KASAMI SEQUENCES FOR SPREAD SPECTRUM COMMUNICATIONS

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DEDICATION

For my muse, Syrope.

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ABSTRACT

Until the '80s, spread spectrum (SS) communications was only heard of as a technology used by the military to transmit signals with low probability of intercept. Then, the Federal Communications Commission (FCC) opened the Industrial, Scientific and Military (ISM) band for unlicensed operation of spread spectrum devices. From then onwards, spread spectrum technology became the prime topic of interest among commercial opportunists as well as communication experts, who foresaw its potential of developing into a new commercial niche. Within a short period of time, commercial spread spectrum applications began to take shape in the field of digital cellular telephone communications, multiple access satellite communications etc. The popularity of spread spectrum technology is mainly due to its capability to relieve spectrum congestion faced by conventional narrowband and wideband communication systems. Many believe that spread spectrum technology could be the ultimate solution to the problems faced by limited bandwidth. In terms of security, spread spectrum's ability to resist jamming is due to the use of a spreading code to spread its bandwidth. The spreading code is a pseudonoise (PN) sequence, which also acts as a characteristic element to differentiate the users in multi-access systems. A study on PN sequences is carried out to gain an understanding of the desirable properties required in spread spectrum applications. It is found that PN sequences with sharp autocorrelation peaks and low crosscorrelation values are most suitable for various SS applications. A family of PN sequences satisfying this set of requirements is the Kasami sequences discovered by T. Kasami in the '60s. An in-depth

investigation of the Kasami sequence is presented in this thesis. Following that, a software known as the *Kasami Code Generator*, is developed to generate the family of Kasami sequences. The program also calculates the correlation values of the sequences and displays its respective distribution. In practice, the Kasami sequences are generated by a linear feedback shift register (LFSR). To inspect an example of this implementation, a four-stage LFSR is constructed to generate the family of binary Kasami sequences.

ABSTRAK

Sehingga tahun 80-an, komunikasi secara sebaran spektrum (spread spectrum communications) hanya dikenali sebagai suatu teknologi yang digunakan dalam bidang ketenteraan untuk menghantar isyarat yang sukar disekat. Kemudian, Suruhanjaya Komunikasi Persekutuan mengisytiharkan lingkaran Industri, Saintifik dan Ketenteraan (Industrial, Scientific and Military band) untuk penggunaan pengantar sebaran spektrum tanpa lesen. Selepas itu, teknologi sebaran spektrum menjadi topik hangat di antara ahli komersil dan pakar komunikasi, yang sedar bahawa teknologi ini berpotensi untuk berkembang menjadi suatu bidang komersil yang baru. Dalam tempoh yang singkat, aplikasi komersil teknologi sebaran spektrum telah mula digunakan dalam sistem komunikasi telefon bersel digital, komunikasi satelit dan sebagainya. Kepopularan teknologi ini disebabkan terutamanya oleh kebolehannya untuk mengurangkan masalah kesesakan spektrum yang dihadapi oleh sistem komunikasi jalur sempit dan jalur lebar. Kebanyakan orang percaya bahawa teknologi ini merupakan penyelesaian yang unggul kepada masalah kesempitan jalur. Dari aspek sekuriti, kebolehan sebaran spektrum untuk menentang sekatan luar disebabkan oleh penggunaan suatu kod sebaran untuk mengembangkan kelebaran jalur spektrum. Kod sebaran ini merupakan suatu kod turutan yang bersifat rawak tiruan (pseudorandom). Ia juga memainkan peranan sebagai elemen yang membezakan pengguna-pengguna dalam sistem berbilang perhubungan (multi-access systems). Suatu kajian tentang kod turutan rawak tiruan dijalankan untuk memahami sifat-sifat kod yang diperlukan untuk aplikasi

sebaran spektrum. Didapati bahawa kod turutan rawak tiruan yang mempunyai nilai puncak autokorelasi yang tinggi dan nilai korelasi-tentangan yang rendah adalah sesuai untuk pelbagai aplikasi sebaran spektrum. Suatu keluarga kod turutan rawak tiruan yang mempunyai sifat-sifat tersebut ialah kod turutan Kasami yang ditemui oleh T. Kasami sekitar tahun 60-an. Suatu kajian yang mendalam tentang turutan Kasami dibentangkan dalam tesis ini. Seterusnya, suatu perisian komputer yang dikenali sebagai *Kasami Code Generator*, dihasilkan untuk menjanakan kod turutan keluarga Kasami. Program ini juga mengira nilai-nilai korelasi turutan-turutan tersebut dan memaparkan taburan korelasi yang sewajarnya. Secara praktis, kod turutan Kasami dijanakan oleh anjakan simpanan linear dengan suapbalik (linear feedback shift register). Untuk mengkaji implementasi contoh ini, suatu anjakan simpanan linear dengan suapbalik tahap-4 telah dibina untuk menjanakan turutan perduaan keluarga Kasami.

