OFDM COMBINED WITH W-CDMA UNDERLAY DIGITAL TRANSMISSION

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STATEMENT OF CANDIDATE

I, Amirali Emami, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment and any academic institution.

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ABSTRACT

In this paper, an underlaid network consisting of an OFDM primary user and a W-CDMA secondary user was examined. The underlaid netowrk is proposed as a way to increase the efficient use of the radio spectrum. Both multi-carrier transmission techniques offer different pros and cons which will be exploited within this network to increase spectrum efficiency. In addition to increased throughput, the underlay network can address OFDM's high sensitivity to frequency synchronisation issues by transmitting the pilot packets through the W-CDMA channel. This results in higher secured throughput by adding small interference margins to both users. An investigation will be conducted to see what the interference levels will be within the network, both on the OFDM and the W-CDMA; and how much increase in secure throughput will be gained. The underlaid network will be modelled and simulated in MATLAB.

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Chapter 1

Introduction

In today's society, the need for faster data has become of large interest. This large interest is due to many factors such as the increase in popularity of Internet of things (IoT), Machine-to-Machine (M2M) and the expansion of mass-market production of smart phones, laptop computers, notebooks and tablets [1]. The growth of data-intensive applications such as social networking, web browsing, video streaming and gaming has had a tremendous impact in increasing the need for higher capacity [2, 3].

Not only is there a huge demand for higher capacity but also more efficient use of the radio spectrum. The design of any communication system stems from determining certain parameters which are shaped by given restraints. The main two factors which restrain any communication systems are either limited bandwidth or limited power and in some cases both limited power and bandwidth. In this paper to meet these increasing content consumption needs, the case of a digital communication system which is both bandwidth and power limited is evaluated to potentially increase overall network throughput and spectrum usage efficiency.

The regulations governing what band of radio spectrum is available for transmission varies for different countries but all require purchasing a licensed band for transmission. Making efficient use of the spectrum has become of utmost importance; one such way to solve the radio spectra scarcity problem is through a Cognitive Radio Network (CRN).

1.1 Cognitive Radio Network

A CRN can be called a smart radio as it is able to dynamically adjust its transmission parameters to allow for more wireless connections, making efficient use of the spectrum [4].

Cognitive Radio (CR) is a vertical spectrum sharing technique. Within CR, there is a Primary User (PU) and a Secondary User (SU). PUs are given first priority of the network and SUs are allowed to exploit the underutilised radio spectrum of the PU's network without causing noticeable interference to the PUs [5, 6].

There are two main types of CRNs, underlay and overlay. In an overlay system, the SU will use spectrum sensing to determine which section of the spectrum is vacant and proceed to exploit those vacant portions accordingly. An underlay system allows the second user to opportunistically access the radio spectrum at a much lower power level to avoid major harm to PU [7–9].

1.2 Project goals and motivation

In this thesis, we will investigate the maximum power levels a SU can have in an underlay CRN, such that the PUs will not suffer any major performance degradation. The PUs will be using Orthogonal Frequency Division Modulation (OFDM) and SUs will be using Wideband-Code Division Multiple Access (W-CDMA).

We will investigate what the maximum transmission data rate an underlay network that uses an OFDM transmission system of N users and an underlay of a CDMA communication system is transmitting in the same frequency band can reach. The system parameters should be such that the total transmission power is constrained below a fixed constant. There will be strict restrictions on what the maximum bit error rate for the OFDM system and for the W-CDMA system can be. The total transmit power must be divided between the W-CDMA and OFDM systems in a way such that the performance degradation of each system from the interference of the other system is bounded and acceptable. Different levels of processing gain for the W-CDMA system will be evaluated to gauge the underlay's performance.

This CRN will encompass a trade off between slight power increase and spectrum utilisation. Increasing the amount of power required at either the PU and/or SU in lieu of increasing the amount of secure data throughput achievable from within a certain bandwidth in turn increasing overall bandwidth usage efficiency. The reason for this trade being plausible is that as a consequence of the increasing legislative and fiscally limiting factors circling around radio spectrum usage, increased power (within certain limits) for increased spectrum usage efficiency is a trade the majority of communications system designers are willing to accept.

Chapter 2

Background and related Work

This chapter will cover the theoretical background required to comprehend the different concepts which will be later employed in this paper. Initially, the concept of orthogonality is defined in section 2.1 and then the building blocks of a digital communication system is explained in sections 2.2, 2.3 and 2.4. The basics of the individual multi-carrier transmission schemes are also covered in section 2.5 and 2.6. Related work and this projects key difference to them is addressed in section 2.7.

The rest of this thesis is organised as follows: chapter 3 will go through the mathematical derivations and specifications which the MATLAB models are based on. Chapter 4 includes the results of the MATLAB codes and observations obtained from them. Chapter 5 contains the final remarks and possible future work which could entail the project. Finally chapter 6 will detail all abbreviations used within this paper.

Furthermore appendix A contain the MATLAB code for the systems employed, where the PN gen code is courtesy of Professor Reisenfeld. The last appendix B is the meeting attendance form along with references at the end.

2.1 Orthogonality

The concept of *orthogonality* is essential to the base theory which both sub-systems rely on. OFDM uses the orthogonality of signal vectors to avoid inter sub-carrier interference and CDMA uses orthogonality of the chip codes to stay clear of any inter sub-carrier disruptions. Using concepts of orthogonality we may detect a signal among other signals that share the same frequency band.
By expanding an N-dimensional vector $\mathbf{x} \in \mathbb{R}^N$ into a base $\{\mathbf{v}_i\}_{i=1}^N$ based on

$$\mathbf{x} = \sum_{i=1}^{N} \alpha_i \mathbf{v}_i.$$

The base $\{\mathbf{v}_i\}_{i=1}^N$ is **orthonormal** if the two different vectors are orthogonal to one another and are normalised to a length 1, which is,

$$\mathbf{v}_i.\mathbf{v}_k = \delta_{ik}.$$

Where δ_{ik} is the Kronecker Delta, $\delta_{ik} = 1$ for $i = k$ and $\delta_{ik} = 0$ otherwise. Two signals are said to be orthonormal if

$$\int_{-\infty}^{\infty} v_i(t)v_k(t)dt = \delta_{ik}.$$

2.1.1 Fourier series

We will consider a signal with a period length of T. We will assume the signal is real and integrable within the time interval $0 \leq t \leq T$ and 0 when outside this interval (e.g $x(t) = 0$). Inside this interval, the signal may be written as

$$x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos(2\pi\frac{k}{T}t) - \sum_{k=1}^{\infty} b_k \sin(2\pi\frac{k}{T}t). \tag{2.1}$$

The Fourier coefficients a_k and b_k are described by

$$a_k = \frac{2}{T}\int_0^T \cos(2\pi\frac{k}{T}t)x(t)dt$$
$$b_k = -\frac{2}{T}\int_0^T \sin(2\pi\frac{k}{T}t)x(t)dt.$$

These coefficients are the values for the amplitudes of the cosine and negative sine waves at the frequencies $f_k = \frac{k}{T}$. These two waves may be used as a *base* for the signals inside the interval and as such every signal may be represented using equation 2.1. It can be stated that different frequencies can be identified within a certain signal. This is due to the orthogonal nature of the Fourier series and how the different values for the coefficients are orthogonal from one another. This can be seen in the following integral where $n \neq k$

$$\int_{-\pi}^{\pi} (\cos nx)(\cos kx)dx = 0$$

and similarly

$$\int_{-\pi}^{\pi} (\sin nx)(\sin kx)dx = 0.$$

Using the above orthogonality, we can separate the different frequencies from each other. This is the mechanism by which OFDM's sub-channels are able to be so closely packed and still be completely orthogonal to each other.

2.2 Link Budget

For a digital communications system, a set of digital information that is given by a finite set of bit sequences is to be transmitted over a physical channel by a passband signal $\hat{s} = \Re\{s(t)e^{j2\pi f_0 t}\}$. A complex baseband signal can be characterised as

$$s(t) = \sum_{k=1}^{K} s_k g_k(t)$$

where s_k is the complex transmit signals and g_k is the base transmission pulses.
The average signal energy is given by

$$E = E\left\{ \int_{-\infty}^{\infty} |s(t)|^2 dt \right\} = E\left\{ \sum_{k=1}^{K} |s_k^2 \right\} = KE\{|s_k|^2\}$$

where we can assume that all the K symbols s_k, have the same statistical properties. The energy per symbol can be given as $E_s = E/K$, where $E_s = E\{|s_k|^2\}$. The energy of the noise is

$$P_n = E\{|n_k|^2\} = N_0 \times W$$

where N_0 is the received noise power spectral density, W is bandwidth and E_b is the energy per bit. Therefore given a set of parameters for a communications system, a link budget can be determined by

$$\frac{E_b}{N_0} = \frac{E_s}{P_n}\frac{W}{R} = \frac{E_s}{N_0}\frac{1}{R}. \tag{2.2}$$

2.2.1 Additive White Gaussian Noise

A received signal will realistically always be corrupted by noise. A way to mathematically model this effect is an Additive White Gaussian Noise (AWGN) channel. AWGN is modelled as a zero mean signal with Power Spectral Density (PSD) defined as N_0. Its variance is σ_N^2. The PSD of AWGN is independent of frequency [10]. The noise $w(t)$ is an additive random interference of the useful signal $s(t)$ in which the received signal $r(t)$ can be summarised by

$$r(t) = s(t) + w(t).$$

Most graphs within this paper will be expressed as Energy per bit (E_b) vs Power Spectral Density (PSD) of noise ($\frac{E_b}{N_0}$).

2.3 M-ary Phase Shift Keying

M-ary Phase Shift Keying (M-ary PSK) is a digital modulation scheme. In M-ary PSK, the available phase of 2π radians is apportioned equally among the M possible phases, each being assigned to a unique block combination of data. The incoming data stream will then be divided into blocks of $\log_2$(M) bits to then get assigned a phase corresponding to that unique data combination. An M-ary PSK signal may be represented as:

$$S(t) = \sqrt{\frac{2E_s}{T}} \cos(2\pi f_c t + \frac{2\pi}{M} i), \qquad \begin{array}{c} i = 0, 1, \ldots, M-1 \\ 0 \leq t \leq T \end{array} \tag{2.3}$$

where E_s is the energy per symbol and f_c is the carrier frequency [10].

2.4 Bandwidth limited systems

The design of a digital communications system is proceeded with a description of the channel, available bandwidth, noise statistical properties, received power, required data rate and other design allowances for impairments. Given a set of descriptions, an appropriate system is proposed to meet the performance requirements. The two primary variables which will determine what type of communication system, the proposed system will be classified as are *available radio spectrum bandwidth* and *received power*. The system will be designed around the idea of which one of these are more precious than the other.

To evaluate a system's performance, we may determine its *bandwidth efficiency*, since this value reflects how efficient the radio spectrum bandwidth usage is. Bandwidth efficiency is the ratio R/W, where R is the data rate bits/s and W is the given bandwidth in hertz. The bound to which any system can achieve a capacity can be evaluated from the well known Shannon's Theorem [11], which is stated as follows:

$$C = W \log_2(1 + \frac{E_s}{P_n}) \tag{2.4}$$

where $\frac{E_s}{P_n}$ is the received power to noise ratio (SNR) and the capacity of a channel is given by C in bits/s. This bound determines the maximum number of bits which can be reliably sent per second over the channel.

2.4.1 Throughput calculation

We can evaluate the amount of data throughput a given system can transmit at which can be used later in equation 2.2 by

$$R = \frac{k}{T_s} = \frac{\log_2(M)}{T_s} \qquad \text{bits/s} \tag{2.5}$$

where k is the number of bits transferred, M is the order of the M-ary modulation and T_s is the symbol for time duration.

Equation 2.5 can be rewritten as

$$T_b = \frac{1}{R} = \frac{T_s}{k} = \frac{1}{kR_s} \tag{2.6}$$

where

$$R_s = \frac{R}{\log_2(M)}.$$

Therefore bandwidth efficiency can be written as

$$\frac{R}{W} = \frac{\log_2(M)}{WT_s} = \frac{1}{WT_b} \qquad \text{bits/s/Hz}. \tag{2.7}$$

2.5 Code Division Multiple Access

CDMA is a multi-carrier transmission scheme where different users can use the same frequency bandwidth at the same time, while causing no interference to each other. The primary mechanism which CDMA is based on is the *spread spectrum* technique, in which the signal bandwidth is extended to a far higher rate which is needed for a given data rate. The different users of CDMA can be identified and their signals can be separated from the other signals by their signature pulses, also known by their individual codes. CDMA was designed and used primarily for its robustness against noise within defence communication systems to prevent unwanted jamming or eavesdropping [12]. In CDMA, a pseudorandom code is generated and is used to map the data to a rudimentary spread spectrum digital physical waveform [13].

2.5.1 Principles of spreading

Spread spectrum refers to the concept of enhancing a signal's bandwidth far beyond what is necessary for a certain data rate and therefore reducing the PSD of the useful signal, even to a level in which the useful data's PSD sinks below the noise level. This is how CDMA can excel at staying undetected under unauthorised receivers and be robust against intended interference (jamming).

Spreading is done by multiplying the data symbols by a sequence of pseudorandom data. The result of this multiplication is called a *pseudonoise* (PN) sequences. A pseudorandom sequence is a sequence of data which shows statistical randomness while in fact being generated by an exclusively deterministic process. Most pseudorandom sequences are generated using Linear Shift Register (LSR) sequence generators. An example of an LSR sequence generator can be observed in the following figure 2.1.

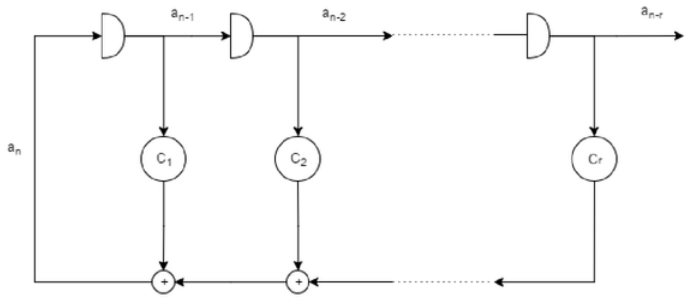

Figure 2.1: Linear shift register sequence generator

With $C_i = 0$ meaning no connection and $C_i = 1$ meaning connected; from [14].

