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CAPACITY ESTIMATION
FOR WIRELESS SPREAD-SPECTRUM
ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (SS-OFDM)

By

WAN FARAHIYAH BINTI WAN ZAKARIA

FINAL PROJECT REPORT

Submitted to the Electrical & Electronic Engineering Programme
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CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

June 2006

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Wan Farahiyah binti Wan Zakaria

ABSTRACT

OFDM is a modulation and multiple access technique that has been a centre of attention in these recent years. Since its development for military application in the 1960s, technical implementations of OFDM have appeared in digital audio broadcasting, asymmetric digital subscriber lines (ADSL), high speed definition television terrestrial broadcasting, and other systems. Because of its capabilities, OFDM becomes a potential candidate as a multiple access technique for beyond 3G mobile technology. This project presents a study on OFDM performance for wireless mobile environment. Spread-spectrum is employed in combination with OFDM. This project paper presents a simulation of spread-spectrum OFDM using MATLAB and capacity estimation of the simulated environment in wireless channel. The results of the simulation are then compared with the theoretical capacity values of available 3G systems.

ACKNOWLEDGEMENTS

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Last but not least, my family and friends, who gave me tremendous support and shoulders to cry on.

Thank you very much.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

3G	3rd Generation cellular systems
3GPP	Third-Generation Partnership Project
3GPP2	Third-Generation Partnership Project 2
4G	4th Generation cellular systems
BPSK	Binary Phase Shift Keying
C/I	Carrier over Interference Ratio
CDMA	Code Division Multiple Access
DS-SS	Direct-Sequence Spread Spectrum
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FH-SS	Frequency-Hopping Spread Spectrum
IFFT	Inverse Fast Fourier Transform
ISI	Inter-Symbol Interference
LAN	Local Area Network
MAN	Metropolitan Area Network
OFDM	Orthogonal Frequency Division Multiplexing
QAM	Quadrature Amplitude Modulation
QPSK	Quaternary Phase Shift Keying
SS-OFDM	Spread-Spectrum Orthogonal Frequency Division Multiplexing
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access (or W-CDMA)

CHAPTER 1
INTRODUCTION

1.1 Background

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation and multiple access technique that has been explored for over 20 years. Only recently it has been finding its way into commercial communications systems such as digital subscriber line (DSL), TV and radio broadcast applications, fixed wireless systems and wireless Local Area Network (WLAN) products.

With the implementation of OFDM, wireless standards like IEEE 802.11a and 802.11g are moving the real-world WLAN speed limit to 50 Mbps and beyond [1]. Vendors working with OFDM have developed their own strategies to take leverage the technology. As a result, a number of hybrid OFDM systems have been produced, which are obtained by combining conventional OFDM with other technique. For example, Flarion Technologies, Inc. employs spread-spectrum altogether with OFDM in its Flash-OFDM™ model [2]. Other hybrid systems combine OFDM with advanced radio techniques such as Multiple-Input Multiple-Output OFDM (MIMO-OFDM) and adaptive antenna systems [3].

The principal driving force behind OFDM's increased popularity is the desire for faster wireless technologies and the increase in multimedia applications, which require higher speeds [4].

Looking through the future prospect of OFDM, it is likely that OFDM becomes the favorite multiple and modulation technique for beyond 3G technology. This project therefore is carried out in order to obtain the estimated capacity for wireless channel by using OFDM technique, which will hopefully contribute to the future development of beyond 3G wireless system.

This project explores the capabilities of OFDM as a potential candidate for the next generation communication standard. This project paper consists of three main chapters; Chapter 2 for Literature Review, Chapter Three for Methodology and Project Work, and Chapter 4 for Results and Discussions. In Chapter 2, the main concept of OFDM is discussed in details. Spread-spectrum and Shannon-Hartley Capacity Theorem is also included in this chapter. In Chapter 3, the detail method of producing OFDM system is further discussed. There is also description of software and tools used for SS-OFDM model and simulation. Finally, analysis of results and discussion is included in Chapter 4.

1.2 Problem Statement

High data rate, wireless access for mobile users is an undisputed goal of telecommunications. Many current efforts concentrate on the technologies, protocols, systems, and even programming languages that will develop broadband wireless capability.

Current employment of CDMA technique for 3G mobile communications does have its limitations, even though it has its merits. The requirement of CDMA technique such as tight power control, careful selection of pseudo-noise codes, time synchronization and inefficient use of radio resource leads to consideration of other potential multiple access technique for the next generation mobile technology. Therefore, this study proposes the use of OFDM combined with spread-spectrum in order to achieve higher capacity compared to CDMA.

1.3 Objective and Scope of Study

The objectives of this project are as follow:

- To simulate SS-OFDM model in MATLAB Simulink;
- To provide an estimation of the capacity experienced by mobile users with the employment of SS-OFDM in mobile environment;
- To compare the estimated SS-OFDM capacity with theoretical values of CDMA for 3G.

The scopes of study covered are:

- Identification of simulation software (MATLAB) and tools (MATLAB Communications Toolbox and Blockset);
- Study on OFDM and spread-spectrum concept;
- Developing the SS-OFDM model using MATLAB Simulink and MATLAB Communications Blockset;
- Testing and troubleshooting SS-OFDM system;
- Estimating SS-OFDM capacity by using Shannon Capacity equation.

CHAPTER 2
LITERATURE REVIEW

2.1 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a special form of multicarrier modulation (MCM), where a single data stream is transmitted over a number of lower rate subcarriers [5]. OFDM can also be seen as either a modulation technique or a multiplexing technique.

2.1.1 Comparison with FDMA

As a multiple access technique, OFDM is similar to Frequency Division Multiple Access (FDMA) because the available bandwidth is subdivided into multiple frequency channels, which are then allocated to multiple users [5]. However, in conventional FDMA, there must be guard bands between the channels to avoid interference between the channels. The exact bandwidth used for data is less than the allocated bandwidth [6]. In a typical system, up to 50% of the total spectrum is wasted due to the extra spacing between channels [7].

OFDM prevents this waste by using multicarriers to transmit data. OFDM splits the available bandwidth into many narrowband channels (typically 100-8000 Hz) [7]. The carriers for each channel are made orthogonal to one another, allowing them to be spaced very close together.

The orthogonality of the carriers means that each carrier has an integer number of cycles over a symbol period. Due to this, the spectrum of each carrier has a null at the centre frequency of each of the other carriers in the system. Therefore, there is virtually no interference between the carriers, allowing them to be spaced as close as theoretically possible. Note that compared to the conventional FDMA technique (Figure 1), OFDM bandwidth is more efficiently used due to its orthogonality nature (Figure 2).

