SIMULATION OF OFDM OVER FIBER FOR WIRELESS COMMUNICATION SYSTEM

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A project report submitted in partly fulfillment of the requirements for the word of the degree of Master of Engineering (Electrical- Electronics & Telecommunications)

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MAY 2007
To
My beloved parents and brothers for their unwavering love, sacrifice and inspiration.
ACKNOWLEDGEMENTS

First and foremost, I would like to express my utmost gratitude to my supervisor, Dr. Razali Bin Ngah for being a dedicated mentor as well as for his valuable and constructive suggestions that enabled this project to run smoothly.

Also, not forgetting my friends and classmates, I convey my full appreciation for their on-going support and contributions toward this project, whether directly or indirectly.

Last but not least, I am forever indebted to all my family members for their constant support throughout the entire duration of this project. Their words of encouragement never failed to keep me going even through the hardest of times and it is here that I express my sincerest gratitude to them.
Radio-over-fiber (RoF) technology has several benefits such as larger bandwidth, reduced power consumption etc. that has made it an attractive implementation option for various communication systems. Orthogonal Frequency Division Multiplexing (OFDM) is seen as the modulation technique for future broadband wireless communications because it provides increased robustness against frequency selective fading and narrowband interference, and is efficient in dealing with multi-path delay spread. This project investigates the feasibility of Orthogonal OFDM as a modulation technique to transmit the basebands signal over fiber. Laser diode and photodiode have been modeled and used as optical modulator and optical demodulator respectively. Results from a MATLAB/SIMULINK system model, which show the QPSK-OFDM transmitted and received signal before and after the transmission over fiber, power spectrum before and after the transmission over fiber, constellation before and after channel estimation. The model of this project can be used with different wireless communication systems such as Wireless LANs and Digital Video Broadcasting (DVB) and it is supporting to the 4th generation cellular systems.
ABSTRAK

Teknologi radio atas gentian (ROF) mempunyai beberapa kelebihan seperti jalurlebar besar, kurang penggunaan kuasa dll. Yang menyebabkan ia menjadi satu pilihan implimentasi yang menarik untuk pelbagai sistem komunikasi. Pembahagian Frekuensi Multipleks Ortogon (OFDM) di lihat sebagai teknik modulasi untuk komunikasi jalur lebar tanpa wayar pada masa hadapan kerana ia memberi ketahanan terhadap pudaran frekuensi pilihan dan gangguan jalur nipis, dan ia cekop dalam menagani perebakan kelewatan pelbagai hala. Projek ini menyiasat sama ada OFDM boleh diguna sebagai teknik modulasi untuk menghantar isyarat jaluratas melalui gentian. Diod laser dan diod foto telah dimodel dan digunakan sebagai pemodulat optik dan demodulator optik. Keputusan daripada model sistem MATLAB/SimuLINK, menunjukkan QPSK – OFDM yang dihantar dan diterima sebelum dan selepas transmisi atas gentian, constellation sebelum dan selepas pengiraan saluran. Model untuk project ini boleh diguna dengan sistem komunikasi tanpa wayar yang berbeza seperti LAN tanpa wayar dan penyiaran video digital dan ia menyokong generasi ke 4 sistem selular.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DECLARATIONS</td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td>DEDICATIONS</td>
<td>iii</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td></td>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>xv</td>
</tr>
<tr>
<td></td>
<td>LIST OF SYMBOLS</td>
<td>xvi</td>
</tr>
<tr>
<td></td>
<td>LIST OF APPENDICES</td>
<td>xxi</td>
</tr>
</tbody>
</table>

1. INTRODUCTION 1

1.1 Introduction 1
1.2 Problem Statement 3
1.3 Objective 3
1.4 Scope of work 3
1.5 Thesis Outline 4

2. RADIO-OVER-FIBRE TECHNOLOGY 5

2.1 Introduction 5
2.2 What is Radio-over-Fibre Technology? 6
2.3 Benefits of Radio-over-Fibre Systems 8
2.3.1 Low Attenuation Loss 9
2.3.2 Large Bandwidth 10
2.3.3 Immunity to Radio Frequency Interference 11
2.3.4 Easy Installation and Maintenance 11
2.3.5 Reduced Power Consumption 12
2.3.6 Multi-Operator and Multi-Service Operation 12
2.3.7 Dynamic Resource Allocation 13

2.4 Radio-Over-Fiber for Fi-Wi Systems 13
2.4.1 Supporting Multiple Wireless Standards 14
2.4.2 Issues with the Fi-Wi System 15
2.4.3 Solutions for the Issues 16
  2.4.3.1 Nonlinearity Compensation 16
  2.4.3.2 Estimation and Equalization 16
  2.4.3.3 Noise Characterization and Cancellation 18

2.5 Myths and realities of fiber-wireless access 18

2.6 Applications of Radio-over-Fiber Technology 20
  2.6.1 Wireless LANs 20
  2.6.2 Cellular Networks 21
  2.6.3 Satellite Communications 21
  2.6.4 Video Distribution Systems 22
  2.6.5 Mobile Broadband Services 22
  2.6.6 Vehicle Communication and Control 23

3. Orthogonal Frequency Division Multiplexing (OFDM) 24

3.1 Introduction 24
3.2 Orthogonal Frequency Division Multiplexing (OFDM) 24
3.3 General Principles 26
  3.3.1 Multicarrier transmission 26
  3.3.2 Fast Fourier Transform 30
3.3.3 Guard interval and its implementation 31
3.4 Coded OFDM 32
3.4.1 Coded OFDM Systems 33
3.4.2 Trellis Coded Modulation 34
3.4.3 Bit-interleaved Coded OFDM 36
3.5 OFDM Advantages 40
3.6 OFDM Disadvantages 40

4. METOHODOLOGY

4.1 Introduction 41
4.2 Project methodology 41
4.3 Blocks Used In Simulink 42

4.3.1 Bernoulli Binary Generator 42
4.3.2 Reed Solomon (Rs) Double Error Correcting (15, 11) Code 43
4.3.3 QPSK Mapping: 43
4.3.4 Training 44
4.3.5 OFDM baseband modulator and add cyclic prefix 44
4.3.6 Training Insertion 46
4.3.7 parallel to serial converter 46
4.3.8 laser diode 47
4.3.9 AWGN Channel and Optical Fiber Link 47
4.3.10 Photodiode 48
4.3.11 serial to parallel converter 48
4.3.12 Training Separation 49
4.3.13 OFDM baseband demodulator and remove cyclic prefix 50
4.3.14 Channel Estimator 50
4.3.15 Channel Compensation 51
4.3.16 Remove Zero
4.3.17 QPSK Demodulator
4.3.18 Reed Solomon (RS) double error correcting (15, 11) decode
3.4.19 Error Rate Calculation
3.5 Laser Diode Modeling
4.4 Simulation model of the project

5

RESULTS AND DISCUSSION

5.1 Introduction
5.2 OFDM Transmitted and Received Signal
5.3 The constellation before and after channel estimation
5.4 power spectrum before the transmission over fiber
5.5 Comparison between Theoretical and Simulation BER
5.6 OFDM over fiber Transmitted and Received Power Spectrum
5.7 OFDM over fiber Transmitted and Received Signal

6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion
6.2 Future of work and recommendations