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CHAPTER 1

INTRODUCTION TO SPREAD SPECTRUM

1.1 A Brief Overview

Over the last decade, a new commercial market opportunity founded on the principles of *spread spectrum* has been emerging in the field of communications. Once only heard of in the military, this technology is currently gaining popularity in various commercial applications including digital cellular mobile communications, multi-access satellite systems, packet radio networks etc.

What is spread spectrum? Spread spectrum is defined as a digital communications technology, which allows multiple users to share similar radio frequencies simultaneously without interfering with one another. It does that by deliberately occupying more channel bandwidth than the minimum required for narrowband data transfer.

The rationale behind the extra bandwidth requirement is to gain an improvement in the signal-to-noise (S/N) performance of the communications system. In other words, spread spectrum describes a modulation technique that sacrifices the bandwidth in order to gain signal-to-noise (S/N) performance.

Spread Spectrum can also be defined as a communication technique that spreads a signal bandwidth over a wide range of frequencies for transmission and then despreads it to the original data bandwidth at the receiver.

Sklar [1] states that:

A system is defined to be a spread spectrum system if it fulfills the following requirements:

1. The signal occupies a bandwidth much in excess of the minimum bandwidth necessary to send the information.
2. Spreading is accomplished by means of a spreading signal, which is independent of the information signal.
3. At the receiver, despreading (recovering the original data) is accomplished by correlating the received spread signal with a synchronized replica of the spreading signal used to spread the information.

The question now is why choose spread spectrum over conventional modulation techniques?

Before spread spectrum was introduced, conventional communications systems used modulation techniques, which did not allow effective use of the frequency spectrum. With frequency spectrum being a limited resource, bandwidth inefficiency posed a serious problem to telecommunications operators. To make matters worse, the last few years saw an unprecedented increase of commercial frequency utilization - so great that the capacity of the existing frequency spectrum was said to be reaching its limits.

One other limitation of conventional communications techniques was the tedious care and planning required for sharing and allocating the bandwidth among users. Other problems associated with conventional technologies included in-band interference, multipath and low security. Spread spectrum possesses the capabilities to overcome these problems and more. A spread spectrum communications system boasts of high security, efficient spectrum utilization, immunity to interference and resistance to multipath. On top of that, data rates and network capacities also improved.

Currently, spread spectrum technologies are being researched and developed to extend their usage to various other digital communications fields. Some of the potential applications include wireless Local Area Networks (LANs), Very Small Aperture Terminal (VSAT) networks, wireless Point-of-Sales (POS) applications (i.e. integrated bar code scanner, cash registers), palmtop computers, radio modem devices, alarm systems etc.

This paper places emphasis on the wireless applications of spread spectrum. It should be noted however, that numerous wire applications such as multi-user multimedia applications on cable network could also benefit from this technology.

1.2 History of Spread Spectrum Communications

The advent of spread spectrum technology came about as a need to tackle problems faced by the military to defeat the enemy in World War II. At that time, the trend was moving towards using radio waves over wire to control military weapons (i.e. torpedoes and missiles) - the limitation of wire being its difficulty in providing a feasible physical communication between the commander and the weapon. Radio waves solved the problem of needing a physical communication connection. However, one of the most serious flaws of radio waves was that it could easily be accessed and thus, jammed by enemies. Therefore, a communications system with anti-jamming properties and low probability of intercept was required.

The earliest form of spread spectrum technology was invented by Hedy Lamarr and George Antheil during World War II. Both were prominent figures in society during their times, but neither in the field of communication science. Lamarr was a celebrated Hollywood actress while Antheil was a forerunner in experimental music.

Lamarr came up with the idea of a Secret Communications System, which would be able to guide torpedoes to their target without being intercepted by the enemy. The plan was to build a radio-control system whereby the transmitted carrier frequency would jump about in a prearranged and randomized manner. The message would move so quickly across the radio waves that anyone tuning in to a particular frequency would only hear a blip, and so would be unable to intercept the message. To help solve the problem of synchronizing the transmitter and receiver as they moved through the frequencies, Lamarr sought Antheil's expertise. Antheil managed to solve the problem by using paper rolls perforated with a pseudorandom pattern to describe the frequency path. The transmitter (base station) and receiver (torpedo) would be installed with two rolls of the same pattern.