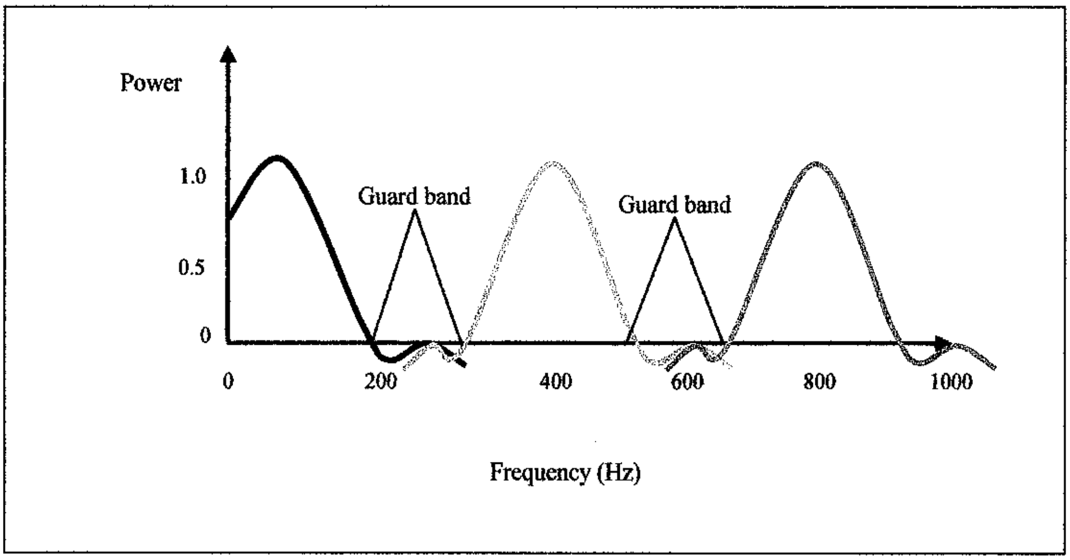


Figure 1 Nature of FDMA

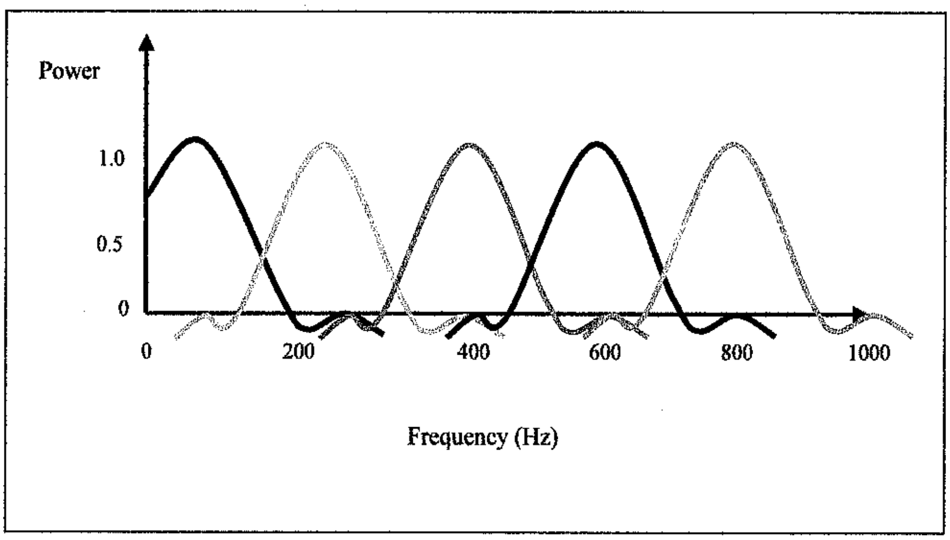


Figure 2 The orthogonal nature of OFDM efficient use of bandwidth

Each carrier in an OFDM signal has a very narrow bandwidth (i.e. 1 kHz), thus the resulting symbol rate is low. This results in the signal having a high tolerance to multipath delay spread, as the delay spread must be very long to cause significant inter-symbol interference (e.g. > 500μs) [7].

Another important feature of OFDM is its robustness against inter-symbol interference (ISI). By adding cyclic extension (guard interval), error correction is performed without requiring complex error correction [4].

2.1.2 *Mathematical Description of OFDM Signal*

The low-pass equivalent OFDM signal is expressed as [6]

$$\nu(t) = \sum_{k=0}^{N-1} I_k e^{i2\pi kt/T}, \quad 0 \leq t < T,$$

Equation 1 Low Pass OFDM Signal

where $\{I_k\}$ are the data symbols, N is the number of subcarriers, and T is the OFDM block time. The subcarriers spacing of $1 / T$ Hz makes the subcarriers orthogonal; this property is expressed as [6]

$$\frac{1}{T}\int_0^T \left(e^{i2\pi k_1 t/T}\right)^* \left(e^{i2\pi k_2 t/T}\right) dt = \frac{1}{T}\int_0^T e^{i2\pi(k_2-k_1)t/T} dt = \begin{cases} 1, & k_1 = k_2, \\ 0, & k_1 \neq k_2, \end{cases}$$

Equation 2 Orthogonal property of OFDM subcarriers

where (.)* denotes the complex conjugate operator.

To avoid intersymbol interference in multipath fading channels, a guard interval, $T_g \leq t \leq 0$ where T_g is the guard period, is inserted prior to the OFDM block [6]. During this interval, a *cyclic prefix* is transmitted. The cyclic prefix is equal to the last T_g of the OFDM block. The OFDM signal with cyclic prefix is thus [6]:

$$\nu(t) = \sum_{k=0}^{N-1} I_k e^{i2\pi kt/T}, \quad -T_g \leq t < T.$$

Equation 3 OFDM Signal with addition of guard period

The low-pass signal above can be either real or complex-valued. Real-valued low-pass equivalent signals are typically transmitted at baseband - wireline applications such as DSL use this approach [6]. For wireless applications, the low-pass signal is typically complex-valued; in which case, the transmitted signal is up-converted to a carrier frequency f_c. In general, the transmitted signal can be represented as [6]

$$s(t) = \Re\left\{\nu(t)e^{i2\pi f_c t}\right\}.$$

Equation 4 Real-valued OFDM Signal

For wireless application, the transmitted signal is represented by [6]

$$s(t) = \sum_{k=0}^{N-1} |I_k| \cos\left(2\pi[f_c + k/T]t + \arg[I_k]\right).$$

Equation 5 Complex-valued OFDM Signal

2.1.3 Advantages and disadvantages of OFDM system

The OFDM transmission scheme has the following advantages [8]:

- OFDM is an efficient way to deal with multipath effects. This is because the symbol duration increases in the case of a low rate multicarrier transmission compared to a single carrier system. Due to this reason, for a given delay spread, an equalizer is not required in an OFDM system, which significantly decreases the implementation complexity in the receiver.
- In a slow flat fading channel, it is possible to increase the spectral efficiency by adapting the data rate per sub carrier according to the signal-to-noise ratio (SNR) of each channel.

On the other hand, there also exist several drawbacks in OFDM transmission [8]:

- OFDM is more sensitive to frequency and phase noise compared to a single carrier modulation.
- OFDM has a relatively large peak-to-average power ratio, which tends to reduce the power efficiency of the RF amplifier.

2.2 OFDM Generation

To generate OFDM successfully, the relationship between all carriers must be carefully controlled to maintain the orthogonality of the carriers. For this reason, OFDM is generated by firstly selecting the spectrum required. The selection is based on the input data and the modulation scheme to be used (typically differential BPSK, QPSK, or QAM). Each subcarrier will be assigned one baseband symbol to transmit, whose amplitude and phase is calculated according to different modulation schemes, typically Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM). After allocating transmitted baseband symbols in the proper frequency band, Inverse Fast Fourier Transform (IFFT) will be performed in order to form the time domain signal. After transmitting the signal through the channel, the FFT transforms the received time domain signal back into its equivalent frequency correspondence at the receiver side.

The FFT transforms a cyclic time domain signal into its equivalent frequency spectrum by finding the equivalent waveform, generated by a sum of orthogonal sinusoidal components. The amplitude and phase of the sinusoidal components represent the frequency spectrum of the time domain signal. The IFFT performs the reverse process, transforming a spectrum (amplitude and phase of each component) into a time domain signal. An IFFT converts a number of complex data points, of length that is a power of 2, into the time domain signal of the same number of points. Each data point in frequency spectrum used for an FFT or IFFT is called a bin.

The orthogonal carriers required for the OFDM signal can be generated by setting the amplitude and phase of each bin, then performing the IFFT. Since each bin of an IFFT corresponds to the amplitude and phase of a set of orthogonal sinusoids, the reverse process guarantees that the carriers generated are orthogonal.

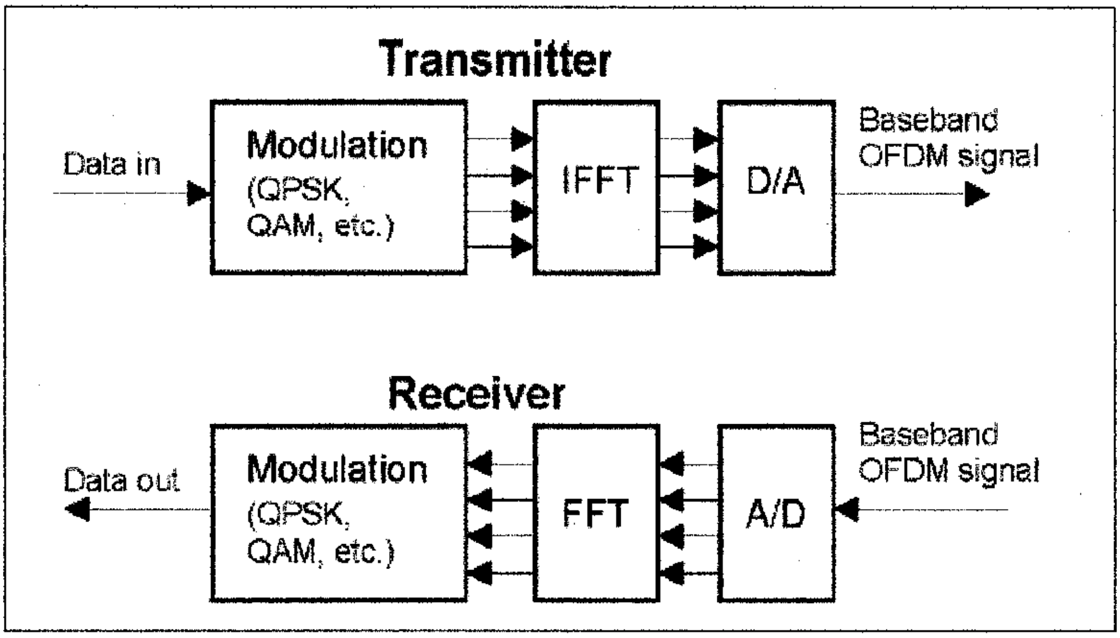


Figure 3 Basic FFT, OFDM transceiver

The figure here above shows the setup for a basic OFDM transmitter and receiver. The signal generated is a baseband, thus the signal is filtered, then stepped up in frequency before transmitting the signal.

2.2.1 Guard Period

One of advantages using OFDM is its robustness against multipath delay spread. Multipath delay can generate two effects, frequency-selective fading and ISI. Having a long symbol period can minimize ISI. Thus, there is no need for an equalizer in the receiver. This is achieved by applying guard period. The guard period allows time from multipath signals from the previous symbol to die away before the information from the current symbol is gathered. The most effective guard period to use is a cyclic extension of the symbol [7].