The following are the mathematical tools used for modelling LSR sequences. In the generation of an LSR sequence, the generating function $G(D)$, where D is the delay operator, can be expressed as:

$$G(D) = \frac{\sum_{i=1}^{r} c_i D^i (a_{-i} D^{-i} + ... + a_{-1} D^{-1})}{1 - \sum_{i=1}^{r} c_i D^i} \equiv \frac{g_0(D)}{f(D)} \tag{2.8}$$

An LSR generator of length r has a period of $2^r - 1$ or less. A primitive polynomial must be used in determining the *characteristic polynomial* $f(D)$ to achieve the maximum period possible.

Primitive polynomials

Primitive polynomials are irreducible polynomials of degree r such that $P = 2^r - 1$. There are cases where using just an irreducible polynomial is not enough and to fully ensure that the maximum period is achieved, a primitive polynomial must be used. Finding primitive polynomials for greater values of r can be challenging but tables exist that can be used to find polynomials of length upto $r = 50$ [14].

Maximum Length Shift Register sequences

When $f(D)$ is a primitive polynomial, there will be no possible common factors between g_0 and $f(D)$, giving us a Maximum Length (linear) Shift Register (MLSR) sequence with period $P = 2^r - 1$ for all non-zero initial vectors. A sequence of MLSR of length M is known to be an M-sequence [14] [15].

Gold Codes

A set of Gold Codes of length M can be obtained by combining two different sets of unique MLSR Codes. Gold Codes are sets of Codes that are orthogonal to each other and have good auto- and cross-correlation properties. They can be generated by combining specific pairs of M-sequences c, c' and the modulo-2 sum of c and all M different cyclically shifted $c's$. The two M-sequences c, c' are called *preferred M-sequences*. A set of Gold Codes sequences consists of $M+2$ sequences, which each sequence has a period 2^{n-1}, where n is the length of the LSR generator [13].

A set of specific pair of M-sequences can be generated by picking a MLSR and decimating it by a factor of q, such that:

- $M \neq 0(\text{modulo } 4)$
- $c' = c[q]$, where q is odd and satisfies either $q = 2^k + 1$ or $q = 2^{2^k} - 2^k + 1$
- Where k must be selected such that,

$$(M,k)\,\text{gcd} = \begin{cases} 1 & \text{if } m \text{ is odd} \\ 2 & \text{if } m = 2 \pmod 4 \end{cases}$$

- Note: it is known that no preferred pairs exist for $M = 4$, 8, 12, 16 and for all M = 0 (mod 4)

2.5.2 Direct Sequence-CDMA

Direct Sequence-CDMA (DS-CDMA) is a form of CDMA, where the data to be transmitted will be modulated using either M-ary Quadrature Amplitude Modulation (M-ary QAM) or M-ary PSK. The modulated data blocks will then be multiplied by the locally generated PN code with period $P = 2^r - 1$. The PN code has a period of T_{chip} and the modulated data has period T_{symb}; with $T_{chip} << T_{symb}$ to ensure that the frequency of the PN codes is much greater than the symbol rate. The ratio T_{symb}/T_{chip} is regarded as the Spreading factor of the system [16].

CDMA uses properties of orthogonality between PN codes to transmit data while having it appear noise-like to any 3rd party [17].

A general CDMA system and its spreading is demonstrated in figures 2.2 and 2.3 below; from [18].

2.5.3 Wideband-CDMA

Wideband-CDMA (W-CDMA) refers to the utilisation of the entire available radio spectrum so that any user may transmit at a bandwidth B which corresponds to the bandwidth of the entire available radio spectrum. There are also other specifications differentiating a W-CDMA system from a CDMA system, which are beyond the scope of this paper.

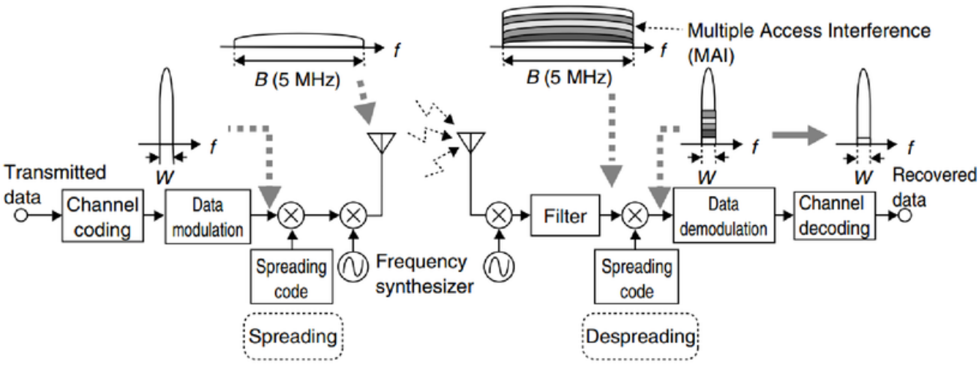

Figure 2.2: Principles of DS-CDMA

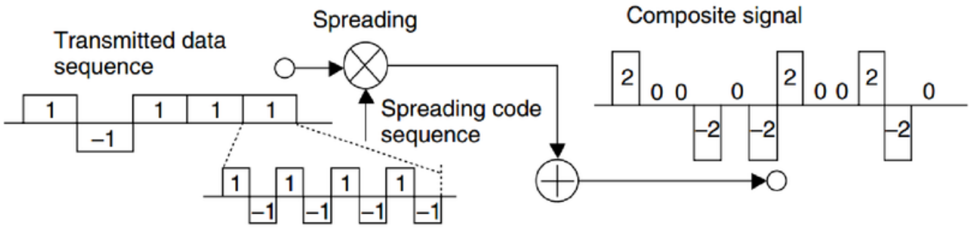

Figure 2.3: The locally generated code multiplied with the modulated data

2.6 Orthogonal frequency division modulation

Orthogonal frequency division modulation (OFDM) is a multi-carrier transmission scheme which only became possible with the invention of modern high performing Integrated Circuits (ICs). OFDM's main principle is to divide the available bandwidth B into multiple narrow-band sub-carriers at equidistant frequencies. Each user will be assigned a set of sub-carriers, which will be used to transmit data independently to the user. The spectrum of the sub-carriers overlap each other but still remain orthogonal [19].

The orthogonality of the sub-carriers stems from the base transmission pulses g(t) being orthogonal to one another. They are chosen such that

$$\langle g_{kl}, g_{k'l'} \rangle = \delta_{kk'}\delta_{ll'}$$

where δ is the Kronecker Delta as previously mentioned in section 2.1, k is sub-carrier index and l is the discrete time index. When the above requirements are satisfied, we can see that the transmitted OFDM signal is given by this (compact) equation

$$s(t) = \sum_{kl} s_{kl} g_{kl}(t) \tag{2.9}$$

Such that $s_{kl}(t)$ for any k and l can be successfully separated and recovered due to the orthogonality between the base transmission pulses.

2.6.1 Fast Fourier Transform

One main component of OFDM modulation is the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT). FFT/IFFT are heuristic algorithms to efficiently implement Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT). DFT is a mathematical model used to map data from its original time domain to a representation in the frequency domain. The IDFT re-maps the data from the frequency domain to the original time domain representation. DFT can be formally defined as [10, 20, 21]:

$$G_k = \sum_{n=0}^{N-1} g_n e^{(\frac{-j2\pi}{N} kn)}, \quad k = 0, 1, \ldots, N-1 \tag{2.10}$$

where G_k is the new sequence representing the frequency value at index k. Correspondingly, the IDFT can be described as:

$$g_n = \frac{1}{N} \sum_{k=0}^{N-1} G_k e^{(\frac{j2\pi}{N} kn)}, \quad n = 0, 1, \ldots, N-1 \tag{2.11}$$

In OFDM, the transmitted data will be modulated using either M-ary PSK or M-ary QAM, which will assign each block of data to a corresponding symbol in the phase constellation diagram. The phase can be represented as a complex number which will be used in the modulation of data using IFFT.

An example of the processing of modulation within OFDM using QPSK can be seen in figure 2.4 [13].

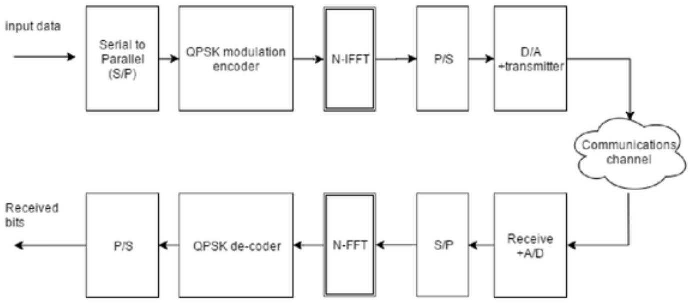

Figure 2.4: The modulation and demodulation of OFDM using FFT and IFFT with QPSK

2.6.2 Sub-channel allocation

The modulated data will be inserted by an N-point IFFT, which will then assign each sub-carrier a segment of the modulated blocks. The sub-carriers are all added into an OFDM symbol and transmitted. Each sub-carrier is spaced at a frequency of Δf from the adjacent sub-carrier. The bandwidth of the sub-carriers is called a sub-channel. Each sub-carrier is orthogonal to its adjacent sub-carrier even though a portion of its sub-channel spill onto the adjacent sub-channels. Orthogonality is maintained such that $T_u = \frac{1}{\Delta f}$.

The sub-carrier spacing can be seen in figure 2.5 below, from [22].

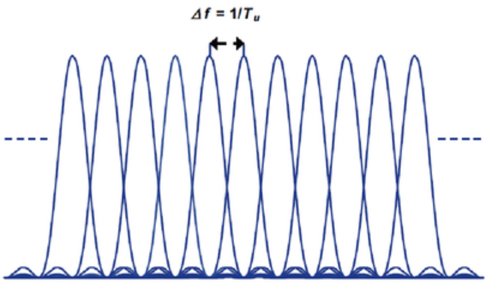

Figure 2.5: Sub-channel spacing in OFDM

An OFDM Signal can be expressed as:

$$x(t) = \frac{1}{N_{IFFT}} \sum_{k=0}^{N-1} a_k^{(m)} e^{j2\pi k \Delta f t} \tag{2.12}$$

where $x(t)$ is the OFDM signal with frequency $f_k = k \cdot \Delta f$, N is the size of the N-point IFFT and $a_k^{(m)}$ is the k_{th} sub-carrier during the m_{th} OFDM symbol interval [23].

2.6.3 Frequency synchronisation

Due to the sub-channels being so tightly packed, accurate frequency synchronisation is an important topic for OFDM systems. The accuracy required to maintain proper frequency synchronisation may not be sufficient from a local oscillator. If these frequency offsets are not corrected, these two effects will come into play:

1. Time-variant phase rotation of the received symbols.
2. Loss of orthogonality between sub-channels.

It should be stated that the first of the two effects occurs for all digital communication systems but the latter is OFDM specific and can have severe effects on the OFDM system.

If these frequency offsets are large enough, major disruptions may arise within the OFDM system. To counteract any frequency offsets that may not have been corrected, a set number of sub-carriers are assigned to transmit special symbols at certain times. These symbols are called *pilot symbols* which can be measured and used by the receiver to estimate the channel.

2.6.4 OFDM properties

Numerous systems have employed OFDM as their multi-carrier transmission scheme due to OFDM's superior data-rate throughput capabilities and reliability. However, OFDM also suffers from certain disadvantages such as:

- High sensitivity to Doppler frequency shift and frequency offsets.
- High sensitivity to frequency synchronisation issues. If the pilot symbols fail to be delivered, the system can suffer heavy degradation due to frequency offsets corrupting inter sub-carrier orthogonality.
- OFDM has a high peak to average ratio, which does not impose many problems on the base-station side but can cause problems with up-link from an energy scarce device such as a mobile phone.

2.7 Related work and key differences

The individual multi-carrier transmission systems have been thoroughly investigated in the literature [12, 14, 22, 24, 25]. The concept of increasing radio spectrum usage efficiency has been the focus of many papers. In [26] a hybrid overlay/underlay CRN with multi-carrier CDMA (MC-CDMA) was proposed. The proposed scheme to increase the overall network efficiency operates by spreading the underlaying signal through the whole bandwidth and to use spectrum sensing to overlay the available bands while keeping orthogonality between the underlay/overlay using Orthogonal Variable Spreading Factor Codes (OVSF Codes). The resultant hybrid system showed significant increase in capacity in both an AWGN and a Rayleigh fading channel.

More specifically in regards to underlay networks, [27] suggested increasing overall network efficiency by allowing Device-to-Device (D2D) users to transmit as a SU in an underlay with the base-station (BS), PU. In this paper, different configurations of Multi-carrier transmission were evaluated within the underlay. Furthermore, the performance of the network was evaluated by analysing the probability that a given link is still connected based on the different parameters and the distance between the D2D devices. A conclusion was made to increase overall network efficiency using two proposed system which was suggested to be picked based on project specifications. The two proposed systems will not be detailed as they are beyond the scope of this paper.

In comparison, in this paper, an underlaid network is proposed as a way to increase overall secured data throughput. It will be thoroughly examined as to what the limitations are and how the different parameters affect the underlay. This project has been approached in an abstract way to ensure it can be more applicable to different scenarios. The underlay's performance is evaluated based on its bandwidth usage efficiency.

2.8 Model approach

The general guidelines for which any of the communications systems are modelled and evaluated are stated in this section. To investigate how a communication system will perform, it will be modelled in MATLAB. The following are general guidelines that were followed in modelling these systems in MATLAB:

- The system will have a range of $\frac{E_b}{N_0}$ values defined.
- The transmitted signal's power or the σ_N^2 will be adjusted depending on the current $\frac{E_b}{N_0}$ value.
- A block-length of random binary data is generated for each user involved.
- Each sub-system will then modulate its data.
- The signals are sent through the AWGN, which will have both noise and/or other sub-systems interference added.
- Each sub-system will demodulate and run the received signal through a decision maker.
- The amount of errors made will be calculated by modulo-2 summing the received data with the transmitted data.
- The system will continue simulating until a set amount of errors have been made, for an accurate estimation of the probability of error per bit (P_b).
- After the set error amount requirement is met, the P_b vs $\frac{E_b}{N_0}$ will be graphed.

Chapter 3

MATLAB models

3.1 W-CDMA

The modulation scheme used in this paper for W-CDMA is *Binary Phase Shift Keying (BPSK)*. E_s can be defined as $E_s = \log_2(M)E_b$, therefore for BPSK $E_s = E_b$ since M is 2. The $\frac{E_b}{N_0}$ for DS-CDMA using BPSK is defined as

$$\frac{E_b}{N_0} = \frac{A^2 S_f}{2\sigma_N^2}, \quad S_f = \frac{T_{symb}}{T_{Chip}} \tag{3.1}$$

where S_f is spreading factor, determined by the period of the symbol divided by the period of the chip.

