generated PN sequence with the received PN sequence. The tracking system prevented errors by ensuring the two PN sequences don’t go out of sync with each other which would result in a loss of signal.

The tracking system allowed for demodulation process to be more reliable by allowing a larger amount of signal energy to be received by the demodulator.

5.2 Recommendations: Future Works
There is scope for improvement in the project. The FHSS system can be demonstrated to show resistance to jamming signals. The two main implementations of FFH and SFH can be used to compare their operation and ability to resist jamming.

Error Control Coding (ECC) may be included in future to improve the performance of the system in a jamming or noisy environment.

The project scope can also be expanded to include an Adaptive system that selects channels for transmission on the precondition that the channels are currently not in use or are not being jammed. Channel occupancy may be determined via the RSSI parameter and this is factored into the algorithm used by the transmitter in selecting carriers from the hop set. [10] This is provided that secrecy of the communication channel is not a priority and the main aim is to utilise the processing gain of the FHSS system to avoid crowded or noisy channels interfering with data transmission.
Bibliography

Appendix A: Primitive Polynomials

Table 1 list of primitive polynomials

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Appendix B: Abbreviations

AWGN – Additive White Gaussian Noise
BER – Bit Error Rate
BPF – Bandpass Filter
CPFSK – Continuous Phase Frequency Shift Keying
DAC – Digital to Analog Converter
DMD – Double Mix Divide
DSSS – Direct Sequence Spread Spectrum
FH – Frequency Hopped
FHSS – Frequency Hopping Spread Spectrum
FFH – Fast Frequency Hopping
FM – Frequency Modulation
FSK – Frequency Shift Keying
GFSK – Gaussian Frequency Shift Keying
IEEE – Institute of Electrical and Electronics Engineers
ISM – Industrial Scientific Medical band
LFSR – Linear Feedback Shift Register
LPF – Lowpass Filter
MFSK – Multiple Frequency Shift Keying
MSK – Minimum Shift Keying
PN – Pseudo noise
RSSI – Received Signal Strength Indicator
SFH – Slow Frequency Hopping
SR – Stored Reference
TR – Transmitted reference
VCC – Voltage Controlled Clock
WLAN – Wireless Local Access Network