Cyclic extension helps to maintain the orthogonality among all the sub carriers by having integer number of cycles within the FFT interval of each OFDM symbols, as long as the delay is shorter than the guard time. Thus, the cross talk between different sub carriers is eliminated, which means that there is no Inter Carrier Interference (ICI) occurring. Figure 4 shows two different ways of adding a cyclic extension. In Figure 4 (a), the cyclic prefix is a copy of the last part of the OFDM symbol; in Figure 4 (b), both cyclic prefix and cyclic postfix are considered, which are the last part and the first part of an OFDM symbol separately. The latter case is more practical when a raised cosine window is added after cyclic extension.

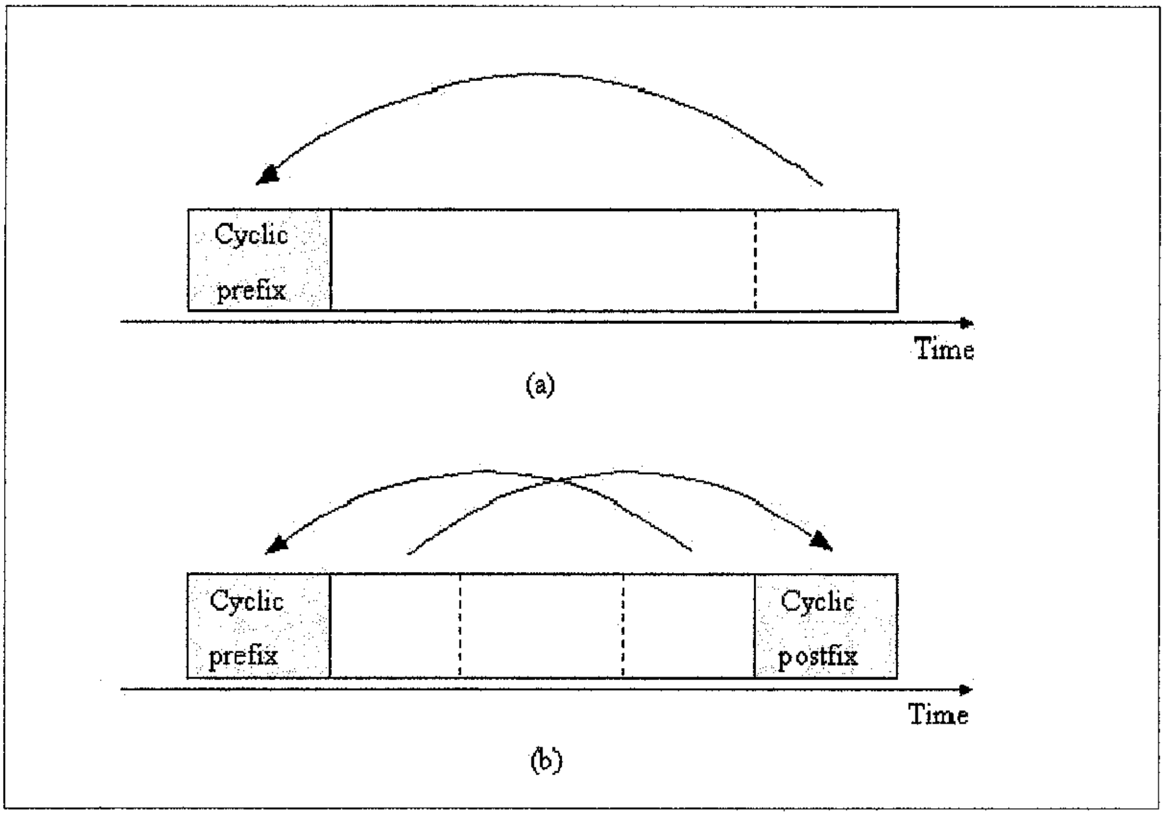


Figure 4 Examples of adding cyclic extension

2.3 OFDM Model

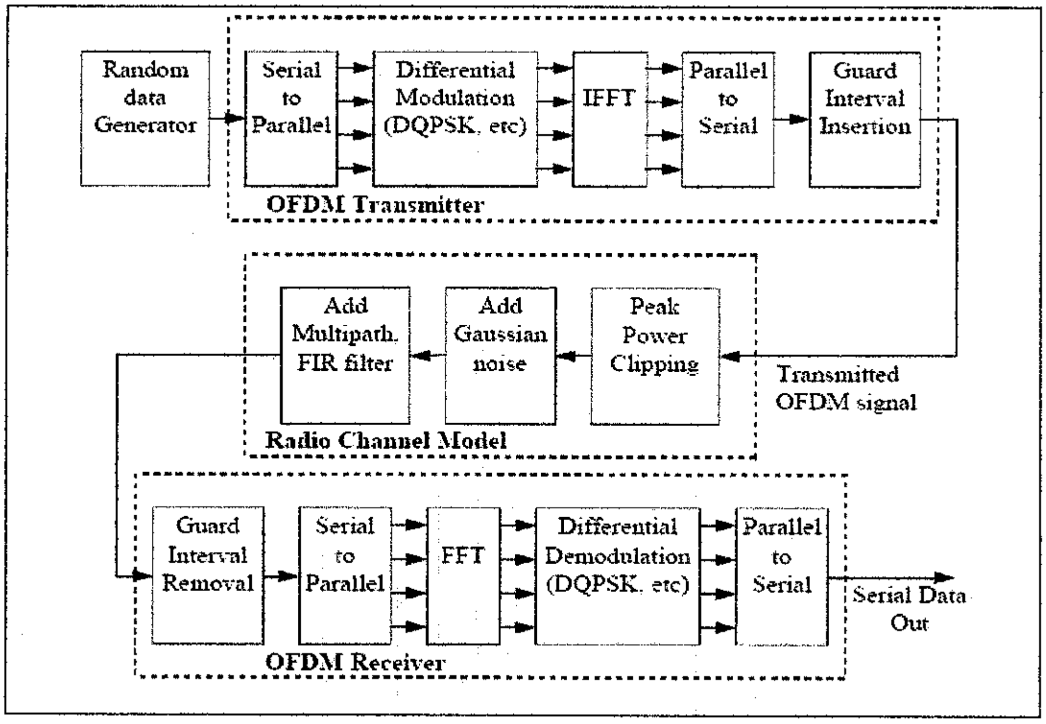


Figure 5 OFDM model for transmitter and receiver

2.3.1 Serial to Parallel Conversion

For transmission, the input serial data stream is formatted into the word size required e.g. 2 bit-per-word for QPSK, and shifted into a parallel format. The data is then transmitted in parallel by assigning each data word to one carrier in the transmission.

2.3.2 Modulation of Data

The data to be transmitted on each carrier is then differential encoded with previous symbols, then mapped into a phase shift keying format. Since differential encoding requires an initial phase reference an extra symbol is added at the start for this purpose. The data on each symbol is then mapped to a phase angle based on the modulation method. For example QPSK the phase angles used are 0°, 90°, 180°, and 270°. Phase shift keying was used to produce a constant amplitude signal and chosen for its simplicity and to reduce problems with amplitude fluctuations due to fading.

2.3.3 Inverse Fourier Transform

After the required spectrum is found, IFFT is used to find the corresponding time waveform. The guard period is then added to the start of each symbol.

2.3.4 Guard Period

The guard period used was made up of two sections. Half of the guard period time is a zero amplitude transmission. The other half of the guard period is a cyclic extension of the symbol to be transmitted. This was to allow for symbol timing to be easily recovered by envelope detection. However it was found that it was not required in any of the simulations as the timing could be accurately determined position of the samples.

After the guard has been added, the symbols are then converted back to a serial time waveform. This is then the base band signal for the OFDM transmission.

2.3.5 Channel

A channel model is then applied to the transmitted signal. The model allows for the signal to noise ratio, multipath, and peak power clipping to be controlled. The signal to noise ratio is set by adding a known amount of white noise to the transmitted signal. Multipath delay spread then added by simulating the delay spread using a Finite Impulse Response (FIR) filter. The length of the FIR filter represents the maximum delay spread, while the coefficient amplitude represents the reflected signal magnitude.

2.3.6 Receiver

The receiver basically does the reverse operation to the transmitter. The guard period is removed. The FFT of each symbol is then taken to find the original transmitted spectrum. The phase angle of each transmission carrier is then evaluated and converted back to the data word by demodulating the received phase. The data words are then combined back to the same word size as the original data.

2.4 Spread Spectrum Technique

Spread spectrum enables a signal to be transmitted across a frequency band that is much wider than the minimum bandwidth required by the information signal. The transmitter "spreads" the energy, originally concentrated in narrowband, across a number of frequency band channels on a wider electromagnetic spectrum.