To investigate how a single user DS-W-CDMA system will behave, the general guidelines mentioned in section 2.8 will be followed. MATLAB will be used to simulate its performance. To model this system as accurately as possible a range for $\frac{E_b}{N_0}$ will be defined for which the CDMA system will be simulated from. Within this model, values of $\frac{E_b}{N_0}$ will only change the value of σ_N^2 accordingly. The formula for σ_N can be expressed as:

$$\begin{aligned} \frac{E_b}{N_0} &= \frac{A^2 S_f}{2\sigma_N^2} \\ \sigma_N^2 &= \frac{A^2 S_f}{2\frac{E_b}{N_0}} \\ \sigma_N &= \sqrt{\frac{A^2 S_f}{2\frac{E_b}{N_0}}} \end{aligned} \tag{3.2}$$

where A is the amplitude of the W-CDMA signal. The value for A^2 will be set to 1 for simplicity. With $A^2 = 1$, the final formula for σ_N can be expressed as:

$$\sigma_N = \sqrt{\frac{S_f}{2\frac{E_b}{N_0}}} \tag{3.3}$$

The model will simulate what the (P_b) will be for each value of $\frac{E_b}{N_0}$. To find the value of P_b, after modulating the input binary data, the modulated signals are sent through an AWGN channel with a variance of σ_N^2 determined by $\frac{E_b}{N_0}$. The noise corrupted signal is then demodulated and the amount of errors made is calculated. For each value of $\frac{E_b}{N_0}$, a set amount of bit errors is required to be made for the program to consider it an acceptable accuracy for estimating the P_b.

The following are the system specifications for the W-CDMA:

- BPSK modulation with a constellation of Q = -1 or 1 will be used.
- M-sequence MLSR has been chosen for the PN codes, with M = 511 and an LSR length of n = 9.
- The range of values for the spreading factor will be 1, 4 and 16.
- The range of $\frac{E_b}{N_0}$ will be from -10 dB to 8 dB.
- A block length of 256 randomly generated data bits will be used.
- 1000 bit errors will need to be made for an accurate estimation of P_b.
- The formula used for σ_N will be equation 3.3.
- An AWGN channel is assumed with no multi-path fading or Doppler frequency shift.

3.2 OFDM

The modulation scheme used within the OFDM system will be Quadrature Phase Shift Keying (QPSK). As mentioned in section 2.6.2 an OFDM signal can be expressed as:

$$x(t) = \frac{1}{N_{IFFT}} \sum_{k=0}^{N-1} a_k^{(m)} e^{j2\pi k \Delta f t} \tag{3.4}$$

with its time-discrete representation being [22]:

$$x_n = \frac{1}{N_{IFFT}} \sum_{k=0}^{N-1} a_k^{(m)} e^{j2\pi kn/N} \tag{3.5}$$

With N being the size of the N-point IFFT and k representing the k_{th} sub-carrier. The value of $a_k^{(m)}$ is a complex valued point z, with :

$$z = (-1)^{(b_1)} + j(-1)^{(b_2)}, \qquad \begin{array}{l} b_1 \in \{0,1\} \\ b_2 \in \{0,1\} \end{array} \tag{3.6}$$

Plugging 3.6 into 3.5 gives[1]:

$$x_n = \sum_{k=0}^{N-1} \frac{z}{N_{IFFT}} e^{j2\pi kn/N}, \qquad 0 \leq n \leq N-1 \tag{3.7}$$

therefore it can be assumed that[2]:

$$\begin{aligned} 2E_s &= \sum_{k=0}^{N-1} (\frac{z}{N_{IFFT}} e^{j2\pi kn/N})(\frac{z^*}{N_{IFFT}} e^{-j2\pi kn/N})\Delta T \\ &= \frac{|z|^2 \Delta T}{N_{IFFT}} \end{aligned} \tag{3.8}$$

Because we are using QPSK modulation, each symbol will contain two bits, meaning $E_s = 2E_b$, giving:

$$E_b = \frac{|z|^2 \Delta T}{4N_{IFFT}} \tag{3.9}$$

The complex envelope can be seen in figure 3.1.

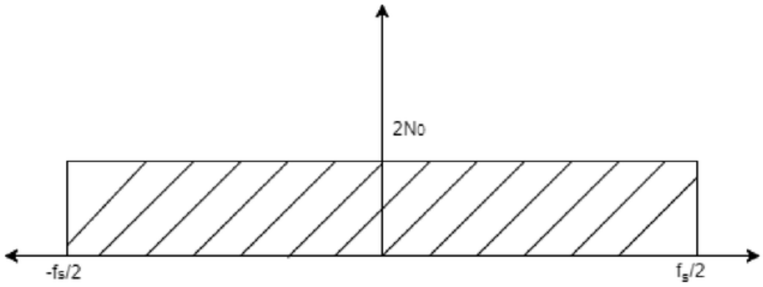

Figure 3.1: Complex envelope of noise in OFDM from $-f_s/2$ to $f_s/2$.

With figure 3.1 in mind σ_N^2 can be expressed as

$$\begin{aligned} \sigma_N^2 &= 2N_0(f_s) \\ N_0 &= \frac{\sigma_N^2}{2f_s} \end{aligned} \tag{3.10}$$

[1]Assuming one carrier, one symbol and for channel k; which $0 \leq k \leq N-1$

[2]The total energy the symbol has is doubled for the complex-real representation compared to just real or complex

We can now write the $\frac{E_b}{N_0}$ using equations 3.10 and 3.9, making:

$$\frac{E_b}{N_0} = \frac{|z|^2 \Delta T}{4N_{IFFT}} \frac{2f_s}{\sigma_N^2}$$
$$\frac{E_b}{N_0} = \frac{|z|^2 \frac{1}{f_s}}{2N_{IFFT}} \frac{f_s}{\sigma_N^2}$$
$$\frac{E_b}{N_0} = \frac{|z|^2}{2N_{IFFT}\sigma_N^2}$$
$$\sigma_N^2 = \frac{|z|^2}{2N_{IFFT}\frac{E_b}{N_0}}$$
$$\sigma_N = \sqrt{\frac{|z|^2}{2N_{IFFT}\frac{E_b}{N_0}}} \tag{3.11}$$

σ_N is twice the real ($\sigma_{N,R}$) or complex ($\sigma_{N,C}$) variance. For simplicity, in equation 3.11, $|z|^2$ can be assumed to be 1. Making the equation:

$$\sigma_{N,R} = \sigma_{N,C} = \sqrt{\frac{1}{4N_{IFFT}\frac{E_b}{N_0}}} = \sqrt{\left(4N_{IFFT}\frac{E_b}{N_0}\right)^{-1}} \tag{3.12}$$

Using equation 3.12 as the formula for σ_N in the MATLAB model, the resulting simulation can be seen in figure 4.7.

The specifications for the OFDM system are as follows:

- QPSK modulation with first phase at $\frac{\pi}{4}$.
- An N-point FFT and IFFT, where N = 128.
- The range of $\frac{E_b}{N_0}$ will be from -10 dB to 8 dB.
- A block length of 256 randomly generated data bits will be used.
- 1000 bit errors will need to be made for an accurate estimation of P_b.
- Equation from 3.12 will be used for σ_N^2 calculation.

3.3 Digital Underlay

3.3.1 Model approach

The underlay is composed of a SU using W-CDMA and a PU using OFDM. To model this system appropriately both systems will transmit in a single channel. Although both systems are transmitting, for better analytical clarity, only one system at a time will be in focus, meaning the other system will only be simulated up until channel transmission. Although the processes leading up to and including transmitting in channel will be simulated in both sub-systems, only the sub-system in focus will have their reception simulated.

Due to not being able to have two separate values for σ_N^2 for the AWGN channel, σ_N^2 will become constant and each sub-system's transmit power will be adjusted instead.

The formula for power adjustment is:

$$P_{adj} = \frac{P}{\sigma_N}$$

where in the case of the W-CDMA

$$\sigma_N = \sqrt{\frac{S_f}{2\frac{E_b}{N_0}}}$$

It should be noted that the spreading factor will be accounted for within the data throughput calculation and will be left out of the power adjustment for the underlay. As such the new σ_N will be

$$\sigma_N = \sqrt{\frac{1}{2\frac{E_b}{N_0}}}$$

If σ_N is now assumed to be set to 1 and the ratio between transmit power and σ_N must be maintained, therefore P_{adj} may be manipulated into become:

$$P_{adj,CDMA} = \frac{P}{\sigma_N}$$

$$P_{adj,CDMA} = \frac{P}{\sqrt{\frac{1}{2\frac{E_b}{N_0}}}}$$

$$P_{adj,CDMA} = \frac{P}{\sqrt{\frac{1}{2\frac{E_b}{N_0}}}} \frac{\sqrt{\frac{2\frac{E_b}{N_0}}{1}}}{\sqrt{\frac{2\frac{E_b}{N_0}}{1}}}$$

$$P_{adj,CDMA} = P\sqrt{2\frac{E_b}{N_0}} \tag{3.13}$$

Similarly for OFDM, if σ_N is assumed to be set to 1, then it can be stated that:

$$P_{adj,OFDM} = \frac{P}{\sigma_N}$$
$$P_{adj,OFDM} = \frac{P}{\sqrt{\left(4N_{IFFT}\frac{E_b}{N_0}\right)^{-1}}}$$
$$P_{adj,OFDM} = \frac{P}{\sqrt{\left(4N_{IFFT}\frac{E_b}{N_0}\right)^{-1}}} \frac{\sqrt{\left(4N_{IFFT}\frac{E_b}{N_0}\right)}}{\sqrt{\left(4N_{IFFT}\frac{E_b}{N_0}\right)}}$$
$$P_{adj,OFDM} = P\sqrt{\left(4N_{IFFT}\frac{E_b}{N_0}\right)} \tag{3.14}$$

Additional difficulties arise with the underlay when the two sub-systems transmission data-rate is different. In order to infect the sub-systems with noise and interference appropriately, both the sub-systems and the vector of σ_N must be of the same length. The OFDM sub-system will take a binary data block of length L and reduce it to $\frac{L}{\log_2(M)}$, where M is the order of the M-ary PSK modulation. Since QPSK is selected, the length of vector for each OFDM symbol becomes $\frac{L}{2}$.

In the CDMA sub-system, the length of the input binary data of block length L would not be effected since BPSK modulation is used. However the CDMA sub-system spreads the data after modulation and as such the length of a W-CDMA symbol becomes $L \times S_f$.

To match the two sub-system's vector lengths, the W-CDMA's input data block length must become:

$$L_{CDMA} = \frac{L_{OFDM}}{2 \times S_f} \tag{3.15}$$

The following is the algorithm used to simulate the underlay:

- The OFDM system will have an $\frac{E_b}{N_0}$ range of 2 dB to 8 dB (with 2 dB intervals).
- The CDMA system will have $\frac{E_b}{N_0}$ values of -4 -1.5917[3], 0, 2, 4 and 6(all in dB).
- Two different sets of random binary data is generated, The OFDM will have a block length 256 with N_{IFFT} length of 128; and CDMA will have block length of $128 \times S_f$
- The W-CDMA system will modulate using BPSK then spread the data according to the SF.

[3]This $\frac{E_b}{N_0}$ value is the theoretical bound for which a CDMA system can communicate in an OFDM underlay

- The OFDM system will modulate using QPSK then use IFFT to allocate data to sub-carriers.
- Both systems will transmit in the same AWGN channel.
- Both sub-systems will adjust their powers, CDMA will use equation 3.13 and OFDM will use 3.14.
- Depending on which sub-system is in focus, the in focus sub-system will receive a signal and the other sub-system will not.
- If the W-CDMA system is in focus it will initially despread then demodulate.
- If the OFDM system is in focus it will firstly use an FFT and then demodulate.
- The system in focus will then calculate and graph the P_b by modulo 2 summing the received data and transmitted data.

3.3.2 Assumptions

There are certain assumptions which have been made within this work. The general assumptions involving the nature of the system models will be explained in this section and specific explanation will be presented when certain equations are used or when required.

In this paper, it is assumed that the transmission channel is only occupied by the underlay sub-systems and an AWGN. No multi-path fading, shadowing or Doppler frequency shift occurs. It is assumed that in both of the sub-systems the transmitter and receiver have full phase-coherence.

3.3.3 Data throughput

The total throughput of the underlay system can be evaluated by

$$\begin{aligned} R_{b,total} &= R_{b,OFDM} + R_{b,CDMA} \\ R_{b,OFDM} &= R_{s,OFDM} \times f_s \\ R_{b,CDMA} &= \frac{R_{s,CDMA} \times f_s}{S_f} \\ R_{s,OFDM} = \log_2(4) = 2, &\quad R_{s,CDMA} = \log_2(2) = 1 \\ R_{b,total} &= 2f_s + \frac{1f_s}{S_f} \end{aligned} \tag{3.16}$$

Using the above equation we can evaluate the bandwidth efficiency

$$\begin{aligned} \frac{R_{b,total}}{W} &= 2f_s + \frac{f_s}{S_f} \\ \frac{R_{b,total}}{W} &= 2 + \frac{1}{S_f} \end{aligned} \tag{3.17}$$

Where f_s is the sampling frequency and is equal to bandwidth W.

Using equation 3.17, we may determine the probability of the amount of effective bits the underlay may transmit at. Given a certain P_b, the amount of bits transmitted for the entire underlay can be represented as:

$$\Big(\frac{R_{b,total}}{W}\Big)_{eff} = (2(1 - P_{b,OFDM})) + (\frac{1}{S_f}(1 - P_{b,CDMA})) \tag{3.18}$$

3.4 Image degradation

After acquiring the P_b vs $\frac{E_b}{N_0}$, for a better illustration of how each system performs, they will then use data from an image to transmit instead of randomly generated data. After receiving and processing the corrupted image data, the image will be reconstructed to show what the systems performance was.
The image is loaded into MATLAB as a 3 by x by y uint8 matrix. Where 3 is the values for Red, Green and Blue (RGB), x is the width of the image and y is the height. It will then be converted into binary data held as doubles in 1 by n matrix; where $n = 3 \times x \times y$ and processed as it would have normally done with randomly generated data. Upon receiving the data, it will be converted into uint8 and reshaped into a 3 by x by y matrix.

For the image degradation algorithm, all systems no longer require a set amount of bit errors to stop the simulation, rather upon completing the transmission of the image data, the simulation will come to an end.