Lamarr and Antheil's joint invention seemed to be a sure-win technique to defeat the enemy. It was also well within the manufacturing capabilities of that time. The Navy however, refused to take the Secret Communications System seriously - questioning the reliability and feasibility of the invention. In the end, the Secret Communications System was never used during World War II. However, the foundation principles set by Lamarr and Antheil went on to become the basis of the revolutionary spread spectrum communications system.

Nevertheless, the works of Lamarr and Antheil did not go to waste. In the 1940s, the civilian mobile radio application using the Lamarr-Antheil technique was proposed in theory, but the practical implementation did not take place due to many technical obstacles. When electronic technologies began to develop around 1950s, engineers from Sylvania Electronic Systems Division revived the Secret Communications System project, this time, replacing the paper rolls with digital components. The successful implementation of the technology was proven when an electronic spread spectrum system that handled secure communications for the United States during the Cuban Missile Crisis in 1962 was developed.

Around the same time, the term "spread spectrum" was introduced. In SS terminology, Lamarr and Antheil's spread spectrum technique is now known as frequency hopping.

In the 1970s, the Global Positioning Satellite (GPS) system was launched using spread spectrum modulation techniques. It is now the world's largest single spread spectrum system. However, commercial usage of spread spectrum was still hardly heard of. Then, in 1983, the United States military declassified the spread spectrum technology, and within a short period of time, spread spectrum for consumer use became the prime topic of interest for commercial opportunists as well as communications experts.

The Federal Communications Commission (FCC) opened the Industrial, Scientific and Military (ISM) band for liberal unlicensed operation of spread spectrum devices. The FCC permits spread spectrum modulation at a maximum transmitter power of 1 W in three bands – 902-928 MHz, 2400-2483.5 MHz and 5725-5850 MHz based on a set of regulations designed to minimize interference and encourage inter-operability [2].

An important platform founded on the principles of spread spectrum technology is the Code Division Multiple Access or in short, CDMA (refer to Section 2.4). Proposed by Qualcomm Corporation for digital cellular phone applications, CDMA suffered initial dismissal by Time Division Multiple Access (TDMA) supporters who regarded CDMA as a technology that only worked in theory. Researches at Qualcomm went ahead to pursue the technology and finally, in 1991, the TDMA supporters were proven wrong when the first field trials of CDMA implementation delivered promising results. A year later, CDMA was officially accepted as a digital cellular technology by the Telecommunications Industry Association (TIA) and the American National Standards Institutions (ANSI).

The first commercial CDMA service was launched in Hong Kong in 1995, followed by a launch in Korea and then in Pennsylvania. Major telecommunications corporations in the United States have also been staking their claims in the future CDMA market. Today, 11 of the top 14 cellular carriers and 10 of the top 17 Personal Communications Systems (PCS) carriers in the United States have selected CDMA as their technology platform for their new digital networks [3].

1.3 Thesis Outline

Chapter One introduces spread spectrum systems to the reader by giving a brief overview of the topic. A historical profile of spread spectrum communications systems is also presented. Special emphasis is given to the founders of spread spectrum, Hedy Lamarr and George Antheil.

Having a general idea of spread spectrum, Chapter Two moves on to provide a more detailed approach to this field of study. Topics covered in Chapter Two include the fundamentals of spread spectrum, various spread spectrum techniques (i.e. direct sequence, frequency hopping, time hopping etc.) and the attributes of spread spectrum. Chapter Two closes with a section on Code Division Multiple Access, which is an important application of spread spectrum.

Chapter Three covers a study of the pseudonoise (PN) sequences, which are used as spreading signals as well as distinguishing elements in spread spectrum multi-access systems. The properties of ideal pseudorandom sequences and the desirable characteristics of pseudorandom sequences for spread spectrum systems are examined here. The last section of this chapter discusses the generation of PN sequences.

Chapter Three is a preamble to Chapter Four, which investigates Kasami sequences for spread spectrum communications system. Kasami sequences is a family of pseudonoise sequences. Some relevant finite field mathematics is introduced in this chapter before proceeding on with the details of the study. The main concerns of this chapter are the definition, the properties and the generation of Kasami sequences.

Finally, Chapter 5 concludes with a summary of the thesis and recommendations for future research.