A spread spectrum system increases the bandwidth of the incoming data with the aid of this pseudo random noise sequence (PRNS). Although the PRNS is noise like in nature, it is deterministic. The rate of the PRNS is set to be much greater than the data rate, which has the effect of increasing the bandwidth of the data. There are two main types of spread spectrum; frequency hopping and direct sequence. However, the way these systems use the PRNS to spread the data is very different to each other.

2.4.1 Frequency Hopping Spread Spectrum (FH-SS)

This concept involves rapidly changing the carrier frequency used to convey the data. The frequency of the carrier is dependant on a Pseudo Noise (PN) sequence. The process involves first modulating the data (often using M-FSK), before mixing it with the carrier frequency, which is determined by a PN code generator linked to an agile digital frequency synthesizer.

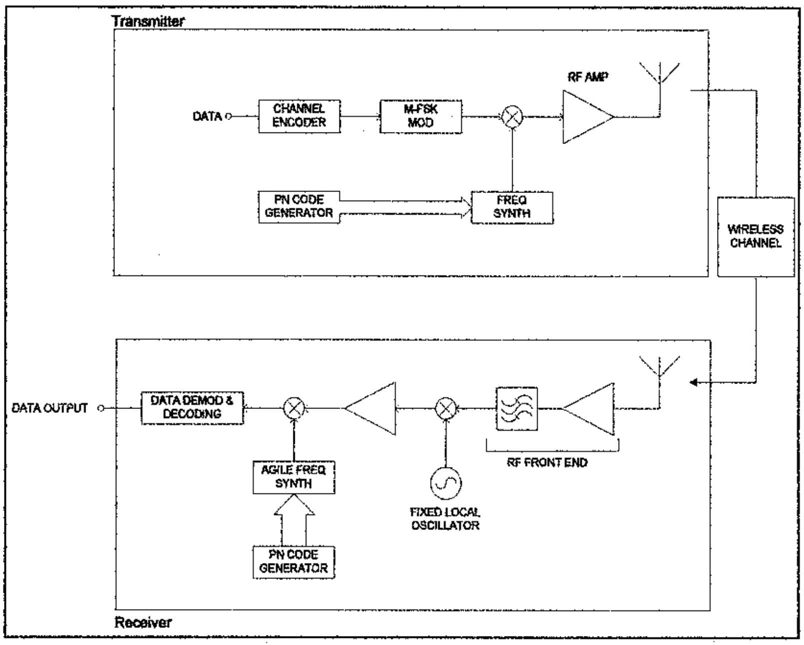


Figure 6 Frequency Hopping Spread Spectrum Transceiver

The output of the FH-SS transmitter is shown in Figure 7. When this output is averaged over a long period, it can be seen to fill all of the frequencies in the chosen frequency band.

One key advantage of the frequency hopping technique is the ability to "program" the PN generator so that the frequency synthesizer avoids specific parts of the RF spectra, if these are being used for other purposes. However, as the frequency synthesizer takes a finite time to hop from one frequency to another, there is a short period where the signal is low and prone to interference. Burst errors can occur which requires advanced channel coding to reduce the errors in the received data.

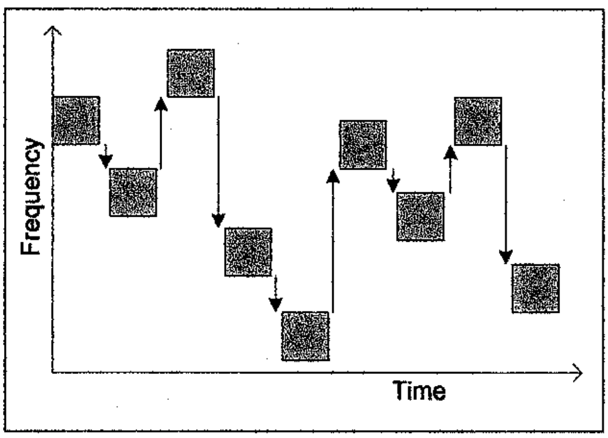


Figure 7 Frequency Spectra Output of a FH-SS Transmitter

2.4.2 Direct Sequence Spread Spectrum (DS-SS)

Unlike FH-SS, DS-SS uses the PRNS to directly modulate the data message. Due to the PN code having a higher rate than the information signal, there will be several chips representing a single information symbol. This adds redundancy to the signal and employs a process gain due to the increase in the signal bandwidth. Together, these help resist interference effects; however high-speed logic circuitry is required which can be expensive.

The high-speed message signal will now have the same bandwidth as the PRNS; hence the message has been 'spread'. Spreading creates a lower power spectral density than the original signal; however the total transmitted power remains the same. This allows the SNR of the signal to be below the noise floor level. This has several advantages for the system, including:

- The signal will be less likely to interfere with other users on the same spectrum
- Other unauthorized users will be unable to detect the signal, as the signal will appear as a slight increase in noise, so adds security to the system.

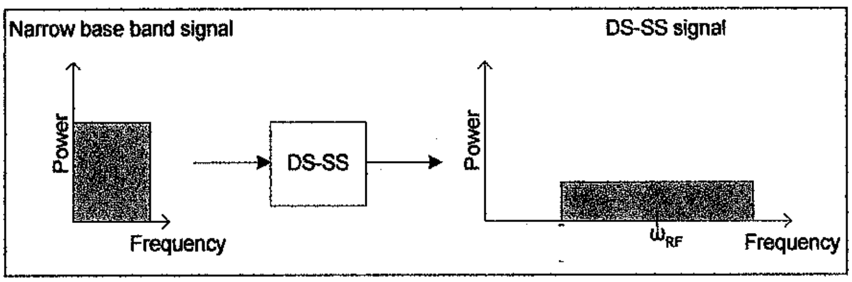


Figure 8 Frequency Spectra Output of a DS-SS Transmitter

Due to the signal being spread over a large bandwidth, there is no way of programming this scheme to avoid certain parts of the RF spectra. This can become a problem if there is a constant interferer in part of the transmitter band i.e. a microwave oven. Another problem is due to DS-SS only using time diversity so if a signal cannot be interpreted, the transmitter waits an arbitrary time before re-transmission. If consistent interference is present, the re-transmitted signal would be undetectable and the receiver would never recover the transmitted signal.

At the receiver, before the signal can be demodulated with a replica PRNS made at the receiver, synchronization is required which will make sure that the replica PRNS is aligned with the receiver PRNS. This is a very important section of the receiver due to effects present in the channel, which will cause phase shift within the received PRNS. Without synchronization, the data message will never be recovered.

2.5 Shannon-Hartley Capacity Theorem

In information theory, the Shannon–Hartley theorem is an application of the noisy channel coding theorem to the case of a continuous-time analogue communications channel subject to Gaussian noise. The result establishes the maximum amount of error-free digital data (that is, information) that can be transmitted over such a communication link with a specified bandwidth in the presence of the noise interference. The Shannon limit or Shannon capacity of a communications channel is the theoretical maximum information transfer rate of the channel [9].

The theorem gives that the theoretical maximum rate of clean (or arbitrarily low bit error rate) data C with a given average signal power that can be sent through an analogue communication channel subject to additive, white, Gaussian-distribution noise interference is [10]:

$$C = B\log_2(1+\frac{S}{N}) = 3.32\log_{10}(1+\frac{S}{N})$$

Equation 6 Shannon Capacity theorem

where

C is the channel capacity in bits per second, net of error correction;

BW is the bandwidth of the channel in Hertz;

S is the total signal power over the bandwidth and

N is the total noise power over the bandwidth.

S/N is the signal-to-noise ratio of the communication signal to the Gaussian noise interference, expressed as a straight power ratio (not as decibels).

2.5.1 Capacity of AWGN Channel

The channel is time-invariant, flat with unit gain h=1, and has AWGN with noise power density $N_0/2$. The channel is AWGN in these four conditions [10]:

- Wired transmission
- Line-of-Sight (LOS) transmission
- Microwave (satellite)
- After fading is mitigated

CHAPTER 3
METHODOLOGY AND PROJECT WORK

3.1 Methodology

The main procedure of completing this project can be divided into six parts:

3.1.1 Literature Review and Information Gathering

- The information regarding spread spectrum and OFDM are gathered by referring to various resources such as books, paper work and the Internet.
- All the gathered information is then selected in order to determine which information has the highest relevancy towards the success of the project.
- The information that has been selected is studied thoroughly in order to obtain the highest understanding possible.
- After gaining sufficient knowledge and information, the project proceeded with the design of SS-OFDM system.

3.1.2 Programming

- To model the system using MATLAB Simulink.
- The programming consists of simulation of SS-OFDM system in AWGN channel.
- The simulation is done with different sets of parameters to obtain different results
- The model needs to be redesigned several times before getting the most reliable system.

3.1.3 Testing and Debugging

This part is carried out after the model has been built in order to check all parameters are properly initialised.

3.1.4 Estimation of SS-OFDM Capacity

After obtaining the required results from simulation, calculation of SS-OFDM capacity is done by using Shannon Capacity equation.

3.1.5 Final Testing and Documentation

The model is tested for the final time in order to check its workability. Project documentation (reports, presentation slide) is done afterwards.