REFERENCES
APPENDICES A
LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Myths and realities of fiber-wireless access</td>
<td>19</td>
</tr>
<tr>
<td>3.1</td>
<td>Data rates and modulation schemes for the 802.11 a W-LAN system</td>
<td>34</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Two types of modulation involved with the radio-over</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>Fiber-wireless solution for cellular radio networks</td>
<td>14</td>
</tr>
<tr>
<td>3.3</td>
<td>OFDM Symbol <strong>a)</strong> Three Orthogonal Sub-carriers in one <strong>b)</strong> Spectra of three OFDM sub-carriers</td>
<td>25</td>
</tr>
<tr>
<td>3.2</td>
<td>A block diagram of an OFDM transmitter</td>
<td>28</td>
</tr>
<tr>
<td>3.3</td>
<td>Block diagram for multicarrier transmission: Version 1</td>
<td>29</td>
</tr>
<tr>
<td>3.4</td>
<td>Block diagram for multicarrier transmission: Version 2</td>
<td>30</td>
</tr>
<tr>
<td>3.5</td>
<td>IFFT/FFT</td>
<td>30</td>
</tr>
<tr>
<td>3.6</td>
<td>Guard Interval</td>
<td>31</td>
</tr>
<tr>
<td>3.7</td>
<td><strong>a)</strong> An example of 8-PSK modulation. <strong>(b)</strong> An example of a trellis diagram for a coded modulation scheme.</td>
<td>35</td>
</tr>
<tr>
<td>3.8</td>
<td>A block diagram of Bit-interleaved coded OFDM</td>
<td>37</td>
</tr>
<tr>
<td>3.9</td>
<td><strong>(a)</strong> Constellations of 16-QAM with Gray mapping. <strong>(b)</strong> Constellations of 16-QAM with set partitioning.</td>
<td>39</td>
</tr>
<tr>
<td>4.1</td>
<td>The flow chart of the methodology of the project</td>
<td>42</td>
</tr>
<tr>
<td>4.2</td>
<td>Bernoulli Binary Generator</td>
<td>43</td>
</tr>
<tr>
<td>4.3</td>
<td>Reed Solomon (Rs) Double Error Correcting (15, 11) Code</td>
<td>43</td>
</tr>
<tr>
<td>4.4</td>
<td>QPSK Mapping</td>
<td>43</td>
</tr>
<tr>
<td>4.5</td>
<td>Training</td>
<td>44</td>
</tr>
</tbody>
</table>
4.6 OFDM baseband modulator and add cyclic prefix
4.7 components of OFDM baseband modulator
4.8 Zero pad blocks
4.9 Cyclic prefix
4.10 Training Insertion
4.11 parallel to serial converter
4.12 laser diode
4.13 AWGN Channel and Optical Fiber Link
4.14 Photodiode
4.15 serial to parallel converter
4.16 Training Separation
4.17 OFDM baseband demodulator and remove cyclic prefix
4.18 Channel Estimator
4.19 Channel Compensation
4.20 Remove Zero
4.21 QPSK Demodulator
4.22 Reed Solomon (RS) double error correcting (15, 11) decode
4.23 Error Rate Calculation
4.24 Laser Diode Modeling
4.25 Simulation model of the project
5.1 OFDM transmitted signal
5.2 OFDM received signal
5.3 The constellation before channel estimation
5.4 The constellation after channel estimation
5.5 OFDM transmitted spectrum over AWGN channel
5.6 OFDM received spectrum over AWGN channel
5.7 Comparison between Theoretical and Simulation BER
5.8 OFDM transmitted spectrum over fiber
5.9 OFDM received spectrum over fiber
5.10 OFDM over fiber Transmitted Signal
5.11 OFDM over fiber Received Signal
**LIST OF SYMBOLS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROF</td>
<td>Radio-over-Fiber</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>DVB</td>
<td>Digital Video Broadcasting</td>
</tr>
<tr>
<td>CS</td>
<td>Central Site</td>
</tr>
<tr>
<td>RS</td>
<td>Remote Site</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>ITS</td>
<td>Intelligent Transport Systems</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>APs</td>
<td>Access Points</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>DAB</td>
<td>Digital Audio Broadcasting</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>Fi-Wi</td>
<td>Fiber-Wireless</td>
</tr>
<tr>
<td>ADROIT</td>
<td>Advanced Radio-Optics Integrated Technology</td>
</tr>
<tr>
<td>MSC</td>
<td>Mobile Switching Centre</td>
</tr>
<tr>
<td>RAP</td>
<td>Radio Access Point</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>SMF</td>
<td>Single Mode Fibre</td>
</tr>
<tr>
<td>POF</td>
<td>Polymer Optical Fibre</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fibre Amplifier</td>
</tr>
<tr>
<td>OTDM</td>
<td>Optical Time Division Multiplexing</td>
</tr>
<tr>
<td>DWDM</td>
<td>Dense Wavelength Division Multiplex</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach Zehnder Interferometer</td>
</tr>
<tr>
<td>SCM</td>
<td>Sub-Carrier Multiplexing</td>
</tr>
<tr>
<td>IM-DD</td>
<td>Intensity Modulation and Direct Detection</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter Symbol Interference</td>
</tr>
<tr>
<td>PN</td>
<td>Pseudo-Noise</td>
</tr>
<tr>
<td>DEF</td>
<td>Decision Feedback Equalizer</td>
</tr>
<tr>
<td>RIN</td>
<td>Relative Intensity Noise</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>ICI</td>
<td>Inter-Carrier Interference</td>
</tr>
<tr>
<td>ADSL</td>
<td>Asymmetric Digital Subscriber Lines</td>
</tr>
<tr>
<td>VDSL</td>
<td>Very high-speed Digital Subscriber Lines</td>
</tr>
<tr>
<td>HDTV</td>
<td>High Definition Television</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>SER</td>
<td>Symbol Error Rate</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse Fast Fourier Transform</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Introduction

Radio-over-Fiber (ROF) is a technology by which microwave (electrical) signals are distributed by means of optical components and techniques. A ROF system consists of a Central Site (CS) and a Remote Site (RS) connected by an optical fiber link or network. One of the major motivation and system requirement for ROF technology is the use simple and cost-effective RS [5]. The electrical signal distributed may be baseband data, modulated IF, or the actual modulated RF signal. The electrical signal is used to modulate the optical source. The resulting optical signal is then carried over the optical fiber link to the remote station. By delivering the radio signals directly, the optical fiber link avoids the necessity to generate high frequency radio carriers at the antenna site. Since antenna sites are usually remote from easy access, there is a lot to gain from such an arrangement. However, the main advantage of ROF systems is the ability to concentrate most of the expensive, high frequency equipment at a centralized location, thereby making it possible to use simpler remote sites [5].

ROF is very attractive technique for wireless access network infrastructure, because it can transmit microwaves and millimeter-waves through optical fibers for a long distance.
Moreover, 5 GHz ROF link using a direct modulation scheme has been developed to support some important future wireless systems such as wireless local area networks (WLAN) intelligent transport systems (ITS), and the 4th generation cellular systems.

In particular, ROF is promising technique for WLAN infrastructures because ROF technique can manage WLAN modems at a base station (BS) and can solve serious interference problem between wireless signals caused by proliferated WLAN access points (APs).

Orthogonal Frequency Division Multiplexing (OFDM) is seen as the modulation technique for future broadband wireless communications because it provides increased robustness against frequency selective fading and narrowband interference, and is efficient in dealing with multi-path delay spread.

As stated above, OFDM uses multiple sub-carriers to transmit low rate data streams in parallel. The sub-carriers are modulated by using Phase shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) and are then carried on a high frequency microwave carrier (e.g. 5 GHz). This is similar to conventional Frequency Division Multiplexing (FDM) or Sub-carrier Multiplexing, except for the stringent requirement of orthogonality between the sub-carriers.