Chapter 4

Simulation and results

4.1 W-CDMA

In spread spectrum systems, different spreading factors will greatly affect their performance, hence the W-CDMA is being evaluated at different spreading factors to seek what performance levels it can achieve.

Spreading factor of 1

The following figures were simulated using the model described by in section 3.1. Figure 4.1 is the P_b vs $\frac{E_b}{N_0}$ of a single user W-CDMA system with no spreading.

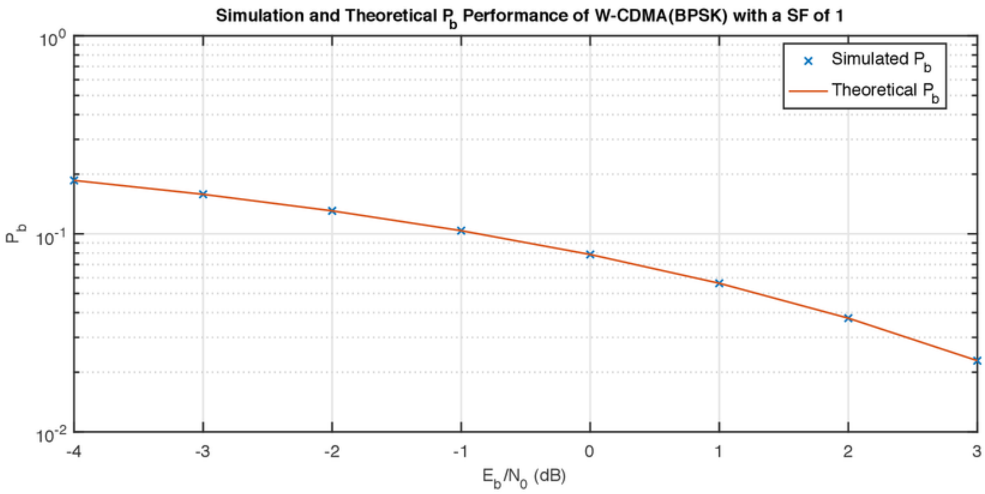

Figure 4.1: Single user W-CDMA with spreading factor of 1

Figure 4.2 is the image degradation, showing a visual illustration of what the P_b is at different $\frac{E_b}{N_0}$ values. It should be noted that the algorithm for simulating the transfer of the image, uses the base RGB values as data rather than compressing the RGB values then transferring. As such the degradation seen within these images is a more accurate representation of the P_b, rather than how the system would perform if used to transfer an image realistically.

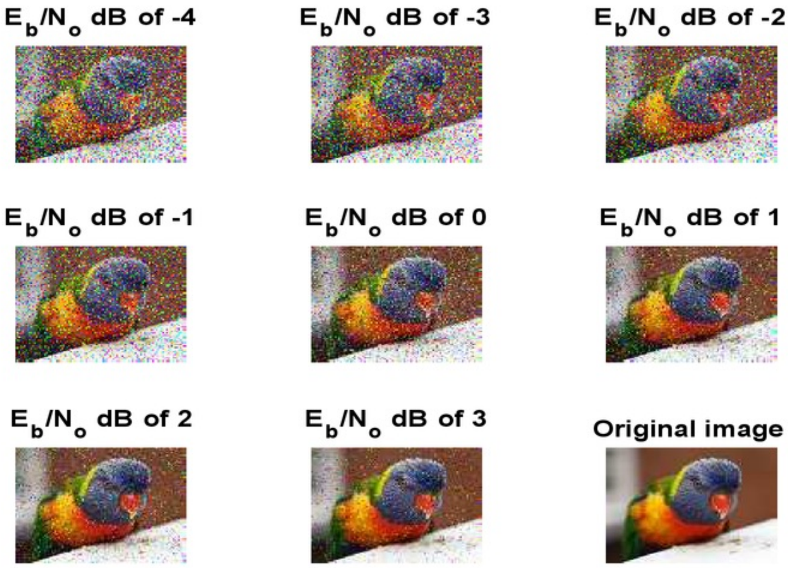

Figure 4.2: Image degradation with a S_f of 1

Spreading factor of 4

Figure 4.3 is the P_b vs $\frac{E_b}{N_0}$ and figure 4.4 is the image degradation, both done with a S_f of 4. The spreading factor has been increased by 4 fold and the P_b has dropped exponentially. It can be seen that the same P_b can be achieved with a lower $\frac{E_b}{N_0}$ using a higher S_f. It should be noted that although the P_b is tremendously lower at a higher S_f, the data-rate drops accordingly.

Spreading factor of 16

Similarly, figure 4.5 is the P_b vs $\frac{E_b}{N_0}$ and figure 4.6 is the image degradation, both done with a S_f of 16. It can be seen that the P_b is so improbable that almost all image are identical to the original. Although at the same $\frac{E_b}{N_0}$ the CDMA system with a higher S_f achieves a much lower P_b, it should be stated that its data rate is lower by a factor of S_f as well.

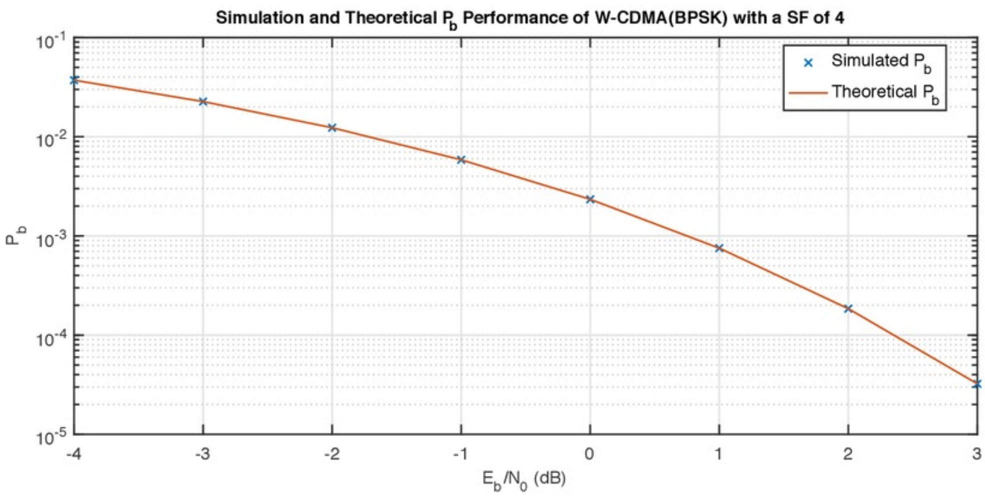

Figure 4.3: single user W-CDMA with spreading factor of 4

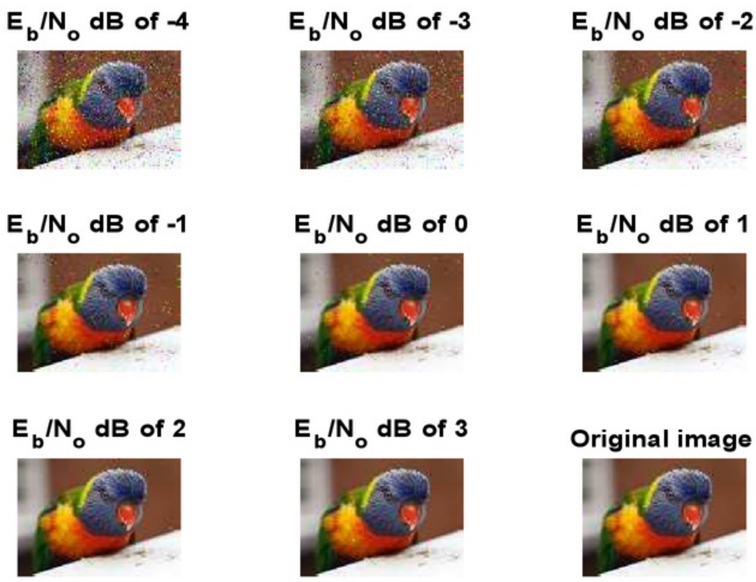

Figure 4.4: Image degradation with a S_f of 4

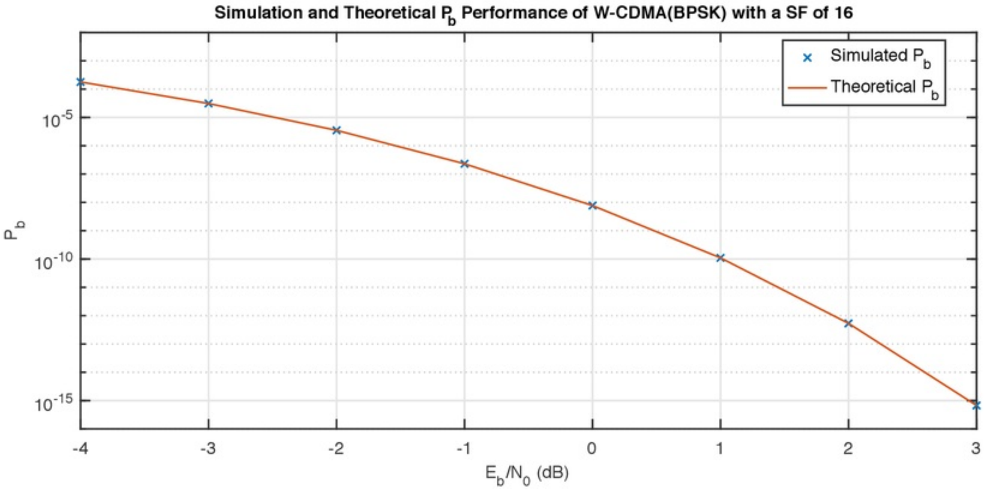

Figure 4.5: single user W-CDMA with spreading factor of 16

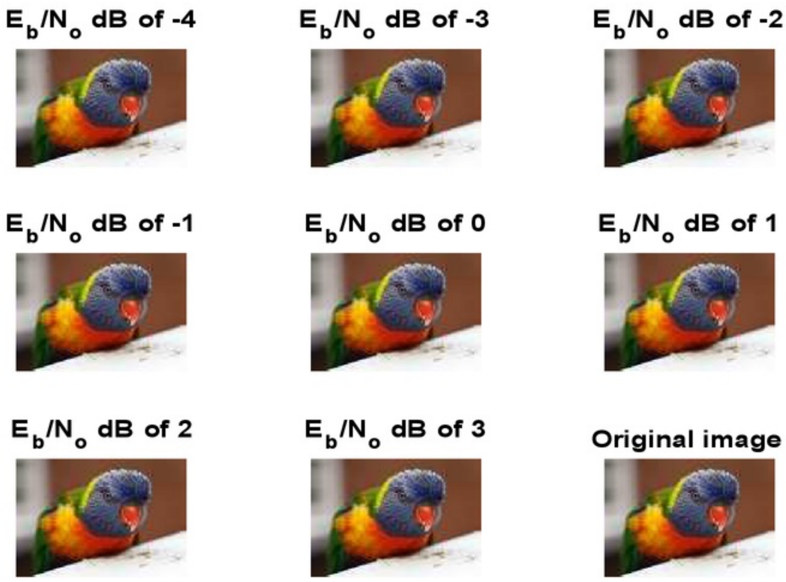

Figure 4.6: Image degradation with a S_f of 16

4.2 OFDM

Figure 4.7 is the P_b vs $\frac{E_b}{N_0}$ of a single user OFDM system with the number of sub-carriers being 128, the exact details of the model has been described in section 3.2. The theoretical

P_b vs $\frac{E_b}{N_0}$ curve for an OFDM system follows the base modulation used, which in this case was QPSK. Although a single user was simulated, the number of users can be extended to 128 with the graph being identical due to the orthogonal nature of the sub-carriers in OFDM.

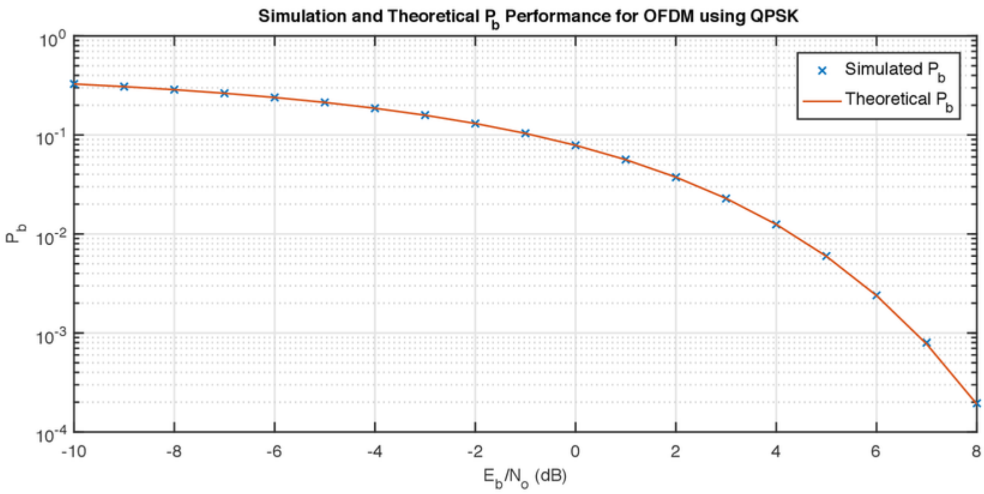

Figure 4.7: OFDM Simulation

Figure 4.8 shows the image degradation of the OFDM system. As before mentioned the severity of degradation is not as it would have been if compression (ex. JPEG) was initially done before the transmission. With lower values of $\frac{E_b}{N_0}$ the image becomes blurry and pixels become misplaced, this is due to noise and corruption in the transmitted signal that carries over into the FFT process, which is the reason why the colour of the pixels are relatively the same.

4.3 Underlay

In this section, both sub-systems of the underlay will be examined. The models used to simulate their performance have been described in detail in section 3.3.