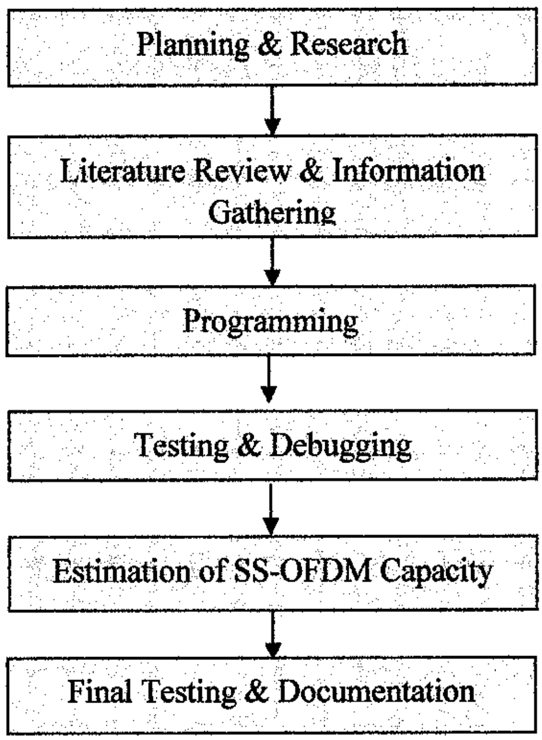


Figure 9 Project Flow

3.2 Simulation Tool

MATLAB Simulink has been used in this project to model the SS-OFDM system. By using Simulink, it is easier to model a communication system because the process of creating one's own program has been cut out. Some of the parameters however, are still written in M-code and the functions are called by the blocksets in Simulink.

3.2.1 MATLAB Simulink

Simulink is a software package for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations.

Models are hierarchical, so users can build models using both top-down and bottom-up approaches. Users can view the system at a high level, and then double-click blocks to go down through the levels to see increasing levels of model detail. This approach provides insight into how a model is organized and how its parts interact [11].

3.2.1.1 MATLAB Communications Blockset

The Communications Blockset extends Simulink with a comprehensive library of blocks to design and simulate the physical layer of communication systems and components. The blockset helps users design communications systems and their semiconductor components, such as commercial or defense wireless and wireline systems [11].

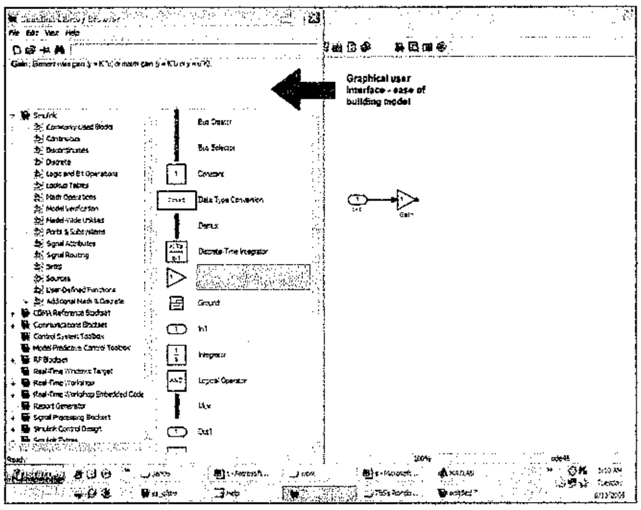
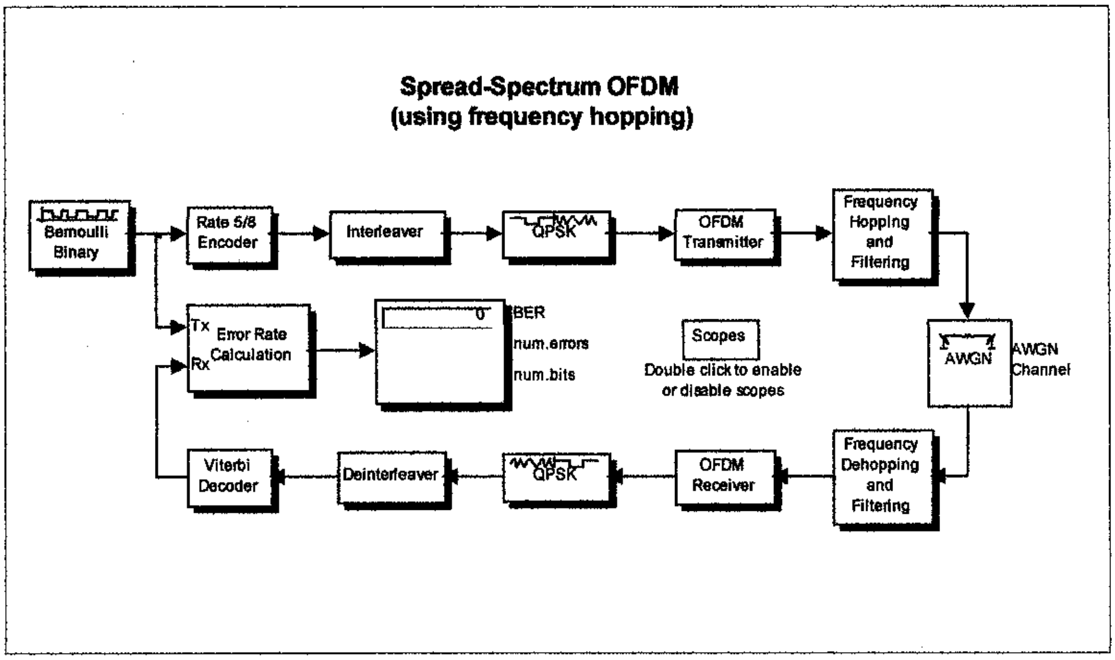


Figure 10 Graphical user interface of Simulink

The key features of the blockset are [11]:

- Blocks for designing and simulating the physical layer of communications systems, including modulation, source and channel encoding, channels, and equalization;
- The ability to tune models and visualize the results;
- Hierarchical, block-based models for visually conveying complex designs;
- Integration with the Communications Toolbox for post-simulation analysis.

3.3 Model Simulation



The model used consists of random binary data generator (Bernoulli Binary Generator), channel encoding and decoding (Encoder-Puncture-Interleaver), signal modulation/demodulation (QPSK), transceiver, frequency hopping/dehopping filter, AWGN channel, error rate calculation, and display.

Table 1 Summary of Communications Blockset Function [12]

Communications Block	**Block Function**
Bernoulli Binary Generator	Generate Bernoulli-distributed random binary numbers
Convolutional Encoder / Viterbi Decoder	Create convolutional code from binary data / Decode convolutionally encoded data using Viterbi algorithm
Interleaver / Deinterleaver	Permutes symbols according to a mapping / Uses the inverse mapping to restore the original sequence of symbols.
QPSK Modulator / Demodulator	Modulate using the quaternary phase shift keying method / Demodulate QPSK-

	modulated data
OFDM Transmitter / Receiver	OFDM transmission / reception system
Frequency Hopping / Dehopping	Changes between assigned carrier frequency / Recovers original signal from hopping frequency
Additive White Gaussian Noise (AWGN) Channel	Add white Gaussian noise to input signal
Error Rate Calculator	Compute bit error rate or symbol error rate of input data

3.3.1 Encoder/Decoder

Data will be transmitted between adjacent rooms; this means that the transmission medium will be noisy because of the interference between signals in addition to multipath fading along the channel. Error detection and correction techniques are required to reduce the bit error rate (BER) and ensure that transmission errors are kept to a minimum. This can be achieved by coding the information bits in such a way that errors occurring during transmission can be easily detected.

For this spread-spectrum OFDM system, Forward Error Correction (FEC) is used; as it has the advantage over error correction and detection by using automatic repeat re-transmission (ARQ) technique, of no return channel or memory requirement at the transmitter. Convolutional encoding combined with Viterbi decoding is used. Convolutional encoders add redundant bits to the original information in such a way that allows the Viterbi decoder to detect and hence correct errors when it occurs.

3.3.2 Convolutional Encoder

The standard convolutional encoder is a ½ rate encoder with the constraint length K = 7 and generating polynomial (177 131) which is an octal representation of the encoder connections. However it was found that by using a 5/8 rate encoder; a large power reduction can be achieved, with only a small effect on the error performance.

3.3.3 Puncturing

Puncturing reduces the amount of data transmitted by omitting some of the bits before transmission. The puncturing vector determines the position of the omitted bits. For example, a puncturing vector of [101110] indicates that the second and last bits are omitted before transmission. At the receiver, zeros are inserted in place of these omitted bits prior to decoding. And thus the puncturing vector has to be known at the receiver. For our system the puncturing vector [110] is used. A bit selector performs the puncturing process, while a bit adder performs the de-puncturing process.

Figure 11 shows an algorithm that can be used for the bit selector that performs the puncturing process.