Coded OFDM offers very robust communications with the frequency diversity that results from channel coding and interleaving.

Each of OFDM has been developed to support wireless communication systems such as WLAN, DAB, and DVB and future wireless systems such as the 4th generation cellular systems.

In this project QPSK-OFDM is used as a modulation technique to transmit baseband signal over single mode optical fiber link. Laser diode and photodiode have been modeled and used as optical modulator and optical demodulator respectively. The project model has simulated using MATLAB/SIMULINK software.
1.2 Problem Statement:

The demand for broadband services has driven research on millimeter-wave frequency band communications for wireless access network due its spectrum availability, and compact size of radio frequency devices.

The mm-wave signals suffer from severe loss along the transmission as well as atmospheric attenuation.

One of the solution to overcome these problems is by using low-attenuation, electromagnetic interference-free optical fiber. ROF is considered to be cost-effective, practical and relatively flexible system configuration for long-haul transport of millimetric frequency band wireless signals using multicarrier modulation OFDM.

1.3 The objective of this study

The aim of this project is to investigates the feasibility of OFDM as a modulation technique to transmit the baseband signal over fiber for wireless communication systems.

1.4 Scope of this work

This project will cover the simulation of the OFDM over Fiber for wireless communication systems using MATLAB/SIMULINK software. A QPSK-OFDM signal will be simulated. Bit error rate (BER) performance of the OFDM will be evaluated.
1.5 Thesis outline

Chapter 1 consists of introduction of the project. The objectives of the project are clearly phased with detailed. The research scope and methodology background are also presented.

Chapter 2 included introduction about Radio-over-Fiber Technology, also introduce the benefits of ROF Technology and discussion Issues with the Fi-Wi System and the solutions for those issues and also mentions the application of ROF Technology where WLAN is one of them.

Chapter 3 presents the Orthogonal Frequency Division Multiplexing (OFDM). Consist of introduction, basic concept and the orthogonality of OFDM and also discusses the advantages and disadvantages of OFDM.

Chapter 4 is the methodology of project which starts with the flow chart of the project. Then, will followed by viewing the simulation model and the blocks used in MATLAB/SIMULINK

Chapter 5 contains results from a MATLAB/SIMULINK system model, which show the QPSK-OFDM transmitted and received signal before and after the transmission over fiber, power spectrum before and after the transmission over fiber, constellation before and after channel estimation

Chapter 6 concludes the thesis. The conclusion is given based on the analysis of results from the previous chapter. Recommendations for future works are also presented.
CHAPTER 2

Radio-over-Fibre Technology

2.1 Introduction

Over the past decade there has been substantial progress in the areas of wireless and optical communications. The driving force behind this advancement has been the growing demand for multimedia services, and hence broadband access. Present consumers are no longer interested in the underlying technology; they simply need reliable and cost effective communication systems that can support anytime, anywhere, any media they want. As a result, broadband radio links will become more prevalent in today’s communication systems.

Furthermore, new wireless subscribers are signing up at an increasing rate demanding more capacity while the radio spectrum is limited. To satisfy this increasing demand, the high capacity of optical networks should be integrated with the flexibility of radio networks. The Advanced Radio-Optics Integrated Technology Research Group (ADROIT) at Ryerson University concentrates on this integration; this leads us to the discussion on the fiber-based wireless access scheme using radio-over-fiber (ROF) technology [6]. ROF refers to a fiber optic link where the optical signal is modulated at radio frequencies (RF) and transmitted via the optical fiber to the receiving end. At the receiving end, the RF signal is demodulated and transmitted to the corresponding wireless user. By implementing the above technique, ROF
technology is able to alleviate the increasing demand for high-bandwidth services through the implementation of micro/pico cellular architectures. The primary focus of the ADROIT research group is to investigate (optical and electrical) signal processing strategies that can provide a cost-effective, high performance solution for high-speed fiber based wireless access.

2.2 What is Radio-over-Fibre Technology?

ROF technology is a technology by which microwave (electrical) signals are distributed by means of optical components and techniques. A ROF system consists of a Central Site (CS) and a Remote Site (RS) connected by an optical fibre link or network. If the application area is in a GSM network, then the CS could be the Mobile Switching Centre (MSC) and the RS the base station (BS). For wireless Local Area Networks (WLANs), the CS would be the headend while the Radio Access Point (RAP) would act as the RS.

The frequencies of the radio signals distributed by ROF systems span a wide range (usually in the GHz region) and depend on the nature of the applications. In this report, the terms microwave and Radio Frequency (RF) are used interchangeably when referring to all the electrical signals generated at the RS of the ROF system. Thus high frequency millimeter waves (mm-waves), microwaves, and lower frequency signals are all loosely referred to as microwave or RF signals in the report.

Pioneer ROF systems such as the one depicted in were primarily used to transport microwave signals, and to achieve mobility functions in the CS. That is, modulated microwave signals had to be available at the input end of the ROF system, which subsequently transported them over a distance to the RS in the form of optical signals. At the RS the microwave signals are re-generated and radiated by antennas. The system was used to distribute GSM 900 network traffic. The added value in using such a system lay in the capability to dynamically allocate capacity based on traffic demands. ROF systems of nowadays, are designed to perform added radio-
For a multifunctional ROF system, the required electrical signal at the input of the ROF system depends on the ROF technology and the functionality desired. The electrical signal may be baseband data, modulated IF, or the actual modulated RF signal to be distributed.

The electrical signal is used to modulate the optical source. The resulting optical signal is then carried over the optical fibre link to the remote station. Here, the data is converted back into electrical form by the photodetector. The generated electrical signal must meet the specifications required by the wireless application be it GSM, UMTS, wireless LAN or other.

By delivering the radio signals directly, the optical fibre link avoids the necessity to generate high frequency radio carriers at the antenna site. Since antenna sites are usually remote from easy access, there is a lot to gain from such an arrangement. However, the main advantage of ROF systems is the ability to concentrate most of the expensive, high frequency equipment at a centralized location, thereby making it possible to use simpler remote sites. Furthermore, ROF technology enables the centralising of mobility functions such as macro-diversity for seamless handover. The benefits of having simple remote sites are many. They are discussed in the following section.

In any RF communication system, the baseband information is modulated to a suitable carrier frequency. Both the modulation scheme and the carrier frequency are predetermined as shown in Figure 2.1. For example, QPSK (with CDMA) is used at 900 MHz in IS-95 cellular radio system and OFDM at 2.4 GHz is used in IEEE 802.11 wireless LAN. The purpose of the ROF link is to provide a transparent, low distortion communication channel for the radio signal for antenna remoting. Laser diodes can be directly modulated up to several GHz of radio frequency depending on their resonance frequency. Up to several GHz directly modulated ROF transceivers
are commercially available. At higher frequencies, external modulators such as the Mach-Zehnder interferometer should be used.