4.3.1 W-CDMA performance

Initially, the performance of the W-CDMA sub-system will be examined in detail. Both sub-systems are initialised and modulated, but in this section only the W-CDMA will be demodulated and graphed. The OFDM sub-system will be used to corrupt the W-CDMA systems signal. For each value of the $\frac{E_b}{N_0}$ assigned to the OFDM, the PU will adjust its power accordingly; the CDMA runs through a series of its own assigned $\frac{E_b}{N_0}$ values and

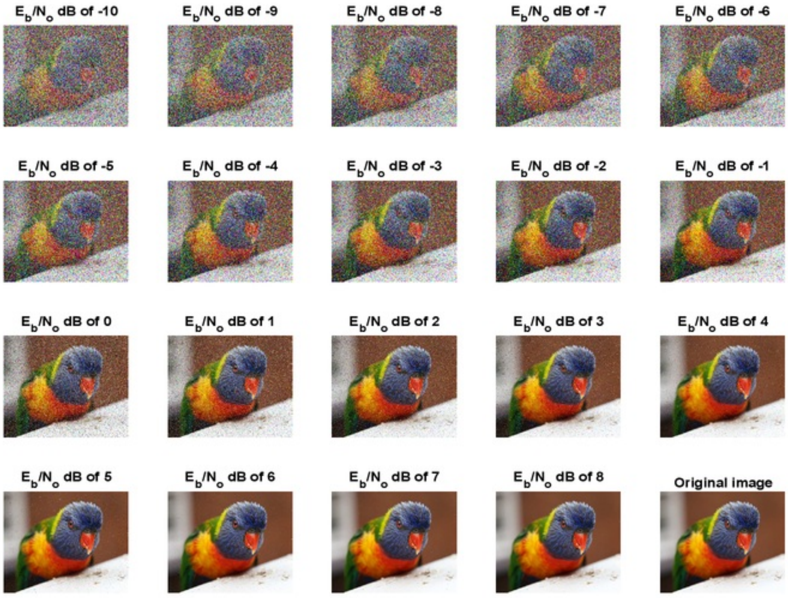

Figure 4.8: Image degradation of an OFDM system

also adjusts its transmit power without accounting for the S_f. If the S_f was accounted for in the power transmission instead of data throughput, the different graphs of different spreading factors would look identical.

Figure 4.9 is the underlay system where the W-CDMA has no spreading in action. The SU is affected by the OFDM interference at 2 dB power and the performance degradation exponentially increases with higher OFDM power levels. With no spreading the W-CDMA is heavily degraded and at all levels of OFDM interference, the W-CDMA has a P_b of 0.2 or higher. Even with W-CDMAs immense robustness towards interference, there are limits to how much the SU's signals may be corrupted and still sustain a connection.

The W-CDMA sub-system adapting a S_f of 4 can be seen to perform much better than the S_f of 1 system and likewise the S_f of 16 system compared to the S_f of 4 and 1 systems. It should be noted that the theoretical CDMA with no interference shown here, is the theoretical CDMA performance with no OFDM interference or spreading applied; in contrast, to the theoretical values for the CDMA shown in figures 4.4 and 4.6 which show the theoretical performance with CDMA with the S_f accounted for in the E_b calculations.

4.3.2 OFDM performance

In this section, the underlay will be examined with the PU being the main focus. As described in both 3.3 and 4.3.1, when the OFDM is the sub-system that is in focus, the

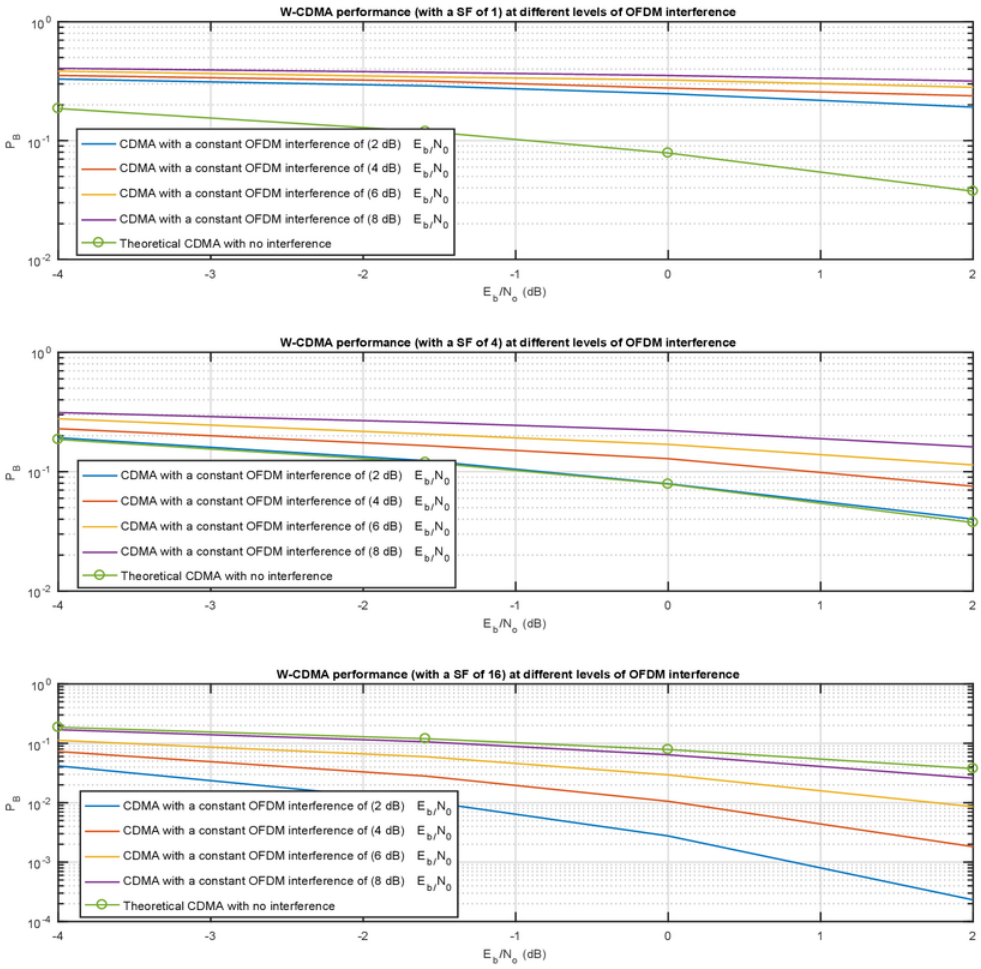

Figure 4.9: Underlay (W-CDMA focused) with different spreading factors at the same transmission power levels

W-CDMA will only be simulated until the channel transmission and the OFDM will be fully simulated. The effect of S_f on the W-CDMA in this section will be on the transmitted power of the W-CDMA. The W-CDMA will achieve the same P_b it would have with a S_f of 1, at any S_f, by decreasing the power it transmits at; resulting to lower interference to the OFDM.

The performance of the underlay with the SU having no spreading applied to it, can be seen in figure 4.10. The Figure shows the performance of the OFDM sub-system within the underlaid network. At all levels of W-CDMA interference, there is noticeable interference. The power levels at which these sub-systems transmit at, should be strongly taken into account when designing an underlay system, due to the amount of interference they cause to one another with the CDMA system at a S_f of 1.

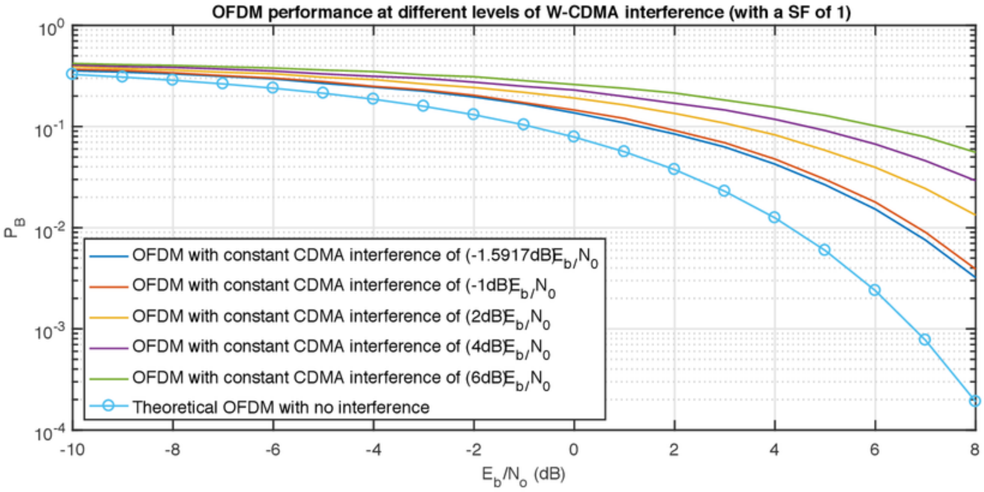

Figure 4.10: Underlay of OFDM with W-CDMA power adjustment based on S_f of 1

Figure 4.11, 4.12 and 4.13 are the underlay systems, with the W-CDMA sub-systems adapting a S_f of 4, 16 and 512 respectively. For the underlay at a S_f of 4, it can be seen that at lower levels of the OFDM $\frac{E_b}{N_0}$, the different underlays at different S_f perform near identically and the interference from the W-CDMA starts becomes apparent around 0 dB. The 1 and 4 S_f underlays have major performance degradation caused to them by the W-CDMA at an interference level of 2 dB or above. In contrast the underlays at a S_f of 16 and 512 have no major performance degradation. In the underlay with a S_f of 512, the system performs almost identical to its theoretical, confirming the reduction of performance degradation on the OFDM from the W-CDMA, as the S_f is increased due to being able to achieve the same P_b using lower power levels.

4.3.3 Data throughput

In this section, the underlay's total effective data throughput efficiency will be analysed. In figure 4.14, the system was tested at different spreading levels to determine whether the increase in processing gain will be beneficial in terms of performance gain it brings against the amount of effective data-throughput lost in increasing the spreading factor. As such in this section the spreading factor does not affect the transmit power of the W-CDMA, as it is already accounted for in the data throughput calculations. The underlay's performance was tested in effective bits transmitted per second per hertz. The bandwidth of the system may be set to any arbitrary value as this graph shows the effective bits per

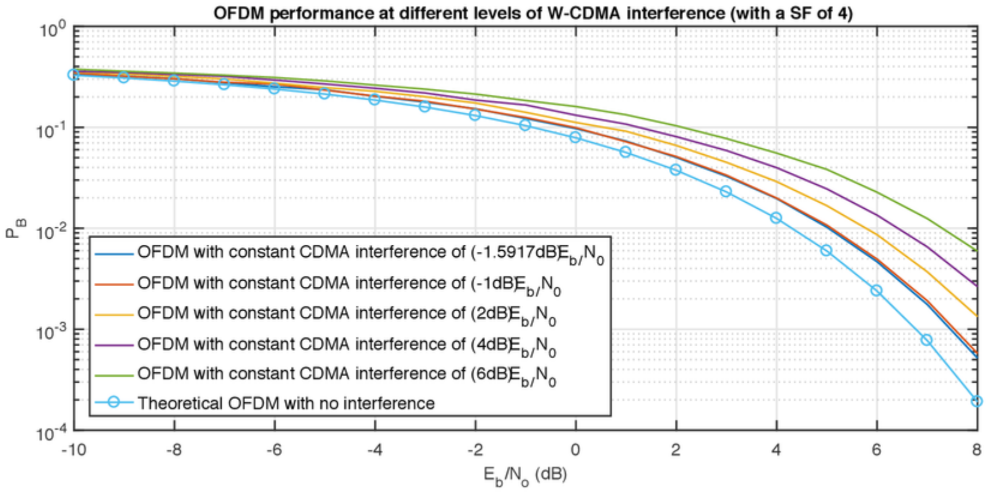

Figure 4.11: OFDM with W-CDMA (S_f of 4) underlay

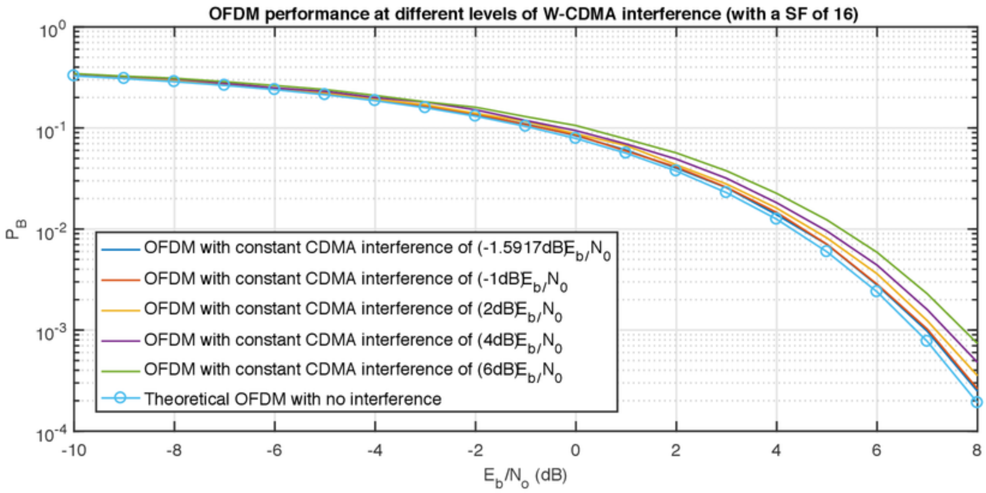

Figure 4.12: OFDM with W-CDMA (S_f of 16) underlay

second per hertz of bandwidth allocated.
It can be seen that the highest effective bits per second per hertz is achieved with no spreading. The theoretical data rate bound for which this underlay may transmit at is limited to 3 bits per second per hertz. The underlay manages to close the gap to this bound with W-CDMA system at 2 dB $\frac{E_b}{N_0}$ and the OFDM at 8 dB $\frac{E_b}{N_0}$. At lower levels of W-CDMA power the high power interference from the OFDM system causes

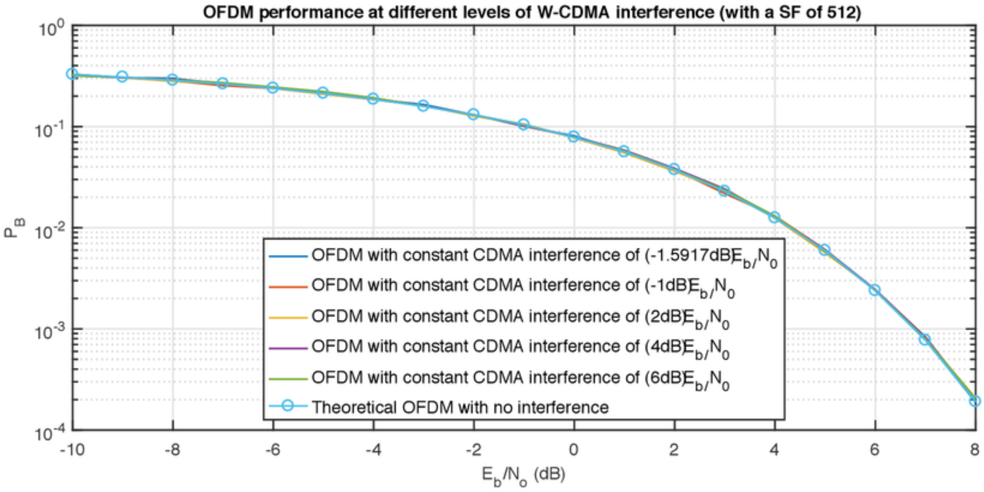

Figure 4.13: OFDM with W-CDMA (S_f of 512) underlay

major degradation to the W-CDMA and therefore to obtain the optimal effective data throughput for the entire underlay, lower levels of OFDM power must be transmitted at lower W-CDMA powers.