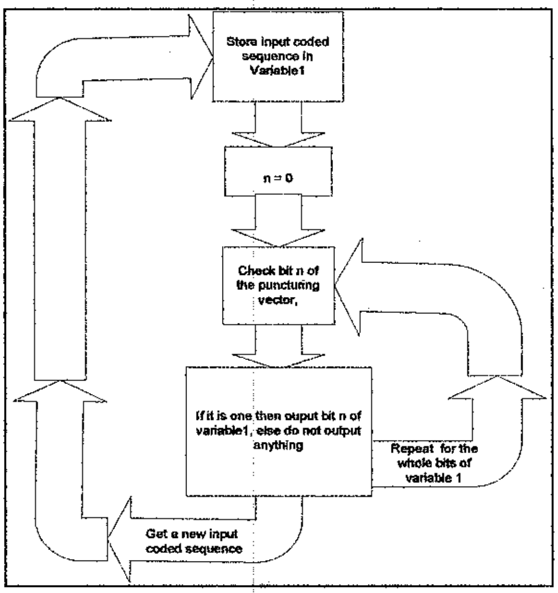


Figure 11 Flowchart of a puncturing algorithm

3.3.4 Convolutional Interleaver/De-interleaver

Interleaving is used as a method to combat burst errors due to multipath fading. The output coded data from the encoder is fed into the interleaver, permuted in such a way that burst errors will be spread out in time and thus can be treated as random errors, and then this permuted data is fed into the channel. In the receiver, the received permutated data is rearranged back into its original order.

For example suppose that we have the following input sequence:

$[A_1\ A_2\ A_3\ A_4\ A_5\ A_6\ A_7\ A_8\ A_9\ A_{10}\ A_{11}\ A_{12}]$

When permutated this sequence will become in the following order:

$[A_1\ A_5\ A_9\ A_2\ A_6\ A_{10}\ A_3\ A_7\ A_{11}\ A_4\ A_8\ A_{12}]$

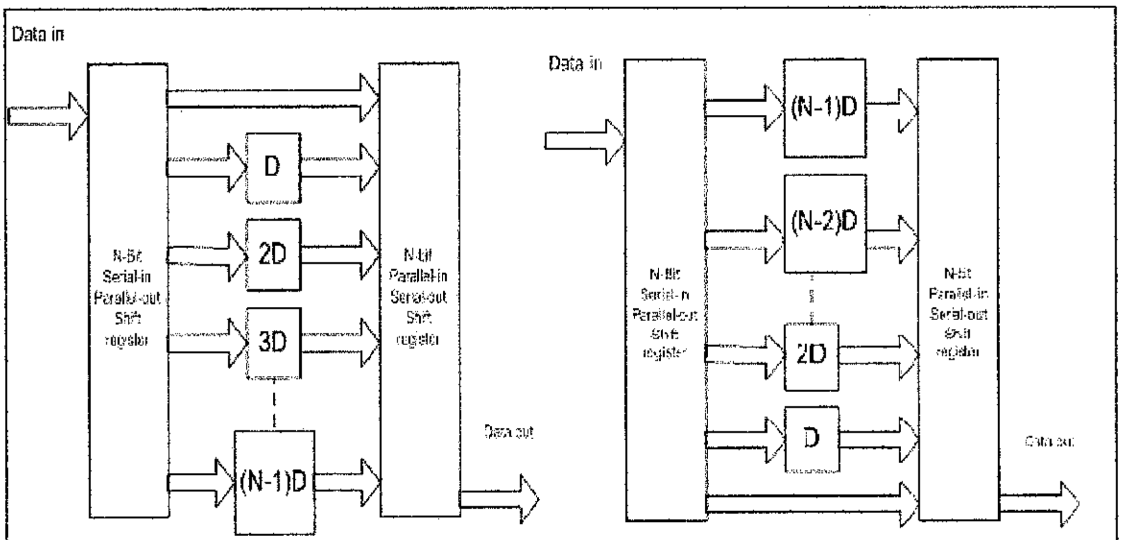
Suppose a burst error occurs in bits $A_2\ A_6\ A_{10}$, and then when the sequence is re-arranged to its original form the errors will be spread out:

$[A_1\quad A_3\ A_4\ A_5\quad A_7\ A_8\ A_9\quad A_{11}\ A_{12}]$

Thus they can now be treated as random errors, and can be easily detected and corrected.

For this system, a convolutional interleaver/de-interleaver is used as it has less memory requirement and better performance than block interleavers. For this type of interleaving, encoded data is fed into a SIPO (Serial In – Parallel Out) shift register of width N bits. The block diagram for the interleaver/de-interleaver is shown in Figure 10.

The first bit that is output form the shift register is fed straight through the interleaver; the second bit is delayed by one delay stage; the third bit is delayed by two delay stages; and so on. Finally the last bit is delayed by N -1 delay stages.



Interleaver at the transmitter

De-interleaver at the receiver

Figure 12 Convolutional Interleaver/de-interleaver

At the receiver, the process is reversed in order for data to be de-interleaved (rearranged) back to its original sequence. Figure 12 shows that the first bit is delayed by (N-1) delay stages; the second bit by (N-2) delay stages; and so on until we reach the last bit which passes straight thought the interleavers without any delays.

3.3.5 Viterbi Decoding

A Viterbi decoder is used to decode convolutional codes. A Viterbi decoder is one that implements the Viterbi algorithm. This algorithm is based on finding the most likely path along the trellis diagram, as it calculates the metric between the received coded sequence and the corresponding branch codeword, and selects the path with the largest metric.

Two methods can be used for decoding: Soft-decision decoding and Hard-decision decoding. In hard decision decoding, each symbol is represented by either a "1" or a "0", i.e. quantized to 1 bit. In soft-decision decoding, each symbol is represented (quantized) by multilevel, so that it does not only indicate whether the symbol is a one or zero, but also gives a measure of confidence about the decision. This can improve the SNR by approximately 2 dB. However, soft decision decoding has the disadvantage of increased complexity and a requirement for more memory capacity at the receiver. For the spread-spectrum OFDM system under consideration, Soft decision decoding will be used.

3.3.6 Summary of Model Parameters

- End-to-end physical layer (streaming mode)
- QPSK modulation, rate-5/8 FEC coding (convolutional + puncturing)
- OFDM transmission: 122 subcarriers, 22 pilots, 128-pt FFTs, zero prefix, guard period
- Data interleaving
- Viterbi decoding
- 3-band frequency hopping

3.3.7 Model Assumptions

- Baseband-equivalent model
- Random data transmission
- Fixed transmit power level; link-SNR specified
- Additive White Gaussian Noise Channel (for simplified capacity estimation)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results and Findings

In this project, simulations were carried out in order to generate a SS-OFDM system and estimate its capacity. The simulation results consist of signal constellation plots, power spectra and spectrogram. The signal constellation plots show both the unequalized and equalized data. The power spectra plots include the transmitted signal and the received signal. The spectrogram shows the power spectrum of the transmitted signal as the function of time to illustrate the frequency-hopping pattern. The calculation of OFDM capacity is obtained from the parameters set during initialization.

4.1.1 MATLAB Simulation

(see next page)

- Signal constellation plots (Figure 13 and 14)
- Power spectra (Figure 15 and 16)
- Spectrogram (Figure 17)

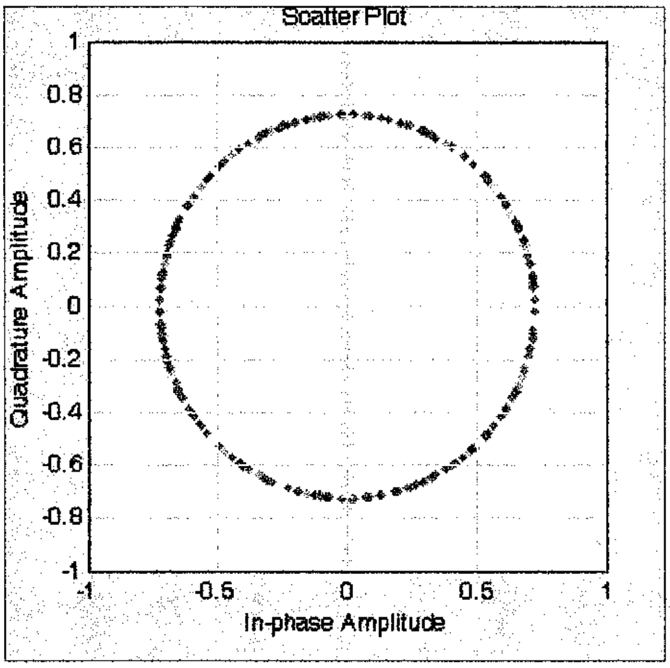


Figure 13 Signal Constellation in AWGN Channel

By using OFDM model shown in previous chapter, OFDM signal is generated by using MATLAB. Frequency hopping spread-spectrum signal is employed. Figure 13 shows the signal constellation in AWGN channel. The signal forms a ring shape as a result of using QPSK modulated signal. The equalized OFDM signal is shown in Figure 14.