**Figure 2.1:** Two types of modulation involved with the radio-over fiber approach

### 2.3 Benefits of Radio-over-Fibre Systems

ROF technology has several benefits such as reduced power consumption, huge bandwidth that enables multiplexing several radio channels; ability to use existing dark/dim fibers to transmit the radio signal (dim fiber can be used with WDM techniques), inherent immunity to electromagnetic interference and allowing for transparent operation because the RF to optical modulation is typically independent of the baseband to RF modulation. This section will discuss the most important benefits of ROF technology.
2.3.1 Low Attenuation Loss

Electrical distribution of high frequency microwave signals either in free space or through transmission lines is problematic and costly. In free space, losses due to absorption and reflection increase with frequency. In transmission lines, impedance rises with frequency as well. Therefore, distributing high frequency radio signals electrically over long distances requires expensive regenerating equipment. As for mm-waves, their distribution via the use of transmission lines is not feasible even for short distances. The alternative solution to this problem is to distribute baseband signals or low intermediate frequencies (IF) from the Switching Centre (SC) to the Base Stations (BS). The baseband or IF signals are then up converted to the required microwave or mm-wave frequency at each base station, amplified and then radiated. Such a system places stringent requirements (such as linearity) on repeater amplifiers and equalisers. In addition, high performance local oscillators would be required for up conversion at each base station. This arrangement leads to complex base stations with tight performance requirements. An alternative solution is to use optical fibres, which offer much lower losses.

Commercially available standard Single Mode Fibres (SMFs) made from glass (silica) have attenuation losses below 0.2 dB/km and 0.5 dB/km in the 1.5 μm and the 1.3 μm windows, respectively. Polymer Optical Fibres (POFs), a more recent kind of optical fibers exhibit higher attenuation ranging from 10 – 40 dB/km in the 500 - 1300 nm regions. These losses are much lower than those encountered in free space propagation and copper wire transmission of high frequency microwaves. Therefore, by transmitting microwaves in the optical form, transmission distances are increased several folds and the required transmission powers reduced greatly.
2.3.2 Large Bandwidth

Optical fibres offer enormous bandwidth. There are three main transmission windows, which offer low attenuation, namely the 850nm, 1310nm and 1550nm wavelengths. For a single SMF optical fibre, the combined bandwidth of the three windows is in the excess of 50THz. However, today’s state-of-the-art commercial systems utilize only a fraction of this capacity (1.6 THz). But developments to exploit more optical capacity per single fibre are still continuing. The main driving factors towards unlocking more and more bandwidth out of the optical fibre include the availability of low dispersion (or dispersion shifted) fibre, the Erbium Doped Fibre Amplifier (EDFA) for the 1550nm window, and the use of advanced multiplex techniques namely Optical Time Division Multiplexing (OTDM) in combination with Dense Wavelength Division Multiplex (DWDM) techniques.

The enormous bandwidth offered by optical fibres has other benefits apart from the high capacity for transmitting microwave signals. The high optical bandwidth enables high speed signal processing that may be more difficult or impossible to do in electronic systems. In other words, some of the demanding microwave functions such as filtering, mixing, up- and down-conversion, can be implemented in the optical domain. For instance, mm-wave filtering can be achieved by first converting the electrical signal to be filtered into an optical signal, then performing the filtering by using optical components such as the Mach Zehnder Interferometer MZI or Bragg gratings), and then converting the filtered signal back into an electrical signal [10]. Furthermore, processing in the optical domain makes it possible to use cheaper low bandwidth optical components such as Laser Diodes and modulators, and still be able to handle high bandwidth signals [10].

The utilization of the enormous bandwidth offered by optical fibres is severely hampered by the limitation in bandwidth of electronic systems, which are the primary sources and end users of transmission data. This problem is referred to as the “electronic bottleneck”. 
The solution around the electronic bottleneck lies in effective multiplexing. OTDM and DWDM techniques mentioned above are used in digital optical systems. In analogue optical systems including ROF technology, Sub-Carrier Multiplexing (SCM) is used to increase optical fibre bandwidth utilization. In SCM, several microwave subcarriers, which are modulated with digital or analogue data, are combined and used to modulate the optical signal, which is then carried on a single fibre. This makes the ROF system cost effective.

2.3.3 Immunity to Radio Frequency Interference

Immunity to electromagnetic interference is a very attractive property of optical fibre communications, especially for microwave transmission. This is so because signals are transmitted in the form of light through the fibre. Because of this immunity, fibre cables are preferred even for short connections at mm-waves. Related to RFI immunity is the immunity to eavesdropping, which is an important characteristic of optical fibre communications, as it provides privacy and security.

2.3.4 Easy Installation and Maintenance

In ROF systems, complex and expensive equipment is kept at the Switching Centre (SCs), thereby making remote base stations simpler. For instance, most ROF techniques eliminate the need for a local oscillator and related equipment at the Remote Station (RS). In such cases a photodetector, an RF amplifier, and an antenna make up the RS equipment. Modulation and switching equipment are kept in the SC at the headend and shared by several RS. This arrangement results in smaller and lighter RS, effectively reducing system installation and maintenance costs. Easy installation and low maintenance costs of RS are very important requirements for mm-wave systems, because of the large numbers of the required antenna sites.
Having expensive RS would render the system costs prohibitive. The numerous antennas are needed to offset the small size of radio cells (micro- and pico-cells), which is a consequence of limited propagation distances of mm-wave microwaves. In applications where RSs are not easily accessible, the reduction in maintenance requirements has many positive implications[9].

2.3.5 Reduced Power Consumption

Reduced power consumption is a consequence of having simple RAUs with reduced equipment. Most of the complex equipment is kept at the centralised headend. In some applications, the RAUs are operated in passive mode. For instance, some 5 GHz Fibre-Radio systems employing pico-cells can have the RAUs operate in passive mode [10]. Reduced power consumption at the RAU is significant considering that RAUs are sometimes placed in remote locations not fed by the power grid.

2.3.6 Multi-Operator and Multi-Service Operation

ROF offers system operational flexibility. Depending on the microwave generation technique, the ROF distribution system can be made signal-format transparent. For instance the Intensity Modulation and Direct Detection (IM-DD) technique can be made to operate as a linear system and therefore as a transparent system. This can be achieved by using Single Mode Fiber (SMF) in combination with pre-modulated RF subcarriers (SCM). In that case, the same ROF network can be used to distribute multi-operator and multi-service traffic, resulting in huge economic savings [9]. The principle of Optical Frequency Multiplication (OFM), which is the focus of this thesis can also be used to achieve multi-service operation in
combination with either WDM or SCM, because it is tolerant to chromatic dispersion.

2.3.7 Dynamic Resource Allocation

Since the switching, modulation, and other RF functions are performed at a centralized headend, it is possible to allocate capacity dynamically. For instance in a ROF distribution system for GSM traffic, more capacity can be allocated to an area (e.g. shopping mall) during peak times and then re-allocated to other areas when offpeak (e.g. to populated residential areas in the evenings). This can be achieved by allocating optical wavelengths through Wavelength Division Multiplexing (WDM) as need arises [9]. Allocating capacity dynamically as need for it arises obviates the requirement for allocating permanent capacity, which would be a waste of resources.

2.4 Radio-Over-Fiber for Fi-Wi Systems

The fiber-wireless solution for cellular networks is shown in Figure 2.2 (the fiber-wireless downlink). This solution increases the frequency reuse and enables broadband access by providing a micro/pico cell scenario for cellular radio networks. The micro/pico cell scenario is possible through the use of radio access points-RAP in Figure 2.1. These inexpensive low power RAPs provide wireless access instead of conventional base stations. It is important to keep the RAPs complexity and cost at a minimum in order to allow for large scale deployment. By doing so, a large cell can easily be split into smaller cells by dispersing RAPs throughout. These robust RAPs are connected to the central base station via the ROF links [6].
2.4.1 Supporting Multiple Wireless Standards

Studying the effects of transmitting multiple wireless standards over a single ROF link can be very beneficial. Today, 3G wireless technologies have a bit rate of more than 2 Mbps and wireless local area network (WLAN) technologies can provide a bit rate as high as 54 Mbps with IEEE 802.11. The integration of these two technologies can increase the bit rate available for applications, while maintaining reasonable mobility for end users.