As the spreading factor is increased the amount of data the W-CDMA can transmit per second is decreased in proportion to the increase in processing gain. As such the system at a S_f of 4 transmits a lower data throughput but the system efficiency for the energy spent per bit is higher. The same concept is further extended for a S_f of 16. It should be noted that although the underlay's bandwidth efficiency is higher, with a S_f of 1, the amount of degradation to the OFDM is significantly greater and must be accounted for. If there are strict limitations and restrictions on what the maximum P_b or performance that the OFDM can have, a higher S_f for the W-CDMA is strongly recommended.

In this paper, the modulation orders of the two sub-systems were of lower orders and as such can tolerate interference to a higher extent than if they were 16-PSK/QAM or 64-PSK/QAM. This is one of the reasons why the effective bits/s/Hz of the S_f of 1 underlay was higher than the higher spreading factors, otherwise if the modulation orders were of a higher degree, not only would there be a clear advantage in having a higher S_f but also require a minimum processing gain to maintain functional.

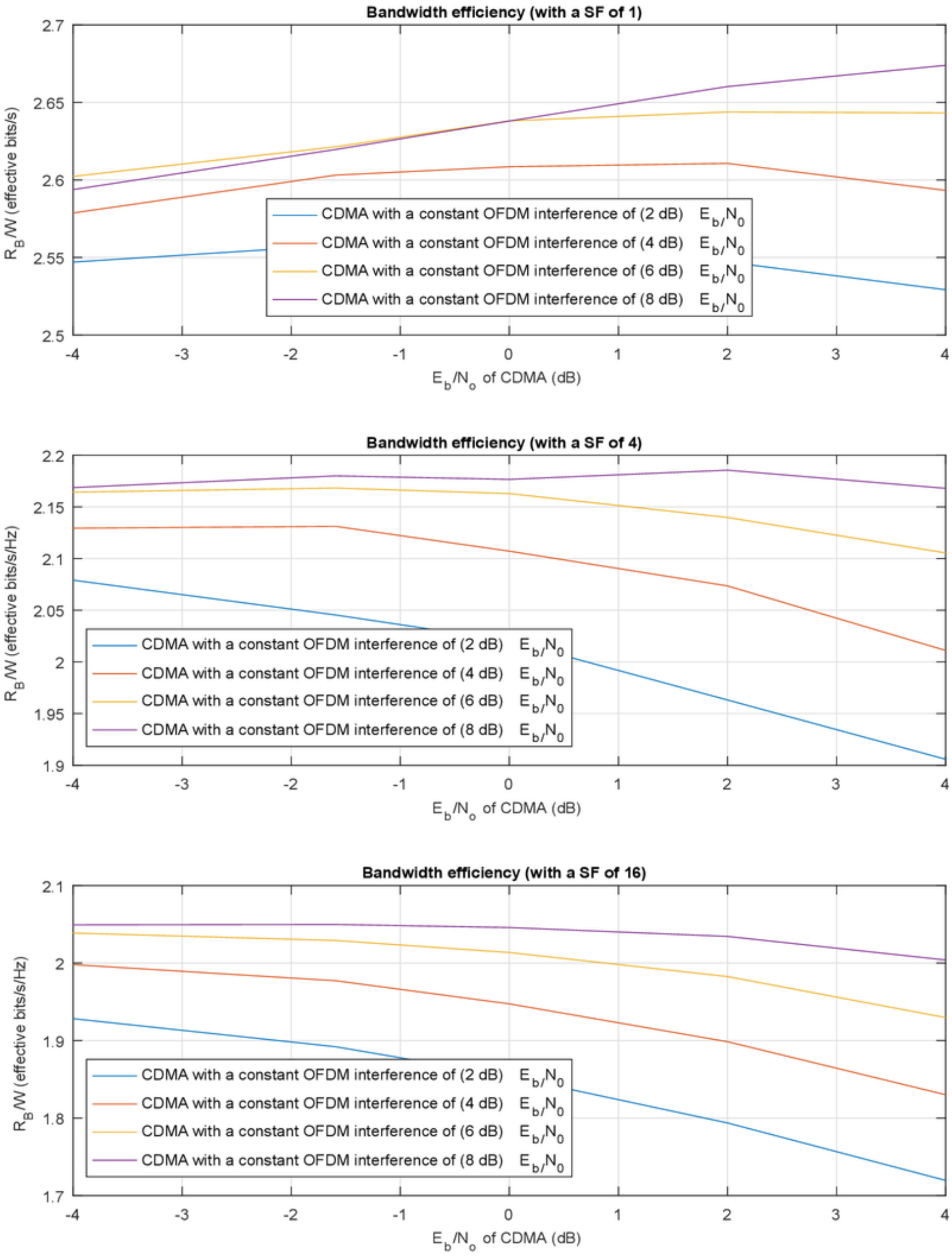

Figure 4.14: Underlay probabilistic bandwidth efficiency at different spreading factors

Chapter 5

Conclusions and future Work

5.1 Conclusion

The main focus of this paper was to increase the spectrum usage efficiency using a CRN underlay of an OFDM PU and a W-CDMA SU. The performance of the underlay was measured using P_b and bandwidth efficiency R/W. The P_b of the two sub-systems were evaluated individually, in addition to a detailed simulation of their individual performance when working in conjunction with each other within the underlay. The underlay network was evaluated with the W-CDMA using different S_f to seek what effects the spreading has on the different aspects of the underlay.

It was observed that with an increased S_f the performance of the W-CDMA drastically improves and can reach the same P_b using a significantly lower $\frac{E_b}{N_0}$. As such to not cause any major degradation to the performance of the OFDM sub-system, either a high S_f is recommended or low power allocation to the W-CDMA. From figures 4.10-4.12 it is evident that the W-CDMA with a $\frac{E_b}{N_0}$ of 2 dB or higher causes major degradation to the OFDM and therefore only a range of 2 dB $\frac{E_b}{N_0}$ or lower was used in the underlay system used for data throughput calculations.

Figure 4.14 shows the underlay's bandwidth efficiency which was used to seek what is the effective bit rate at certain power levels within the underlay and at what spreading factors. It was shown that the underlay with no spreading achieves the highest data throughput efficiency and the highest spreading factor of 16 has the lowest. This was explained to be caused by a number of reasons, mainly the spreading factor cutting the data rate by the factor of spreading, in addition to the low order modulations selected which are significantly more robust to noise and interference than higher orders, causing the spreading to do more harm than good.

5.2 Future work

Certain improvements and possible direction this research could have been looked into If more time was present while doing the project, such as:

- In section 3.1 the proposed W-CDMA system was assumed to have a single user. A possible improvement could be a multi-user W-CDMA. Although the design and generation of the PN codes are intended to create orthogonality between the different users, there is still some interference between the codes and as such will have an effect on the system (OFDM has full orthogonality between all sub-carriers and has no difference whether a single user is using all sub-channels or only one sub-carrier per user).

- Also in section 3.1, it was stated that PN codes of M=511 were used. The type of PN codes used are MLSR, therefore a possible improvement to the W-CDMA could be the integration of Gold/Kasami Codes instead of MLSR codes for the spreading of W-CDMA. Gold/Kasami Codes are known for their better auto- and cross-correlations properties and will therefore caused the different PN codes to become more orthogonal to one another, increasing system efficiency.

- In chapter 3, the OFDM and W-CDMA sub-systems used QPSK and BPSK modulation. Possible further research and improvement would be the evaluation of different modulation orders for the different sub-systems. As mentioned the selection of lower order modulations which are significantly more robust to noise and interference have rendered the spreading factor less useful in this case study and as such increasing the order of modulation could significantly increase both overall underlay efficiency and create a greater need for a minimum processing gain.

- Finally, another possible direction the project could be pushed towards could be the evaluation of the underlay if the W-CDMA were to have convolution coding to be able to further reduce the amount of power it can transmit to achieve the same P_b. Much like a spreading factor, convolution coding decreases the data throughput in lieu of increases the $\frac{E_b}{N_0}$ vs P_b efficiency.

Chapter 6

Abbreviations

AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
BS	Base Station
CDMA	Code Division Multiple Access
CR	Cognitive Network
CRN	Cognitive Radio Network
D2D	Device-to-Device
DFT	Discrete Fourier Transform
DS-CDMA	Direct Sequence-Code Division Multiple Access
$\frac{E_b}{N_0}$	Energy per bit vs Power Spectral density
E_b	Energy per bit
FFT	Fast Fourier Transform
IC	Integrated Circuit
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IoT	Internet of Things
LSR	Linear Shift Register
M2M	Machine-to-Machine
M-ary PSK	M-ary Phase Shift Keying
M-ary QAM	M-ary Quadrature amplitude modulation
MC-CDMA	Multicarrier-CDMA
MLSR	Maximum Linear Shift Register
N_0	Power Spectral Density of Noise
OFDM	Orthogonal Frequency Division Modulation
OVSF	Orthogonal Variable Spreading Factor
P_b	Probability of bit error
PSD	Power Spectral density
PU	Primary User
QPSK	Quadrature Phase Shift Keying
RGB	Red Green Blue

S_f	Spreading Factor
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SU	Secondary User
W-CDMA	Wideband Code Division Multiple Access

Appendix A

MATLAB codes

```
%Author: Amirali Emami
%BER vs Eb_N0 for DC-CDMA simulation vs theroretical for one user
%25/09/2017
clc
clear
%-----------------------------------------------
Eb_N0_dB=-4:1:3; %energy per bit over noise in dB
N=100; %number of bit errors for error determination (not used here
 for image)

SF = 16; % spreading factor
Data_R=[]; %data recieved

%Loading image data
Imgdata = imread('par2.jpg');
[imw,imh,im3] = size(Imgdata); %image vector dimensions
%reshaping data for processing
Imgdata2=Imgdata(:);
databin=cell2mat(cellstr(dec2bin(Imgdata2,8))');
Data=ones(1,length(databin));
for count= 1:1:length(databin)
    Data(count)=str2double(databin(count));
end
blocklength = length(Data);

%Calling upon a function to get PN sequence
%the input to the PNGEN function is a seed and output is the pn
 sequence
PN_Data=PNGEN(ones(9,1));

Eb_No =10.^(Eb_N0_dB./10); %translating into linear from decibel
figure(1)
for iiEbNo= 1:length(Eb_No)
    N_errors=0;   %counter for number of bit errors
    N_bits=0; %counter for number of bits

    sigma_n=1;% Noise standard deviation
    Cond=0; %N bits errors not occured yet

    while Cond==0

        Data_C=[]; %Data with rate extened to chip rate
        %placed here to reset Data with every iteration
        N_bits=N_bits+blocklength;

        phidab=ones(1,blocklength);
        for ii=1:length(Data)  % Generate BPSK phases
            a=Data(ii);
            if a==0
                phidab(ii)=0;
            elseif a==1
                phidab(ii)=pi;
            end
```

```
        end


        % Generate the signal vector for the block
        for ii=1:blocklength
            Data_C((ii-1)*SF+1:ii*SF)=exp(j*phidab(ii)).*ones(1,SF);
        end

        %the spreading
        PN_ind=1; %for iterating through PN_Data
        for k=1:length(Data_C)
            if PN_ind==length(PN_Data)
                PN_ind=1;
            end
            Data_T(k)=Data_C(k)*PN_Data(PN_ind);
            PN_ind=PN_ind+1;
        end
        Data_T=Data_T*sqrt(2*Eb_No(iiEbNo)); %correcting the signal
power to Eb/N0

        %creating noise vectors
        n=sigma_n.*(randn(1,SF*blocklength));

        %COMMUNICATIONS CHANNEL
        y=Data_T+n;

        %despreading
        PN_ind=1; %for iterating through PN_Data
        for i=1:length(y)
            if PN_ind==length(PN_Data)
                PN_ind=1;
            end
            y(i)=y(i)*PN_Data(PN_ind);
            PN_ind=PN_ind+1;
        end

        %decision maker
        iir=0;    % Counter on the bit number in a block
        for ii=1:blocklength % symbol detection loop
            u=real(sum(y((ii-1)*SF+1:ii*SF)));  % Sum real samples
            % bit detection
            iir=iir+1;
            if u>0
                Data_R(iir)=0;
            else
                Data_R(iir)=1;
            end
        end

        %error counting
        errornumber=sum(mod((Data+Data_R),2));
        N_errors=N_errors+errornumber;
        Cond=1;

        %reshaping recieve image data for processing
```

```
        datarec=dec2bin(Data_R)';
        for count2= 1:1:(length(Data_R)/8)

 datarec1(count2)=bin2dec(datarec(((count2*8)-7):count2*8));
        end
        datarec2=datarec1';
        datarec3=reshape(datarec2,imw,imh,3);
        %drawing the images
        subplot(3,3,iiEbNo),imshow(uint8(datarec3))
        title(['{E_b/N_o dB} of ' num2str(Eb_N0_dB(iiEbNo))])

    end
    PB(iiEbNo)=N_errors/N_bits;
end
%drawing the orignial image
subplot(3,3,9),imshow(Imgdata)
title('Original image')
```

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```
function PN_D=PNGEN(x)

Q=[9, 8, 7, 6, 5, 3];
% x_new(1)=g(m-1)*x(1)+g(m-2)*x(2)+...+g(1)*x(m-1)+x(m)
% Create the coefficients defining the code
m=Q(1);  % The length of the shift register
% Initialize the g(k) coefficients
g(1:m-1)=0;
g(m)=1;
g_zero=1;
for k1=2:length(Q)
    for k=1:m-1
        if m-k==Q(k1)
            g(m-k)=1;
        end
    end
end
% Create the initial conditions for the shift register
x=ones(m,1);
% Create the shift matrix
A=zeros(m,m);
for k=1:m-1
    A(k+1,k)=1;
end
for k=1:(2^m-1)