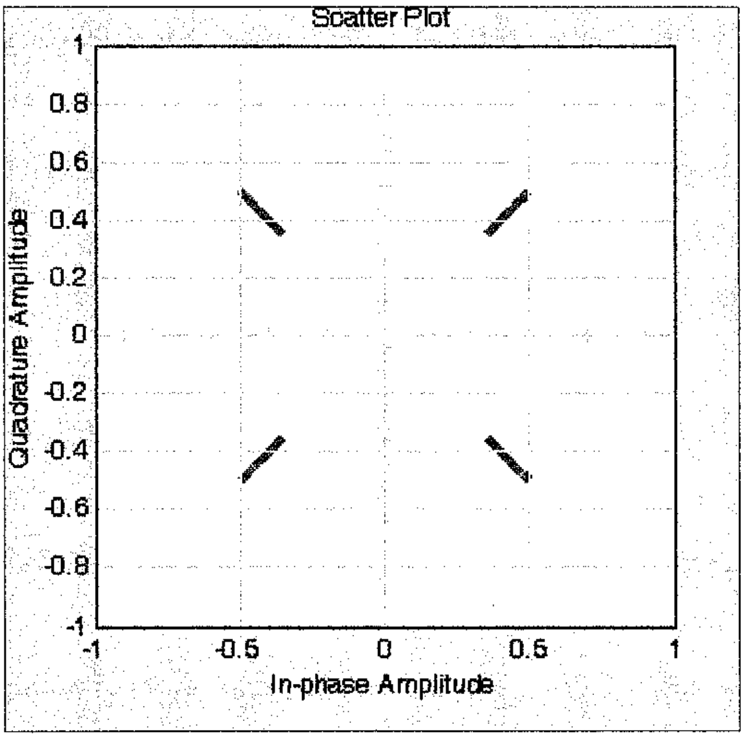


Figure 14 Signal Constellation (Equalized)

From Figure 15, the magnitude of signal power at the transmitter is 0 dB (10 W).

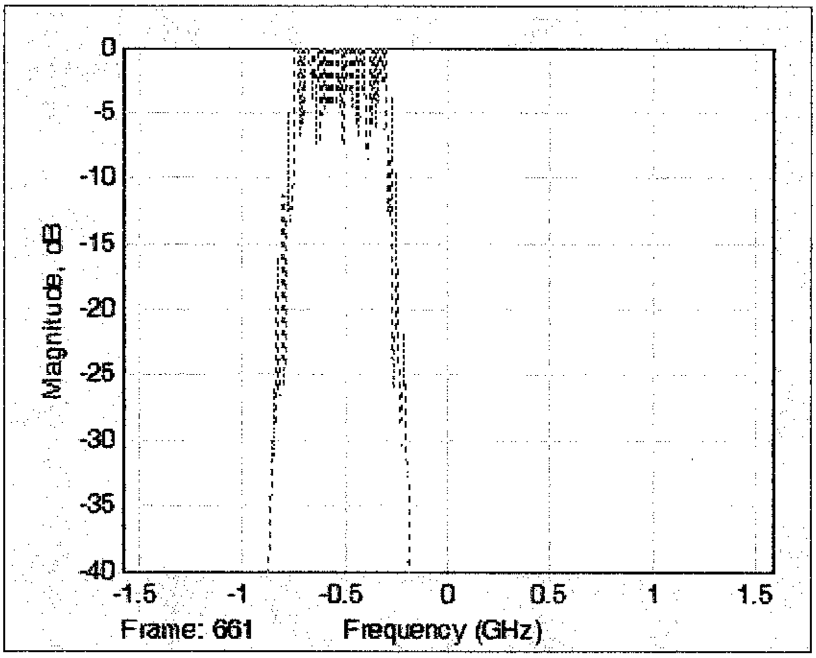


Figure 15   Power Spectrum at Transmitter

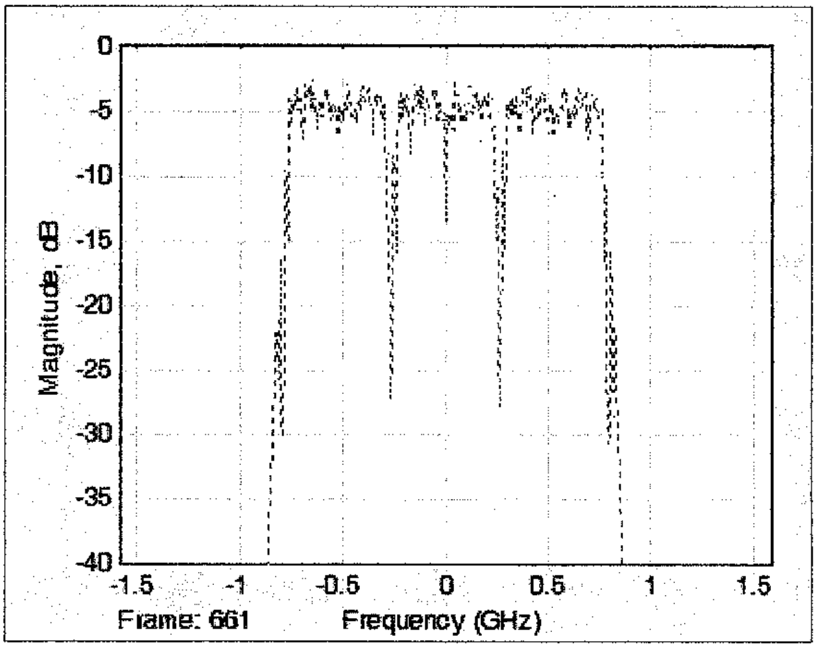


Figure 16   Power Spectrum at Receiver

From Figure 16, the magnitude of signal power at the receiver is -3 dB (0.5 W). Note that the signal spectrum has been 'spread' three times larger than the original spectrum at the receiver, due to three-band frequency hopping.

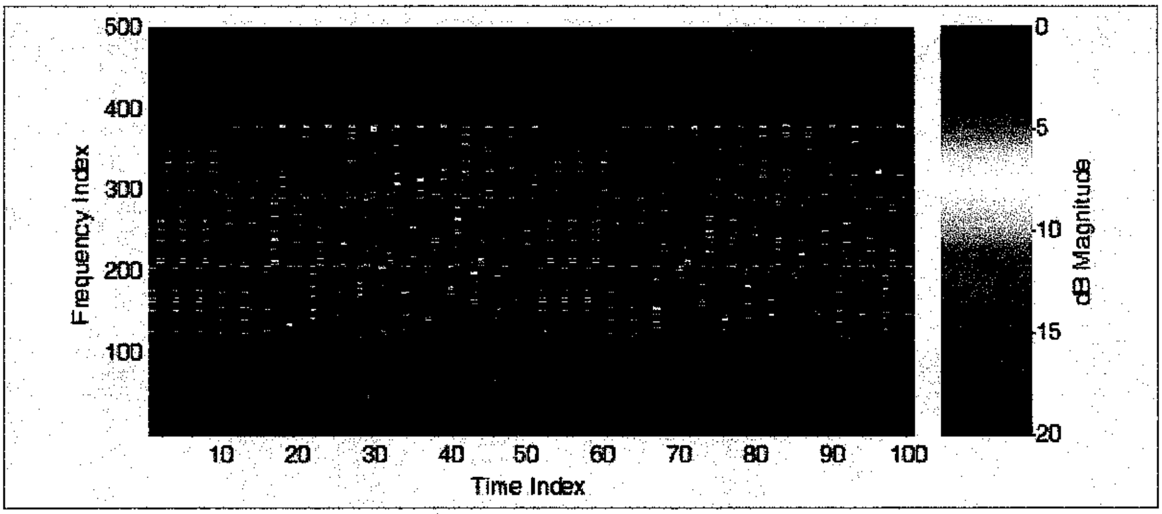


Figure 17 Spectogram

Figure 17 illustrates the frequency hopping pattern by using a spectrogram. The frequency used here is from 100 MHz to 400 MHz with 100-MHz bandwidth per spectrum. The varying colors of the spectrum indicates the magnitude of spectrum power (in dB), with the red is the strongest while the blue is the weakest spectrum power.

4.1.2 Capacity Estimation

Using Eq. 1, the capacity of SS-OFDM is estimated for 2 different values of SNR:

- For SNR = -60 dB,

  C = 3.32 x 528e6 x log (1 + 0.000001)

  C = 7.612 Mbps

- For SNR = -30 dB,

  C = 3.32 x 528e6 x log (1 + 0.001)

  C = 7.609 Mbps

4.1.3 Comparison with WCDMA capacity

There are a few points of consideration prior to comparison between SS-OFDM and WCDMA capacity. These points are important in order to make comparison is reliable enough from the writer's point of view.

- Firstly, the comparison is based on theoretical values of WCDMA capacity, not the actual values when WCDMA system is simulated in real environment.
- SS-OFDM capacity is calculated by using Shannon Capacity theorem, while WCDMA capacity is unknown to be under which environment it is modelled. This condition may give unfair comparison as SS-OFDM is simulated under a simplified channel, which results in higher capacity. However, the comparison is done in order to obtain general overview of what SS-OFDM system can offer.
- The SS-OFDM capacity obtained in this project is an estimation value. The actual values may differ because of propagation losses and transmission impairments.