Some work in this area has been done where the transmission of multiple wireless standards over an ROF network is investigated; however, the knowledge in this area is still limited. Currently, we concentrate on the different issues of supporting both cellular CDMA and IEEE 802.11 type Wi-Fi signals over the fiber-wireless system.

This can be done either in a sub-carrier multiplexed or baseband plus ROF manner. Although the fiber has several GHz of bandwidth, the cross coupling due to
nonlinearity impairs system performance and our focus is to quantify it and to find feasible solutions.

2.4.2 Issues with the Fi-Wi System

Several observations can be made from Figure 2.2. First, signal processing should not be done at the RAP for cost considerations. Therefore, compensation should be done at the portable unit or at the central base station. By performing most of the signal processing at the central base station, i.e. by asymmetric distribution of the complexity, the cost can be shared by many users and therefore helps reduce overall system cost.

Second, the compensation of the concatenated fiber-wireless channel should be handled jointly. This is a challenging task because of the time varying multipath wireless channel in series with the nonlinear optical channel. Furthermore, the uplink and downlink require different solutions.

Third, it is desirable not to modify the portable units because of the ROF link. In other words, the portable unit should not be aware of the existence of the ROF link. This makes seamless roaming between fiber-based and conventional wireless systems possible.

One of the major issues with ROF is the nonlinear distortion of the optical link. This is due mainly to the laser diode (and partly to the high gain RF amplifier at the optical receiver), and is most dominant in a multiuser environment. Several approaches have been proposed to characterize and solve the problem of nonlinear distortion., the authors demonstrated how external light injection into a directly modulated laser diode can be used to enhance the linear performance of a multi-channel ROF system operating at a frequency of 6 GHz., low-cost predistortion circuits able to compensate second- and thirdorder laser distortions in multiservice
ROF industrial systems were developed. Another approach mitigated the nonlinear distortion in the network layer.

2.4.3 Solutions for the Issues [6]

2.4.3.1 Nonlinearity Compensation

An adaptive baseband model for the ROF link was developed and two different predistortion schemes for the nonlinearity were proposed; one is currently being implemented in an FPGA platform. With the first scheme, the predistortion is done using a look-up table. In the second scheme, higher order adaptive filters are trained to inverse model the ROF link. With both of these approaches, simulation results show good performance improvement, but sometimes requiring a power back off.

Asymmetric compensation is a scheme that allows for most of the signal processing to be done at the central base station. This is achieved by doing predistortion for the downlink and post compensation for the uplink. The issues associated with this asymmetric arrangement are discussed in detail and a unified analysis carried out.

2.4.3.2 Estimation and Equalization

Even though ROF provides an excellent broadband link allowing for the communication of several channels, the wireless channel introduces inter symbol interference (ISI) at high bit rates. Along with the nonlinearity, available linear dynamic range becomes a major concern, especially in the uplink. A large linear
dynamic range is required in the uplink, where the received signal first travels through the wireless channel (resulting in path losses, fading and shadowing) before entering the optical fiber. Several researchers address the issue where rapidly fading dispersive linear channels are estimated and equalized. However, in the Fi-Wi system, the ISI is coupled with the nonlinear distortion of the optical link, thereby demanding nonlinear channel estimation and equalization techniques.

Estimation

In order to limit the effect of nonlinear and ISI distortions, estimation, and subsequently equalization, of the concatenated fiber-wireless system should be done. Estimation of the concatenated fiber-wireless channel is an important step towards equalization of the linear channel and linearization of the nonlinear channel. In our estimation algorithms we always consider both wireless channel noise and optical channel noise (quantum, thermal and relative intensity) which are shown in Figure 2.2 as $n_{wl}(t)$ and $n_{op}(t)$, respectively.

A complete identification of the ROF uplink has been performed in for a single user environment. Expanding identification to a multiuser environment is currently being studied; simulations yield promising results. The wireless channel was identified using correlation analysis, and the nonlinear link was identified using a least squares polynomial fit. It should be noted that our identification was performed using multiple maximal-length pseudonoise (PN) sequences. This is a major advantage because multiple PN sequences are already widely used in spread spectrum communications.

Equalization

Once the channel is estimated, an appropriate equalizer must be devised for the compensation of the linear and nonlinear parts. The fiber-wireless uplink is a Wiener system and therefore a Hammerstein type decision feedback equalizer (DEF) was developed to compensate for it. This equalizer compensates for the linear and nonlinear distortions separately. This modular architecture is attractive for
commercial implementation. The receiver consists of a polynomial filter, which
inverse models the optical link, and a linear DFE arrangement that compensates for
the wireless channel dispersion. The DFE filter parameters were optimized and
performance analysis was carried out. The Hammerstein type equalizer discussed
above was implemented for a single user.

2.4.3.3 Noise Characterization and Cancellation

From Figure 2.2 it is observed that there are two signal to noise ratios
involved in the fiber-wireless system. The optical noise \( n_{op}(t) \), will be dominant if
the fiber is too long and the wireless channel noise \( n_{wc}(t) \) will be dominant if the
radio cell is too large. The cumulative SNR will be smaller than the smallest SNR. The
optical SNR deteriorates with wideband RF signals; this becomes an issue in
emerging 4G systems that opt for WCDMA type wideband RF signals. ADROIT has
also been working on improving the SNR performance of the Fi-Wi system. Relative
intensity noise (RIN) plays an important role in analog fiber optic links. This is
especially true with ROF applications because the SNR at the remote antenna end is
critical for system performance. Conventionally, the RIN is taken to be proportional
to the square of the mean optical power; however, it has been shown that RIN also
depends on the modulation index. An improved mathematical expression for the
dynamic RIN was derived from fundamental principles and as a function of the
modulation index as well. This is a fundamental contribution and will most likely
change the way ROF links are analyzed.

2.5 Myths and realities of fiber-wireless access

There are several common myths relative to fiber-wireless access; Table 2.1
clears the opposite realities for these myths.
Table 2.1: Myths and realities of fiber-wireless access

<table>
<thead>
<tr>
<th>N</th>
<th>The Myth</th>
<th>The Reality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Optical fiber is mostly useful to transmit digital (SONET) type data</td>
<td>Not true. Optical fiber is an excellent wideband channel and any broadband (analog or digital) signal can be transmitted via fiber with very low distortion. Analog transmission has been widely used in CATV systems.</td>
</tr>
<tr>
<td></td>
<td>carrying voice (telephony) signals.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Optical access networks means running fiber to every house (fiber-to-the-</td>
<td>Not necessarily. There is plenty of dark (unused) and dim (partly used) fiber running in our neighborhood in most major cities. These existing fibers can dramatically enhance the access network capacity with the Fi-Wi approach.</td>
</tr>
<tr>
<td></td>
<td>home, FTTH). This is too expensive and will not materialize in the near</td>
<td></td>
</tr>
<tr>
<td></td>
<td>future.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Optical and wireless networks are independent.</td>
<td>Access networks can be effective combinations of both optical and wireless techniques. This combination supports mobility as well as broadband access.</td>
</tr>
<tr>
<td>4</td>
<td>Optical fiber may be useful to transmit millimeter waves which otherwise</td>
<td>Even at 900 MHz, 1800 MHz and 2400 MHz frequencies radio-over-fiber technology is cost effective; see the Sydney Olympics example below.??</td>
</tr>
<tr>
<td></td>
<td>can’t be transmitted cost effectively.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Only few isolated researchers work in this area.</td>
<td>There are commercial products available for Fi-Wi networks and even books have been written on the technology.</td>
</tr>
</tbody>
</table>
2.6 Applications of Radio-over-Fiber Technology

There are many applications of ROF technology. This section gives brief explanation to some of them

2.6.1 Wireless LANs

As portable devices and computers become more and more powerful as well as widespread, the demand for mobile broadband access to LANs will also be on the increase.