    % shift the register contents
    x_new=A*x;
    x_new(1)=0;
    for n=1:m-1
        x_new(1)=x_new(1)+x(n)*g(m-n);
    end
    x_new(1)=mod(x_new(1)+x(m),2);
    z(k)=x_new(1);
    x=x_new;
end
for i=1:length(z)
    if z(i)==0
        PN_D(i)=1;
    else
        PN_D(i)=-1;
    end
end
```

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```
%Author: Amirali Emami
%Supervisor: A/Prof Sam Reisenfeld
%22/08/2017
%Macquarie University
%Thesis project
clc
clear

%Loading image data
Imgdata = imread('parrot.jpg');
[imw,imh,im3] = size(Imgdata);
Imgdata2=Imgdata(:);
databin=cell2mat(cellstr(dec2bin(Imgdata2,8))');
data=ones(1,length(databin));
for count= 1:1:length(databin)
   data(count)=str2double(databin(count));
end

Eb_No_dB=-10:1:8;% Eb_No_dB
N=1;% The number of bit error counted
blocklength=length(data);  % The bit error rate is obtained in blocks
 of data
N_fftlength=blocklength/2;
```

Derived parameters

```
Eb_No=10.^(Eb_No_dB./10);
figure(1)
for iiEbNo=1:length(Eb_No) % Eb/No loop
    N_errors=0; % Counter for the number of bit errors
    N_bits=0;   % Counter for the number of bits

    sigma_n=1;

      condition=0;  % N bit error not yet obtained
    while condition ==0
        N_bits=N_bits+blocklength;

        %modulation into QPSK
        phi=ones(1,blocklength/2);
        for ii=1:2:blocklength   % Generate QPSK phases
            a=data(ii);
            b=data(ii+1);
            if a==0 & b==0
                phi(ii/2+1/2)=pi/4;
            elseif a==1 & b==0
                phi(ii/2+1/2)=3*pi/4;
            elseif a==1 & b==1
                phi(ii/2+1/2)=5*pi/4;
            else
                phi(ii/2+1/2)=7*pi/4;
            end
        end
```

```
        for ii=1:blocklength/2
            x((ii-1)+1:ii)=exp(j*phi(ii));
        end
        Tx=ifft(x,N_fftlength); %Sub-carrier generation


        %Signal power adjustment according to Eb/N0
        Tx=Tx.*sqrt((N_fftlength.*4*(Eb_No(iiEbNo))));

%_______________________________________________________________
        % Generate the noise vector
        n=sigma_n.*(randn(1,N_fftlength)+ ...
             1i.*randn(1,N_fftlength));

%_______________________________________________________________
        y=Tx+n;      % COMMUNICATIONS CHANNEL

%_______________________________________________________________
        %OFDM RECEPTION
        %Downconversion
        Rx=fft(y,N_fftlength);
        iir=0;
        datar=ones(1,blocklength);

        for k=1:length(Rx) % symbol detection loop
            u=real(Rx(k));
            v=imag(Rx(k));
            iir=iir+1;
            if u>0
                datar(iir)=0;
            else
                datar(iir)=1;
            end
            iir=iir+1;
            if v>0
                datar(iir)=0;
            else
                datar(iir)=1;
            end
        end
        errornumber=sum(mod(data+datar,2));
        %number of bit errors in a block
        condition=1;
        N_errors=N_errors+errornumber; % Total number of bit errors

    end

    %image data reshaping for processing
       datarec=dec2bin(datar)';
      for count2= 1:1:(length(datar)/8)
 datarec1(count2)=bin2dec(datarec(((count2*8)-7):count2*8));
      end
     datarec2=datarec1';
     datarec3=reshape(datarec2,imw,imh,3);
```

```
     subplot(4,5,iiEbNo),imshow(uint8(datarec3))
    title(['{E_b/N_o dB} of ' num2str(Eb_No_dB(iiEbNo))])
        clc
        PB(iiEbNo)=N_errors/N_bits; % bit error rate estimate
        for i=1:iiEbNo
            fprintf('Eb/No_dB=%14.6f,   PB=%14.6e
\n',Eb_No_dB(i),PB(i))
        end
end

subplot(4,5,20),imshow(Imgdata)
title('Original image')

           PB_theory=qfunc(sqrt(2.*Eb_No));
           figure(2)
           semilogy(Eb_No_dB,PB,'x',Eb_No_dB,PB_theory)
           grid
           xlabel('E_b/N_o (dB)')
           ylabel('P_{b}')
           title('Simulation and Theoretical P_{b} Performance for OFDM using QPSK
           legend('Simulated P_{b}','Theoretical P_{b}')
```

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```
%Author: Amirali Emami
%Supervisor: A/Prof Sam Reisenfeld
%20/10/2017
%Macquarie University
%Thesis project
clc
clear

%OFDM initilisation
Eb_No_dB_OFDM=2:2:8;
N=1000; %The number of bit error to stop
blocklength_OFDM=1024;
N_fftlength=blocklength_OFDM/2;

%CDMA initilisation
specialval=10*log10(1/(log2(exp(1))));
Eb_No_dB_CDMA=[-4 specialval 0 2 4];
%Eb_No_dB_CDMA=0:1:5;
SF = [1 4 16]; % spreading factor

Data_R=[]; %data recieved
PN_Data=PNGEN(ones(9,1));

Eb_No_CDMA=10.^(Eb_No_dB_CDMA./10);
Eb_No_OFDM=10.^(Eb_No_dB_OFDM./10);

%probability of bit error matrix for each system
PBmat_OFDM=ones(length(Eb_No_dB_OFDM),length(Eb_No_dB_CDMA));
PBmat_CDMA=ones(length(Eb_No_dB_OFDM),length(Eb_No_dB_CDMA));
PB_OFDM=ones(1,length(Eb_No_dB_CDMA));
PB_CDMA=ones(1,length(Eb_No_dB_CDMA));

for isf = 1:3

    blocklength_CDMA=blocklength_OFDM/(SF(isf)*2);
    for iOFDM=1:length(Eb_No_OFDM)

        for iiEbNo=1:length(Eb_No_CDMA)

            N_errors_OFDM=0;
            N_bits_OFDM=0;
            N_bits_CDMA=0;
            N_errors_CDMA=0;

            sigma_n=1; %the transmitted signals will be amplified
 instead

            condition=0;
            while condition ==0

                N_bits_OFDM=N_bits_OFDM+blocklength_OFDM;
                N_bits_CDMA=N_bits_CDMA+blocklength_CDMA;
                Data_OFDM=randi([0,1],1,blocklength_OFDM);
```

```
Data_CDMA=randi([0,1],1,blocklength_CDMA);

%OFDM  modulation
phi=ones(1,blocklength_OFDM/2);
for ii=1:2:blocklength_OFDM   % Generating QPSK phases
    A1=Data_OFDM(ii);
    A2=Data_OFDM(ii+1);
    if A1==0 & A2==0
        phi(ii/2+1/2)=pi/4;
    elseif A1==1 & A2==0
        phi(ii/2+1/2)=3*pi/4;
    elseif A1==1 & A2==1
        phi(ii/2+1/2)=5*pi/4;
    else
        phi(ii/2+1/2)=7*pi/4;
    end
end
for ii=1:blocklength_OFDM/2
    sig_OFDM((ii-1)+1:ii)=exp(1i*phi(ii));
end
subcarinfo=ifft(sig_OFDM,N_fftlength); %Sub-carrier
generation
%adjust transmit power for current Eb/N0

Tx_OFDM=subcarinfo.*sqrt((N_fftlength.*4*(Eb_No_OFDM(iOFDM))));
Power_Tx_OFDM=var(Tx_OFDM);
%CDMA MOD

phi_CDMA=ones(1,blocklength_CDMA);
for ii=1:length(Data_CDMA)  % Generate BPSK phases
    B1=Data_CDMA(ii);
    if B1==0
        phi_CDMA(ii)=0;
    elseif B1==1
        phi_CDMA(ii)=pi;
    end
end
```

Generate the signal vector for the block

```
for ii=1:blocklength_CDMA

Data_C((ii-1)*SF(isf)+1:ii*SF(isf))=exp(1i*phi_CDMA(ii)).*ones(1,SF(isf));
end

%the spreading
DATA_T=ones(1,blocklength_CDMA*SF(isf));
PN_ind=1; %for iterating through PN_Data
for k=1:length(Data_C)
    if PN_ind==length(PN_Data)
        PN_ind=1;
    end
    DATA_T(k)=Data_C(k)*PN_Data(PN_ind);
    PN_ind=PN_ind+1;
end
```

```
%adjust transmit power for current Eb/N0
Tx_CDMA=DATA_T*sqrt(2*Eb_No_CDMA(iiEbNo));
%./(sqrt(SF(isf)));
Power_Tx_CDMA=var(Tx_CDMA);
```

Generate the noise vector

```
n=sigma_n.*(randn(1,N_fftlength)+ ...
    1i.*randn(1,N_fftlength));


%_____________________________________________________________
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Channel
y=n+Tx_CDMA+Tx_OFDM;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%_____________________________________________________________
%OFDM RECEPTION
%Downconversion
Rx_OFDM=fft(y,N_fftlength);
%decision maker (OFDM)
iir=0;
datar_OFDM=ones(1,blocklength_OFDM);
for k=1:length(Rx_OFDM)
    u1=real(Rx_OFDM(k));
    v1=imag(Rx_OFDM(k));
    iir=iir+1;
    if u1>0
        datar_OFDM(iir)=0;
    else
        datar_OFDM(iir)=1;
    end
    iir=iir+1;
    if v1>0
        datar_OFDM(iir)=0;
    else
        datar_OFDM(iir)=1;
    end
end

%CDMA reception
PN_ind=1; %for iterating through PN_Data
for i=1:length(y)
    if PN_ind==length(PN_Data)
        PN_ind=1;
    end
    y(i)=y(i)*PN_Data(PN_ind);
    PN_ind=PN_ind+1;
end

%decision maker (CDMA)
```

```
                Data_R=ones(1,blocklength_CDMA);
                iir=0;
                for ii=1:blocklength_CDMA
                    u=real(sum(y((ii-1)*SF(isf)+1:ii*SF(isf))));
                    iir=iir+1;
                    if u>0
                        Data_R(iir)=0;
                    else
                        Data_R(iir)=1;
                    end
                end

                errornumber_CDMA=sum(mod((Data_CDMA+Data_R),2));
                errornumber_OFDM=sum(mod(Data_OFDM+datar_OFDM,2));

                %number of bit errors in a block for the respective
sub-system
                N_errors_CDMA=N_errors_CDMA+errornumber_CDMA;
                N_errors_OFDM=N_errors_OFDM+errornumber_OFDM;
                % Total number of bit errors

                if (N_errors_CDMA>N && N_errors_OFDM>N)  % Condition
to terminate the simulation
                    condition=1;
                end

            end

            clc
            PB_CDMA(iiEbNo)=N_errors_CDMA/N_bits_CDMA;
            PB_OFDM(iiEbNo)=N_errors_OFDM/N_bits_OFDM;
            fprintf('for OFDM with Eb/No_dB=%14.6f,   spreding factor
%14.6f\n',Eb_No_dB_OFDM(iOFDM),SF(isf))
            for i=1:iiEbNo
                fprintf('Eb/No_dB of CDMA=%14.6f,   PB_CDMA=%14.6f,
PB_OFDM=%14.6e\n',Eb_No_dB_CDMA(i),PB_CDMA(i),PB_OFDM(i))
            end

        end

        PBmat_OFDM(iOFDM,:)=PB_OFDM;
        PBmat_CDMA(iOFDM,:)=PB_CDMA;

    end

    %generating a refrence Pb vs Eb/No theory
    PB_theory_CDMA=qfunc(sqrt(2.*Eb_No_CDMA));
    %for inclusion of spreading factor within Eb/N0 use below after
2.*
    %%%%
    %.*(SF(isf))
    %%%%
    %creating a color matrix for the legend
    figure(1)
    subplot(3,1,isf)
```

```
    %drawing the OFDM with constant CDMA
    for draw = 1:1:length(Eb_No_OFDM)
        semilogy(Eb_No_dB_CDMA,PBmat_CDMA(draw,:))
        hold on
        legendInfo{(draw)} = ['CDMA with a constant OFDM interference
 of (' num2str(Eb_No_dB_OFDM(draw)) ' dB) {E_b_/N_0}'];
    end
    semilogy(Eb_No_dB_CDMA,PB_theory_CDMA,'-o')
    legendInfo{(draw+1)}= ['Theoretical CDMA with no interference'];
    grid
    xlabel('E_b/N_o (dB)')
    ylabel('P_B')
    title(['W-CDMA performance (with a SF of ' num2str(SF(isf)) ') at
 different levels of OFDM interference'])
    legend('Location','best')
    legend(legendInfo)

    figure(2)
    subplot(3,1,isf)
    %drawing the OFDM with constant CDMA
    [s1,s2]=size(PBmat_CDMA);
    for draw = 1:s1
        for iter=1:s2
            Rb_CDMA(draw,iter)=1-PBmat_CDMA(draw,iter);
            Rb_OFDM(draw,iter)=1-PBmat_OFDM(draw,iter);
        end
    end
    Rb_total=2.*Rb_OFDM + Rb_CDMA./SF(isf);
    plot(Eb_No_dB_CDMA,Rb_total)
    grid
    xlabel('E_b/N_o of CDMA (dB)')
    ylabel('R_B/W (effective bits/s)')
    title(['Bandwidth efficiency (with a SF of '
 num2str(SF(isf)) ')'])
    legend(legendInfo)