From the previous calculation, it is found that the capacity of SS-OFDM (using frequency hopping technique) is very promising; 7.612 Mbps for SNR = -60 dB, and 7.609 Mbps for SNR = -30 dB. It is much larger than the current capacity of WCDMA for 3G systems, which are 2 Mbps for indoor users, 384 kbps for outdoor users (low mobility) and 144 kbps for outdoor users with high mobility.

4.1.4 Discussions

From the calculation results, it is clear that SS-OFDM system can give higher capacity for mobile users than that of WCDMA. Apart from this, SS-OFDM system has many other benefits such as high-spectrum efficiency, resistance against multipath fading, especially in wireless environment and ease of filtering out noise. Also, the upstream and downstream speeds can be varied by allocating either more or fewer carriers for each purpose.

Another extremely important benefit from using multiple sub-carriers is the duration of each symbol is relatively long because each carrier operates at a relatively low bitrate. If one sends, say, a million bits per second over a single baseband channel, then the duration of each bit must be under a microsecond. This imposes severe constraints on synchronization and removal of multipath interference. If the same million bits per second are spread among N subcarriers, the duration of each bit can be longer by a factor of N, and the constraints of timing and multipath sensitivity are greatly relaxed.

By combining SS-OFDM with error-correcting codes, SS-OFDM has the following properties:

- resistance against link dispersion
- resistance against slowly changing phase distortion and fading
- resistance against multipath using guard interval and cyclic prefix
- resistance against frequency response nulls and constant frequency interference
- resistance against burst noise

CONCLUSION

As a conclusion, OFDM appears to be a suitable technique as a modulation technique for high performance wireless telecommunications. Its popularity and reputation as the next generation of broadband wireless becomes more prominent with its employment in vendors' solution and innovation. In this project, an OFDM system has been simulated with the employment of frequency-hopping spread-spectrum signal. It is also found that the capacity of SS-OFDM, which is 7.612 Mbps for SNR = -60 dB, and 7.609 Mbps for SNR = -30 dB are larger than the current capacity of WCDMA for 3G systems. SS-OFDM also has many other benefits such as high-spectrum efficiency, resistance against multipath fading, ease of synchronization and filtering out noise and resistance against burst noise. This technique, however, is also more sensitive to frequency and phase noise compared to a single carrier modulation, and has relatively large peak-to-average power ratio which tends to reduce the power efficiency of the RF amplifier. Nevertheless, with its high-capacity offerings and benefits, it is undeniable that SS-OFDM can be a potential multiple access technique for beyond 3G technology.

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[12] MATLAB 7.0 Help Document

APPENDICES

APPENDIX A

CODING IN MATLAB

```
% This file has been adapted from code downloaded from the following
site:
% http://www.mathworks.com/matlabcentral/fileexchange

function params = OFDM_settings(OFDMDataSymPerFrame, OFDMWordLength);

% Modulation and coding
p.bitsPerBlock = 125;
p.trellisStructure = poly2trellis(7, [133 145 175]);
p.punctureVector = [1 0 1 1 0 0 1 0 1 0 0 1 1 0 1].';
p.codeRate = 5/8;
p.codedBitsPerBlock = p.bitsPerBlock / p.codeRate;
p.codedBitsPerQPSKSymbol = 2;
p.spreadFactor = 2;

% OFDM/FFT
p.NSD = 100;  % data subcarriers in OFDM symbol
p.NST = 122;  % subcarriers used in OFDM symbol
p.NFFT = 128; % number of points for FFT
p.NCyclicPrefix = 32;
p.NFFT2 = p.NFFT + p.NCyclicPrefix;

% FFT-related indices
p.TXFFTShiftIndices = [p.NST/2+1:p.NFFT 1:p.NST/2];
p.TXCyclicPrefixIndices = [p.NFFT-[p.NCyclicPrefix-1:-1:0] 1:p.NFFT];
p.RXCyclicPrefixIndices = [p.NCyclicPrefix+1:p.NFFT2];
p.RXSelectFFTIndices = [p.NFFT-[p.NST/2-1:-1:0] 1:p.NST/2+1];

% Number of OFDM symbols
p.OFDMDataSymPerFrame = OFDMDataSymPerFrame;  % payload
p.OFDMSpreadSymPerFrame = OFDMDataSymPerFrame * p.spreadFactor;
p.CEPerFrame = 6;  % channel estimation preamble
p.PSPerFrame = 3;  % Packet sync sequence
p.FSPerFrame = 6;  % Frame sync sequence
p.OFDMTotalSymPerFrame = p.OFDMSpreadSymPerFrame + p.CEPerFrame +
p.PSPerFrame + p.FSPerFrame;
p.NGuard = 5;  % Guard period (samples)

%p.filterDelay = 2;  % OFDM frame delay for tx/rx filtering

% Viterbi trace back depth and link delay
p.vtbd = 34;
p.linkDelay =
(floor(p.OFDMSpreadSymPerFrame/2)+3)*3*p.bitsPerBlock+p.vtbd - 250;

% Fixed point word length and data type
```

```
p.OFDMWordLength = OFDMWordLength;
p.OFDMDataType = sfix(OFDMWordLength);  % Signed

% Channel
p.channel.chan = 1;
p.channel.chan_idx = 12;

p.PSSequence = PSMatrix;
p.FSSequence = -p.PSSequence;

% Timing-related parameters
p.W = 528e6;  % two-sided bandwidth (output samples)
p.bitPeriod = 1/p.W ...
            * 1/p.codeRate ...
            * (p.NFFT2+p.NGuard)/p.NSD ...
            * p.OFDMTotalSymPerFrame/p.OFDMSpreadSymPerFrame;

params = p;


function s = CEMatrix;
s = [...
 1-j     1-j     1+j     1+j
-1+j     1-j    -1-j    -1-j
-1+j    -1+j     1+j    -1-j
 1-j    -1+j    -1-j     1+j
 1-j    -1+j    -1-j    -1-j
 1-j     1-j    -1-j    -1-j
-1+j    -1+j    -1-j    -1-j
 1-j    -1+j    -1-j     1+j
-1+j     1-j     1+j    -1-j
-1+j    -1+j     1+j     1+j
-1+j    -1+j     1+j    -1-j
 1-j    -1+j    -1-j    -1-j
-1+j    -1+j     1+j    -1-j
-1+j     1-j    -1-j    -1-j
-1+j    -1+j     1+j    -1-j
-1+j     1-j    -1-j    -1-j
-1+j    -1+j    -1-j     1+j
-1+j     1-j    -1-j    -1-j
 1-j     1-j    -1-j    -1-j
-1+j     1-j     1+j    -1-j
 1-j    -1+j    -1-j     1+j
-1+j    -1+j    -1-j    -1-j
-1+j    -1+j     1+j     1+j
-1+j    -1+j    -1-j     1+j
 1-j    -1+j    -1-j     1+j
-1+j     1-j    -1-j    -1-j
-1+j    -1+j     1+j    -1-j
 1-j     1-j     1+j     1+j
]/sqrt(2);

function s = PSMatrix;
s = [...
 1   1   1   1
```

1	1	-1	-1
1	-1	1	-1
-1	1	1	-1
-1	1	-1	1
1	-1	-1	1
-1	-1	-1	-1
-1	-1	1	1
-1	1	-1	1
-1	1	1	-1
-1	-1	-1	-1
1	1	-1	-1
1	1	1	1
-1	-1	1	1
1	-1	1	-1
1	-1	-1	1
-1	-1	-1	1
-1	-1	1	-1
-1	1	-1	-1
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-1	1	1	1
1	1	1	-1
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1	-1	-1	1
1	-1	1	-1
1	1	-1	-1
-1	-1	-1	-1
-1	-1	1	1
1	1	1	1
-1	1	1	-1
-1	1	-1	1
-1	-1	-1	-1
-1	-1	1	1
-1	1	-1	1
1	-1	-1	1
1	-1	1	-1
-1	1	1	-1
1	1	1	1
1	1	-1	-1
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-1	1	1	-1
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1	-1	1	-1
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-1	-1	-1	1
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1	1	1	-1
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1	1	1	1
-1	-1	1	1
-1	-1	-1	-1
1	1	-1	-1
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-1	-1	1	-1
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1	1	-1	1
-1	-1	-1	1
1	-1	-1	-1
1	-1	1	1
-1	-1	-1	-1
-1	-1	1	1
-1	1	-1	1
1	-1	-1	1
1	-1	1	-1
-1	1	1	-1
1	1	1	1
1	1	-1	-1
-1	1	-1	1
-1	1	1	-1
-1	-1	-1	-1

```
 1   1  -1  -1
 1   1   1   1
-1  -1   1   1
 1  -1   1  -1
 1  -1  -1   1
 1   1   1   1
 1   1  -1  -1
 1  -1   1  -1
-1   1   1  -1
-1   1  -1   1
 1  -1  -1   1
-1  -1  -1  -1
-1  -1   1   1
];
```