This will lead once again, to higher carrier frequencies in the bid to meet the demand for capacity. For instance current wireless LANs operate at the 2.4 GHz ISM bands and offer the maximum capacity of 11 Mbps per carrier (IEEE 802.11b). Next generation broadband wireless LANs are primed to offer up to 54 Mbps per carrier, and will require higher carrier frequencies in the 5 GHz band (IEEE802.11a/D7.0) [10].

Higher carrier frequencies in turn lead to micro- and pico-cells, and all the difficulties associated with coverage discussed above arise. A cost effective way around this problem is to deploy ROF technology. A wireless LAN at 60 GHz has been realised [10] by first transmitting from the BS (Central Station), a stable oscillator frequency at an IF together with the data over the fiber. The oscillator frequency is then used to up-convert the data to mm-waves at the transponders (Remote Stations). This greatly simplifies the remote transponders and also leads to efficient base station design.
2.6.2 Cellular Networks

The field of mobile networks is an important application area of ROF technology. The ever-rising number of mobile subscribers coupled with the increasing demand for broadband services have kept sustained pressure on mobile networks to offer increased capacity. Therefore, mobile traffic (GSM or UMTS) can be relayed cost effectively between the SCs and the BSs by exploiting the benefits of SMF technology. Other ROF functionalities such as dynamic capacity allocation offer significant operational benefits to cellular networks.

2.6.3 Satellite Communications

Satellite communications was one of the first practical uses of ROF technology. One of the applications involves the remoting of antennas to suitable locations at satellite earth stations. In this case, small optical fibre links of less than 1 km and operating at frequencies between 1 GHz and 15 GHz are used. By so doing, high frequency equipment can be centralised.

The second application involves the remoting of earth stations themselves. With the use of ROF technology the antennae need not be within the control area (e.g. Switching Centre). They can be sited many kilometres away for the purpose of, for instance improved satellite visibility or reduction in interference from other terrestrial systems. Switching equipment may also be appropriately sited, for say environmental or accessibility reasons or reasons relating to the cost of premises, without requiring to be in the vicinity of the earth station antennas.
2.6.4 Video Distribution Systems

One of the major promising application areas of ROF systems is video distribution. A case in point is the Multipoint Video Distribution Services (MVDS). MVDS is a cellular terrestrial transmission system for video (TV) broadcast. It was originally meant to be a transmit-only service but recently, a small return channel has been incorporated in order to make the service interactive. MVDS can be used to serve areas the size of a small town. Allocated frequencies for this service are in the 40 GHz band. At these frequencies, the maximum cell size is about 5km. To extend coverage, relay stations are required.

In MVDS the coverage area is served by a transmitter, which is located either on a mast or a tall building. The rooftop equipment can be simplified by employing ROF techniques. For instance, instead of using Gunn oscillators with their own antennas and heat pipes for frequency stabilisation, an optical fibre link may be used to feed either a traveling wave tube or a solid state amplifier at the transmit frequency. This greatly reduces the weight and wind loading of the transmitter. In addition, a single optical fiber could feed the transmitter unit from a distance of several hundred meters.

2.6.4 Mobile Broadband Services

The Mobile Broadband System or Service (MBS) concept is intended to extend the services available in fixed Broadband Integrated Services Digital Network (B-ISDN) to mobile users of all kinds. Future services that might evolve on the B-ISDN networks must also be supported on the MBS system. Since very high bit rates of about 155 Mbps per user must be supported, carrier frequencies are pushed into mm-waves. Therefore, frequency bands in the 60 GHz band have been allocated. The 62-63 GHz band is allocated for the downlink while 65-66 GHz is allocated for the uplink transmission. The size of cells is in diameters of hundreds of meters (micro-
cells). Therefore, a high density of radio cells is required in order to achieve the desired coverage. The micro-cells could be connected to the fixed B-ISDN networks by optical fibre links. If ROF technology is used to generate the mm-waves, the base stations would be made simpler and therefore of low cost, thereby making full scale deployment of MBS networks economically feasible.

2.6.5 Vehicle Communication and Control

This is another potential application area of ROF technology. Frequencies between 63-64 GHz and 76-77 GHz have already been allocated for this service within Europe. The objective is to provide continuous mobile communication coverage on major roads for the purpose of Intelligent Transport Systems (ITS) such as Road-to-Vehicle Communication (RVC) and Inter-Vehicle Communication (IVC). ITS systems aim to provide traffic information, improve transportation efficiency, reduce burden on drivers, and contribute to the improvement of the environment. In order to achieve the required (extended) coverage of the road network, numerous base stations are required. These can be made simple and of low cost by feeding them through ROF systems, thereby making the complete system cost effective and manageable.
CHAPTER 3

Orthogonal Frequency Division Multiplexing (OFDM)

3.1 Introduction

This chapter highlights in brief the basic concept of OFDM and clears the general principles such as multicarrier transmission, Fast Fourier Transform (FFT) and Guard interval and its implementation.

Coded OFDM is very important concept to understand. This chapter also discusses the advantages and disadvantages of OFDM.

3.2 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) is seen as the modulation technique for future broadband wireless communications because it provides increased robustness against frequency selective fading and narrowband interference, and is efficient in dealing with multi-path delay spread. To achieve this, OFDM splits high-rate data streams into lower rate streams, which are then transmitted simultaneously over several sub-carriers.
By so doing, the symbol duration is increased. The advantage of this is that the relative amount of dispersion in time caused by multi-path delay spread is decreased significantly. Furthermore, introducing a guard time in every OFDM symbol eliminates Inter-Symbol Interference (ISI) almost completely. Within the guard time, the OFDM symbol is cyclically extended to avoid Inter-Carrier Interference (ICI). OFDM can in fact be considered as both a multiplexing method as well as a modulation method.

As stated above, OFDM uses multiple subcarriers to transmit low rate data streams in parallel. The subcarriers are themselves modulated by using Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) and are then carried on a high frequency microwave carrier (e.g. 5 GHz). This is similar to conventional Frequency Division Multiplexing (FDM) or Sub-Carrier Multiplexing, except for the stringent requirement of orthogonality between the sub-carriers. Sub-carrier orthogonality can be viewed in two ways, namely the time, and the frequency domains. In the time domain, each sub-carrier must have an integer number of cycles during each OFDM symbol interval (duration). In other words, the number of cycles between adjacent sub-carriers differs by exactly one as shown in Figure 3.1.a In the frequency domain, the amplitude spectra of individual sub-carriers (which are PSK or QAM modulated) overlap as shown in Figure 3.1.b However, at the maximum of each subcarrier spectrum, all other sub-carrier spectra are zero. Since the OFDM receiver calculates the spectrum values at the maximum points of individual sub-carriers, it can recover each sub-carrier without ICI interference from other sub-carriers.