CHAPTER 2

SPREAD SPECTRUM SYSTEMS

2.1 Fundamentals of Spread Spectrum Systems

In the simplest sense, a *spread spectrum system* can be literally translated as a communications *system*, which *spreads* its bandwidth or *spectrum* to transmit data.

A spread spectrum system can be easily distinguished from other communications systems by its *spreading* phenomena. The term *spreading* refers to the expansion of the signal bandwidth beyond what is required to transmit data in standard narrowband transmissions. In other words, the transmitted data bandwidth is much wider than the information signal bandwidth (i.e. baseband). Refer to Figure 1.

The process of spreading the transmitted signal bandwidth is performed to gain signal-to-noise (S/N) performance. This is possible because the spreading process increases the probability that the received information will be correct since each signal is comprised of a principal signal at the fundamental frequency and many other smaller signals at its harmonics. Hence, a more accurate reconstruction of the original signal can be obtained.

One measure of system performance is the bandwidth expansion factor. It is known as the **processing gain** of the system and can also be defined as the ratio of spreading bandwidth to base bandwidth (refer to Figure 1). The processing gain describes the received signal fidelity gained at the expense of the bandwidth.

To demonstrate an example of the degree of spreading, a system transmitting data at a rate D of 100 Mbps using approximately 100 MHz of bandwidth W, is not spread at all (i.e. $W/D = 1$). On the contrary, a system transmitting at a rate D' of 100 bps over a spectrum W' of 100 MHz, has a factor $W'/D' = 10^6$ of 60dB.

Processing gain of 10 to 100 are common for commercial systems while for military systems, the value can be as huge as 1,000,000.

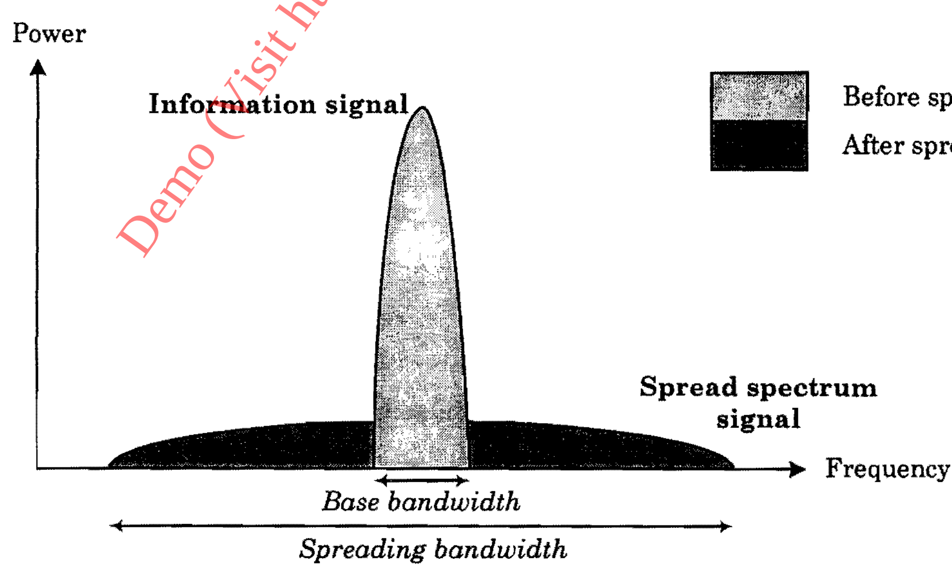

Figure 1: Bandwidth Spreading of Spread Spectrum System

Referring to Figure 1, if the total signal power is represented by the area under the spectral density curve, then, signals with equivalent total power may either have a high signal power concentrated in a narrow bandwidth or a low signal power spread over a wide bandwidth. Therefore, although spread spectrum systems transmit a total power equivalent to narrowband systems, the spectral power density of the former is much lower than the latter.

Spread spectrum systems are usually used in channels with poor signal-to-noise ratio (S/N) i.e. the average power of noise N and interference I are much larger than that of a desired signal S. For these systems, the signal-to-noise and interference ratio ($S/N+I$) is often less than –20dB. In such bad channel conditions, it is important that the processing gain of the system be sufficiently large so that the stream of chips of the transmitted signals can be recognized through a process known as correlation detection. The processing gain, in this case, represents the capability to suppress noise as well as interference.

The capacity of any communications channel is given by Claude E. Shannon's information rate theorem:

$$C = W \log_2 (1 + \frac{S}{N}) \qquad (2.1)$$

where C = Channel capacity (bps)

W = Bandwidth (Hz)

S = Signal Power (W)

N = Noise Power (W)