end
```

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```
%Author: Amirali Emami
%Supervisor: A/Prof Sam Reisenfeld
%24/10/2017
%Macquarie University
%Thesis project
clc
clear

%OFDM initilisation
Eb_No_dB_OFDM=-10:1:8;% Eb_No_dB
N=2000;% The number of bit error counted
blocklength_OFDM=1024;  % The bit error rate is obtained in blocks of
 data
N_fftlength=blocklength_OFDM/2;

%CDMA initilisation
%special value is the bound for which CDMA can transmit at reliably
specialval=10*log10(1/(log2(exp(1))));
Eb_No_dB_CDMA=[-4 specialval 2 4 6];
SF = 512; % spreading factor
Nspb = SF; %number of samples per baud(symbol)
blocklength_CDMA=blocklength_OFDM/(SF*2);
Data_R=[]; %data recieved
PN_Data=PNGEN(ones(9,1));

Eb_No_CDMA=10.^(Eb_No_dB_CDMA./10);
Eb_No_OFDM=10.^(Eb_No_dB_OFDM./10);

PBmat_OFDM=ones(length(Eb_No_dB_CDMA),length(Eb_No_dB_OFDM));
PBmat_CDMA=ones(length(Eb_No_dB_CDMA),length(Eb_No_dB_OFDM));
PB_OFDM=ones(1,length(Eb_No_dB_OFDM));
PB_CDMA=ones(1,length(Eb_No_dB_OFDM));

for iCDMA=1:length(Eb_No_CDMA)

    for iiEbNo=1:length(Eb_No_OFDM) % Eb/No loop

        N_errors_OFDM=0; % Counter for the number of bit errors
        N_bits_OFDM=0;   % Counter for the number of bits
        N_bits_CDMA=0;
        N_errors_CDMA=0;
        sigma_n=1; %the transmitted signals will be amplified instead
        condition=0;  % N bit error not yet obtained
        while condition ==0

            N_bits_OFDM=N_bits_OFDM+blocklength_OFDM;
            N_bits_CDMA=N_bits_CDMA+blocklength_CDMA;
            Data_OFDM=randi([0,1],1,blocklength_OFDM); % Generated
 random Gaussian data
            Data_CDMA=randi([0,1],1,blocklength_CDMA);

            %OFDM  modulation
            phi=ones(1,blocklength_OFDM/2);
            for ii=1:2:blocklength_OFDM   % Generate QPSK phases
```

```
            A1=Data_OFDM(ii);
            A2=Data_OFDM(ii+1);
            if A1==0 & A2==0
                phi(ii/2+1/2)=pi/4;
            elseif A1==1 & A2==0
                phi(ii/2+1/2)=3*pi/4;
            elseif A1==1 & A2==1
                phi(ii/2+1/2)=5*pi/4;
            else
                phi(ii/2+1/2)=7*pi/4;
            end
        end
        for ii=1:blocklength_OFDM/2
            sig_OFDM((ii-1)+1:ii)=exp(1i*phi(ii));
        end
        subcarinfo=ifft(sig_OFDM,N_fftlength); %Sub-carrier
generation
        %adjust transmit power for current Eb/N0

Tx_OFDM=subcarinfo.*sqrt((N_fftlength.*4*(Eb_No_OFDM(iiEbNo))));
        Power_Tx_OFDM=var(Tx_OFDM);
        %CDMA modulation

        phi_CDMA=ones(1,blocklength_CDMA);
        for ii=1:length(Data_CDMA)  % Generate BPSK phases
            B1=Data_CDMA(ii);
            if B1==0
                phi_CDMA(ii)=0;
            elseif B1==1
                phi_CDMA(ii)=pi;
            end
        end
```

Generate the signal vector for the block

```
        for ii=1:blocklength_CDMA
            Data_C((ii-1)*Nspb
+1:ii*Nspb)=exp(1i*phi_CDMA(ii)).*ones(1,Nspb);
        end

        %the spreading
        DATA_T=ones(1,blocklength_CDMA*SF);
        PN_ind=1; %for iterating through PN_Data
        for k=1:length(Data_C)
            if PN_ind==length(PN_Data)
                PN_ind=1;
            end
            DATA_T(k)=Data_C(k)*PN_Data(PN_ind);
            PN_ind=PN_ind+1;
        end
        %adjust transmit power for current Eb/N0
        Tx_CDMA=DATA_T*sqrt(2*Eb_No_CDMA(iCDMA))/(sqrt(Nspb));
        Power_Tx_CDMA=var(Tx_CDMA);

        n=sigma_n.*(randn(1,N_fftlength)+ ...
```

```
        1i.*randn(1,N_fftlength));

  %______________________________________________________________
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%
    %Channel
    y=n+Tx_CDMA+Tx_OFDM;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

  %______________________________________________________________

    %OFDM RECEPTION
    %Downconversion
    Rx_OFDM=fft(y,N_fftlength);
    %decision maker (OFDM)
    iir=0;
    datar_OFDM=ones(1,blocklength_OFDM);
    for k=1:length(Rx_OFDM)
        u1=real(Rx_OFDM(k));
        v1=imag(Rx_OFDM(k));
        iir=iir+1;
        if u1>0
            datar_OFDM(iir)=0;
        else
            datar_OFDM(iir)=1;
        end
        iir=iir+1;
        if v1>0
            datar_OFDM(iir)=0;
        else
            datar_OFDM(iir)=1;
        end
    end

    %CDMA reception
    PN_ind=1; %for iterating through PN_Data
    for i=1:length(y)
        if PN_ind==length(PN_Data)
            PN_ind=1;
        end
        y(i)=y(i)*PN_Data(PN_ind);
        PN_ind=PN_ind+1;
    end

    %decision maker (CDMA)
    Data_R=ones(1,blocklength_CDMA);
    iir=0;
    for ii=1:blocklength_CDMA
        u=real(sum(y((ii-1)*Nspb+1:ii*Nspb)));

        iir=iir+1;
        if u>0
            Data_R(iir)=0;
        else
```

```
                        Data_R(iir)=1;
                    end
                end

                errornumber_CDMA=sum(mod((Data_CDMA+Data_R),2));
                errornumber_OFDM=sum(mod(Data_OFDM+datar_OFDM,2));
                %number of bit errors in a block for the respective sub-
system
                N_errors_CDMA=N_errors_CDMA+errornumber_CDMA;
                N_errors_OFDM=N_errors_OFDM+errornumber_OFDM; % Total
 number of bit errors

                if (N_errors_OFDM>N)  % Condition to terminate the
 simulation
                    condition=1;
                end

            end

            clc
            PB_OFDM(iiEbNo)=N_errors_OFDM/N_bits_OFDM; % bit error rate
 estimate
            PB_CDMA(iiEbNo)=N_errors_CDMA/N_bits_CDMA;
            fprintf('for CDMA with Eb/No_dB=%14.6f
\n',Eb_No_dB_CDMA(iCDMA))
            for i=1:iiEbNo
                fprintf('Eb/No_dB of OFDM=%14.6f,   PB_OFDM=%14.6f,
 PB_CDMA=%14.6e\n',Eb_No_dB_OFDM(i),PB_OFDM(i),PB_CDMA(i))
            end

        end

        PBmat_OFDM(iCDMA, :)=PB_OFDM;
        PBmat_CDMA(iCDMA, :)=PB_CDMA;

end

%generating a refrence Pb vs Eb/No theory
PB_theory_OFDM=qfunc(sqrt(2.*Eb_No_OFDM));
%creating a color matrix for the legend
figure(1)
%drawing the OFDM with constant CDMA
for draw = 1:1:length(Eb_No_CDMA)
    semilogy(Eb_No_dB_OFDM,PBmat_OFDM(draw,:))
    hold on
    legendInfo{(draw)} = ['OFDM with constant CDMA interference of ('
 num2str(Eb_No_dB_CDMA(draw)) 'dB) {E_b_/N_0}'];
end
semilogy(Eb_No_dB_OFDM,PB_theory_OFDM,'-o')
legendInfo{(draw+1)}= ['Theoretical OFDM with no interference'];
grid
xlabel('E_b/N_o (dB)')
ylabel('P_B')
title(['OFDM performance at different levels of W-CDMA interference
 (with a SF of ' num2str(SF) ')'])
```

```
legend(legendInfo)

figure(2)
%drawing the OFDM with constant CDMA
[s1,s2]=size(PBmat_CDMA);
RB_theory=log2((2.*Eb_No_dB_OFDM)+1)+log2((Eb_No_dB_CDMA./SF)+1);
for draw = 1:s1
    for iter=1:s2
    Rb_CDMA(draw,iter)=1-PBmat_CDMA(draw,iter);
    Rb_OFDM(draw,iter)=1-PBmat_OFDM(draw,iter);
    end
end
    Rb_total=2.*Rb_OFDM + Rb_CDMA./SF;
    plot(Eb_No_dB_OFDM,Rb_total,Eb_No_dB_OFDM,RB_theory)
grid
xlabel('E_b/N_o (dB)')
ylabel('R_B')
title(['Total system throughput (with a SF of ' num2str(SF) ') at
 different levels of OFDM interference'])
legend(legendInfo)
```

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Appendix B

Consultation meeting attendance form

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
1	1/8/17	Discussion of Combined OFDM and WCDMA System	A. A. Emami	Sam Reisenfeld
3	18/8/17	Research Topic Discussion OFDM & WCDMA	A. A. Emami	Sam Reisenfeld
5	29/8/17	OFDM & WCDMA Noise Variance Derivation	A. A. Emami	Sam Reisenfeld
7	14/9/17	Simulation Performance Results	A. A. Emami	Sam Reisenfeld
8	5/10/17	Discussion & Advice	A. A. Emami	Sam Reisenfeld
9	12/10/17	Error Correction Coding + Spreading	A. A. Emami	Sam Reisenfeld
12	30/10/17	Bandwidth efficiency	A. A. Emami	Sam Reisenfeld
13	6/11/17	Report Review	A. A. Emami	Sam Reisenfeld

References

[1] J. Thompson, X. Ge, H. C. Wu, R. Irmer, H. Jiang, G. Fettweis, and S. Alamouti, "5g wireless communication systems: prospects and challenges part 2 [guest editorial]," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 24–26, May 2014.

[2] 2017. [Online]. Available: http://www.acma.gov.au/theACMA/engage-blogs/engage-blogs/Research-snapshots/Australians-get-mobile

[3] 2017. [Online]. Available: https://aifs.gov.au/cfca/publications/using-technology-service-delivery-families-children/technology-use-australia

[4] E. Hossain, *Radio Resource Management in Multi-Tier Cellular Wireless Ne.* WILEY ACADEMIC, 2013. [Online]. Available: http://www.ebook.de/de/product/20353037/ekram_hossain_radio_resource_management_in_multi_tier_cellular_wireless_ne.html

[5] C. W. Bostian, N. J. Kaminski, A. S. Fayez, and A. Fayez, *Cognitive Radio Engineering*. The Institution of Engineering and Technology, 2016. [Online]. Available: http://www.ebook.de/de/product/28154156/charles_w_bostian_nicholas_j_kaminski_almohanad_s_fayez_almohanad_fayez_cognitive_radio_engineering.html

[6] K. B. Letaief and W. Zhang, "Cooperative communications for cognitive radio networks," *Proceedings of the IEEE*, vol. 97, no. 5, pp. 878–893, May 2009.

[7] C. W. Bostian, N. J. Kaminski, A. Fayez, and A. Young, *Cognitive Radio Engineering*. SciTech Publishing Inc, 2016. [Online]. Available: http://www.ebook.de/de/product/24032428/charles_w_bostian_nicholas_j_kaminski_almohanad_fayez_alexander_young_cognitive_radio_engineering.html

[8] J. Lunden, V. Koivunen, and H. V. Poor, "Spectrum exploration and exploitation for cognitive radio: Recent advances," *IEEE Signal Processing Magazine*, vol. 32, no. 3, pp. 123–140, May 2015.

[9] A. Wyglinski, *Cognitive Radio Communications and Networks*. ACADEMIC PRESS, 2009. [Online]. Available: http://www.ebook.de/de/product/9020308/alexander_wyglinski_cognitive_radio_communications_and_networks.html

[10] S. Haykin and M. Moher, *An Introduction to Analog and Digital Communications.* JOHN WILEY & SONS INC, 2006.

[11] C. E. Shannon, "A mathematical theory of communication," *The Bell System Technical Journal*, vol. 27, no. 3, pp. 379–423, July 1948.

[12] S. Verdu and S. Shamai, "Spectral efficiency of cdma with random spreading," *IEEE Transactions on Information Theory*, vol. 45, no. 2, pp. 622–640, Mar 1999.

[13] H. Schulze and C. Lueders, *Theory and Applications of Ofdm and Cdma: Wideband Wireless Communications.* JOHN WILEY & SONS INC, 2005. [Online]. Available: http://www.ebook.de/de/product/4007924/henrik_schulze_christian_lueders_theory_and_applications_of_ofdm_and_cdma_wideband_wireless_communications.html

[14] A. J. Viterbi, *CDMA*, 1st ed. Addison-Wesley Pub. Co., 1995.

[15] "feedback taps for maximal length sequences," 2017. [Online]. Available: http://www.newwaveinstruments.com/resources/articles/m_sequence_linear_feedback_shift_register_lfsr.htm

[16] M. Pursley, "Performance evaluation for phase-coded spread-spectrum multiple-access communication - part i: System analysis," *IEEE Transactions on Communications*, vol. 25, no. 8, pp. 795–799, August 1977.

[17] J. L. Burbank, J. Andrusenko, J. S. Everett, and W. T. M. Kasch, *Third-Generation (3G) Cellular Communications.* Wiley-IEEE Press, 2013, pp. 712–. [Online]. Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6583353

[18] K. Tachikawa, *W-CDMA mobile communication systems.* Wiley, 2003.

[19] H. Yin and S. Alamouti, "Ofdma: A broadband wireless access technology," in *2006 IEEE Sarnoff Symposium*, March 2006, pp. 1–4.

[20] O. Mix, *Wavelets.* John Wiley & Sons, 2003. [Online]. Available: http://www.ebook.de/de/product/3611771/mix_olejniczak_wavelets.html

[21] C. L. Phillips, J. M. Parr, and E. A. Riskin, *Signals, Systems, and Transforms.* Prentice Hall, 2002. [Online]. Available: http://www.ebook.de/de/product/3668555/charles_l_phillips_john_m_parr_eve_a_riskin_signals_systems_and_transforms.html

[22] E. Dahlman, S. Parkvall, and J. Skold, *4G: LTE/LTE-Advanced for Mobile Broadband.* Academic Press, 2011.

[23] H. Rohling, *OFDM*, 1st ed. Springer, 2011.

[24] S. Kaiser, "Ofdm-cdma versus ds-cdma: performance evaluation for fading channels," in *Communications, 1995. ICC '95 Seattle, 'Gateway to Globalization', 1995 IEEE International Conference on*, vol. 3, Jun 1995, pp. 1722–1726 vol.3.

[25] W. M. Jang, L. Nguyen, and P. Bidarkar, "Multiple access and inter-carrier interference in ofdm-cdma with random sequences," *Journal of Communications and Networks*, vol. 7, no. 1, pp. 21–28, March 2005.

[26] F. Jasbi and D. K. So, "Hybrid overlay/underlay cognitive radio network with mc-cdma," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 4, pp. 2038–2047, 2016.

[27] R. M. Amorim, R. D. Vieira, and P. H. P. Carvalho, "Network efficiency maximization exploiting wcdma spectrum nature for enhancement of d2d underlaying communications," *Analog Integrated Circuits and Signal Processing*, vol. 78, no. 3, pp. 741–752, 2014.