Figure 3.1 OFDM Symbol a) Three Orthogonal Sub-carriers in one b) Spectra of three OFDM sub-carriers
OFDM is processor intensive because the basic OFDM signal is formed using the Inverse Fast Fourier Transform (IFFT), adding a cyclic extension and performing windowing to get steeper spectral roll off. In the receiver, the sub-carriers are demodulated by using Fast Fourier Transformation (FFT). The requirement for the intensive computations accounts for the complexity of OFDM transmitters and receivers. In comparison to single-carrier modulation systems, OFDM is more sensitive to Frequency offset and phase noise. Furthermore, OFDM has a relatively large peak-to-average power ratio, which reduces the power efficiency of the RF amplifier. OFDM is already used in many access network technologies including High-bit-rate, Digital Subscriber Lines (HDSL), Asymmetric Digital Subscriber Lines (ADSL), Veryhigh-speed Digital Subscriber Lines (VDSL), Digital Audio Broadcasting (DAB), and High Definition Television (HDTV) broadcasting. It is discussed in detail in [10].

3.3 General Principles

3.3.1 Multicarrier transmission

A multicarrier communication system with orthogonal subcarriers is called an Orthogonal Frequency Division Multiplex (OFDM) system. In an OFDM system, the carrier spacing $\Delta f$ is $1/NT$, where $N$ is the number of the carriers and $1/T$ is the overall symbol rate. With this carrier spacing, the subchannels can maintain orthogonality, although the subchannels overlap. Therefore, there is no inter-subcarrier interference with ideal OFDM systems. The number of subcarriers $N$ is chosen so that the subchannel bandwidth is less than the channel coherence bandwidth. Under this condition, each subchannel does not experience significant Inter-symbol Interference (ISI).
The transmitted signal of an OFDM system for one OFDM symbol period is of following form[11]

\[ s(t) = \text{Re}\left\{ \sum_n a_n h(t) \exp(j 2\pi f_n t + \phi) \right\} \]  

(3.1)

where \( a_n \) is the transmitted data symbol for the n-th subcarrier, \( h(t) \) is the pulse shaping filter response, \( f_n \) is the n-th subcarrier frequency \( f_n = f_c + n\Delta f \).

As the number of OFDM subcarriers increases, the complexity of the modulator and demodulator is increased accordingly. However, the OFDM modulator and demodulator can be implemented easily by the inverse discrete Fourier transform (IDFT) and discrete Fourier transform (DFT) respectively. Figure 3.2 shows a block diagram of the OFDM modulator. The time domain coefficients \( c_m \) can be computed by IDFT as [11]

\[ c_m = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} a_n \exp\left(-j \frac{2\pi nm}{N}\right) \]  

(3.2)

where \( a_n \) is the input of the IDFT block which is the data symbol for n-th subcarrier, \( c_m \) is the m-th output of the IDFT block. After the IDFT operation, the parallel output of IDFT block \( c_m(m = 1, \cdots, N - 1) \) is converted to a serial data stream. From the IDFT operation of Equation (3.2), we can convert the frequency domain data symbols into a series of time domain samples. The digital samples are digital to analog converted, filtered and converted to a carrier frequency \( f_c \).

At the receiver, the received signal is downconverted to base band and sampled at the symbol rate \( 1/T \). Then, N serial samples are converted to parallel data and passed to a DFT which converts the time domain signal into parallel signals in the frequency domain.
Figure 3.2: A block diagram of an OFDM transmitter.

The OFDM system transmits the wideband data over many narrowband subchannels. The symbol duration of each subcarrier becomes NΔt, where Δt is the symbol duration of the input data symbols. We assume that each subchannel experiences flat-fading. If the gain of the i-th channel is |αi|^2, then the received signal-to-noise ratio (SNR) of the i-th channel becomes [11]

$$SNR_i = \frac{P_i |\alpha_i|^2}{B N_0}$$  \hspace{1cm} (3.3)

where Pi is the signal power at the transmitter, B is the bandwidth of each subchannel and N0 is the noise spectral density.

If the i-th subchannel has low channel gain |αi|^2, the subchannel will have low received SNRi for constant transmission power. This can cause a higher symbol error rate in the subchannels with low channel gain. There are several schemes to compensate for the degradation due to low gain subchannels. One of the techniques is presetting transmission power with the channel inversion [11][3]. With the channel inversion presetting, the transmitter allocates more power to the subchannels with lower channel gain. The transmission power of i-th subchannel Pi is proportional to the inverse of the channel gain |αi|^2

$$P_i \propto \frac{1}{|\alpha_i|^2}$$ \hspace{1cm} (3.4)

With channel inversion, the received SNR of each subcarrier is the same and we can maintain the symbol error rate of each subcarrier the same. However, channel inversion is not a power efficient technique in fading channels since it can waste
much power at the subchannels with low gain. Furthermore, a large amount of power would be required for a Rayleigh fading channel. For example, for the frequency response, infinite power is required for channel inversion. Therefore, channel inversion is not widely used in practical multi-carrier communication systems. Instead, there are two other transmission techniques for compensating the frequency selectivity. One technique is coding across the tones and the other technique is transmission with adaptive bit and power loading. These transmission techniques will be discussed in detail in the following sections.

Multicarrier modulation methods transmit data on several different subcarrier frequencies. The multicarrier method most frequently used in wireless communications is orthogonal frequency-division multiplexing (OFDM). OFDM is a part of several standards for WLANs (IEEE 802.11a,g), fixed broadband wireless access (IEEE 802.16), digital audio broadcasting (DAB), digital TV (DVB-T), and wireless personal area networks (IEEE 802.15). It is also a promising candidate for future "beyond 3G" communication systems.

![Figure 3.3: Block diagram for multicarrier transmission: Version 1.](image)

Figure 3.3: The parallel data stream excites replicas of the same pulse-shaping filter \( g(t) \), and the filtered signals are modulated on the different carriers and summed up before transmission. Figure 3.4 the parallel data stream excites a filter bank of \( K \) (or \( K + 1 \)) different bandpass filters. The filter outputs are then summed up before transmission.
3.3.2 Fast Fourier Transform

At the transmitter of an OFDM system, data are apportioned in the frequency domain and an IFFT is used to modulate the data into the time domain. The FFT output data are guaranteed to be real-valued if conjugate symmetry is imposed on the input data.

In the receiver, an FFT is used to recover the original data. The FFT allows an efficient implementation of modulation of data onto multiple carriers [11]. Due to the similarity between the forward and inverse transform, the same circuitry, with trivial modifications, can be used for both modulation and demodulation in a transceiver. Figure 3.5 shows the block diagram of IFFT/FFT operation of OFDM transmitter and receiver.
3.3.3 Guard interval and its implementation

The orthogonality of subchannels in OFDM can be maintained and individual subchannels can be completely separated by the FFT at the receiver when there are no intersymbol interference (ISI) and intercarrier interference (ICI) introduced by transmission channel distortion. In practice these conditions can not be obtained. Since the spectra of an OFDM signal is not strictly band limited (sinc(f) function), linear distortion such as multipath cause each subchannel to spread energy into the adjacent channels and consequently cause ISI. A simple solution is to increase symbol duration or the number of carriers so that distortion becomes insignificant. However, this method may be difficult to implement in terms of carrier stability, Doppler shift, FFT size and latency.

![Figure 3.5: IFFT/FFT](image)

![Figure 3.6: Guard Interval](image)
One way to prevent ISI is to create a cyclically extended guard interval, where each OFDM symbol is preceded by a periodic extension of the signal itself. Figure 3.6 shows the guard interval with symbol. The total symbol duration is $T_{total} = T_g + T$, where $T_g$ is the guard interval and $T$ is the useful symbol duration. When the guard interval is longer than the channel impulse response, or the multipath delay, the ISI can be eliminated. However, the ICI, or in-band fading, still exists. The ratio of the guard interval to useful symbol duration is application-dependent. Since the insertion of guard interval will reduce data throughput, $T_g$ is usually less than $T/4$.

The reason to use a cyclic prefix for the guard interval is to maintain the receiver carrier synchronization; some signals instead of a long silence must always be transmitted; and cyclic convolution can still be applied between the OFDM signal and the channel response to model the transmission system.

### 3.4 Coded OFDM

Coded OFDM (COFDM) is one of the widely used transmission techniques for overcoming the frequency selectivity of the channel. The basic idea of coded OFDM is to encode input data and interleave the coded symbols. The interleaved symbols are split into several subchannels to achieve frequency diversity. Even though the uncoded symbol error rate is high for the subcarriers with low channel gains, with the channel coding and interleaving it is possible to correct the errors in the low gain channels. With the channel coding and interleaving, coded OFDM provides a robust communication link for many wireless channel environments.

This technique is very effective for channels with narrow coherence bandwidth. However, if the coherence bandwidth is large, then the channel gains of neighboring subchannels are highly correlated, and this may limit the diversity gain of coded OFDM systems.
3.4.1 **Coded OFDM Systems**

Coded OFDM is a transmission technique which puts equal amounts of data bits and transmission power on each subchannel. Originally, it was designed for a broadcasting channel where a feedback link does not exist from the receivers to the transmitter [12].

In many wireless environments, optimization of bit and power allocation is not possible due to rapid change of the channel responses. Coded OFDM is also used in time-varying wireless channels to recover errors or erasures in the subchannels located close to the nulls of the frequency response.

The information data is coded by a channel encoder. One of the most popular forms for the channel code is a trellis code. The encoded symbols are interleaved by an interleaver. The interleaved symbols are modulated onto a carrier at an OFDM modulator.

An example of a coded OFDM system is the 802.11a Wireless Local Area Network (W-LAN) system in the 5GHz band [14]. The IEEE 802.11a standard uses a coded OFDM scheme which demultiplexes coded symbols into 52 separate subcarriers. Data rates of the 802.11a system are 6, 9, 12, 18, 24, 36 and 48 Mbps. Data rates below 24 Mbps are mandatory. Table 3.1 presents the data rates and modulation schemes for the 802.11a coded OFDM system. Coded data symbols are transmitted over 48 subcarriers. The remaining 4 subcarriers are used as pilot subcarriers. A pseudo-random sequence is transmitted through the pilot subcarriers to avoid spectral lines. The receiver knows the signal sent on the pilot subcarriers and uses the pilot subcarriers for channel estimation.

For channel coding, a convolutional code with constraint length $k = 7$ and rate 1/2 is used. A rate 3/4 code is made by puncturing a coded symbol among three symbols.
In the time domain, a guard period is inserted between two OFDM symbols to prevent overlapping of two consecutive symbols by multipath delay spread. The guard period contains a copy of the end of the IDFT output and is called a cyclic prefix. The symbol rate of the system is 250 KHz and the guard period is 0.8 $\mu$s. The frequency spacing between subcarriers is 312.5 KHz, which is the inverse of 3.2 $\mu$s.

3.4.2 Trellis Coded Modulation

Coded Modulation is a technique to combine the channel coding and modulation for multi-level modulation. Ungerboeck first designed trellis coded modulation for AWGN channels with the concept [12].

Table 3.1: Data rates and modulation schemes for the 802.11 a W-LAN system.

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>Modulation</th>
<th>Coding Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>BPSK</td>
<td>1/2</td>
</tr>
<tr>
<td>9</td>
<td>BPSK</td>
<td>3/4</td>
</tr>
<tr>
<td>12</td>
<td>QPSK</td>
<td>1/2</td>
</tr>
<tr>
<td>18</td>
<td>QPSK</td>
<td>3/4</td>
</tr>
<tr>
<td>24</td>
<td>16-QAM</td>
<td>1/2</td>
</tr>
<tr>
<td>36</td>
<td>16-QAM</td>
<td>3/4</td>
</tr>
<tr>
<td>48</td>
<td>64-QAM</td>
<td>1/2</td>
</tr>
<tr>
<td>54</td>
<td>64-QAM</td>
<td>3/4</td>
</tr>
</tbody>
</table>

The main advantage of the trellis-coded modulation is significant coding gain without a loss of bandwidth efficiency.
Figure 3.7: (a) An example of 8-PSK modulation. (b) An example of a trellis diagram for a coded modulation scheme.
Figure 3.7 shows an example of an 8-PSK trellis-coded modulation. Figure 3.7 (a) shows an 8-PSK modulation scheme. Each constellation point of the 8-PSK is denoted with a number and the distance values in the figure are $\Delta_0 = 2\sin(\pi/8)$, $\Delta_1 = \sqrt{2}$ and $\Delta_2 = 2$. Figure 3.7 (b) shows a trellis diagram of a rate 2/3 encoder. There are four states in the encoder which are the contents of the shift register. With a new information input, the state of the encoder changes. There are four possible state transitions with 2 bit inputs. There are two pairs of parallel state transitions from each state. The number on the transition indicates the constellation point of the modulation associated with the state transition.

Consider the state transitions merging to the zero state or diverging from the zero state. The distance between two constellation points for these transitions are at least $\Delta_1 = \sqrt{2}$. With this property, the minimum distance between two sequences diverging from one state and merging into another is at least $\Delta_1^2 + \Delta_0^2 + \Delta_1^2$. The distance between two constellation points associated with the parallel transitions are $\Delta_2 = 2$, which is the maximum distance in the constellation. With the trellis diagram and modulation mapping in Figure 3.7, we can obtain the distance free as

$$d_{\text{free}}^2 = \min(\Delta_2^2, 2\Delta_1^2 + \Delta_0^2) = \Delta_2^3$$

(3.5)

Compared with the $d_{\text{free}} = 2$ of 4-PSK modulation, we observe about 3 dB coding gain with the modulation and trellis diagram of Figure 3.7. The performance of a communication link can be improved by 3 dB in an AWGN channel with a simple four state TCM scheme without reducing the data rate or increasing the bandwidth. If more states are allowed at the encoder, it is possible to achieve coding gains up to 6 dB [16]. In 1984, a TCM scheme was adopted for voiceband modems by the International Telephone and Telephone Consultative Committee (CCITT) [12].
3.4.3 Bit-interleaved Coded OFDM

Trellis coded modulation is a transmission technique to combine channel coding and modulation. However, the combination of channel coding and modulation may not be the best solution for fading channels, especially for fast Rayleigh fading channels.

In fading channel environments, we can achieve better performance by separating the channel coding and modulation [20][21]. Bit-interleaved Coded OFDM is a technique which separates the coding and modulation with a bit-level interleaver. For the decoding of the received signal, it is necessary to obtain a soft-bit metric for the input of the Viterbi decoder.

Figure 3.8 shows a block diagram of a transmitter and receiver using bit-interleaved coded modulation. Input data are encoded with a channel encoder which is characterized by the coding rate and the minimum distance between two nearest data sequences. The coded bits are interleaved at the interleaver. The interleaved bits are mapped to a point in a modulation constellation. The modulation scheme can be M-ary PSK or QAM, where M is assumed to be a power of 2. A mapper is a memoryless mapper between the interleaved bits $b_k$ and a constellation symbol $x_n$ that will be sent over the channel. $\log_2 M$ interleaved bits are mapped to one modulation symbol. The relation between the position $k$ of interleaved bit position $b_k$ and the position of the modulation symbol is

$$n = \frac{k}{\log_2 M}$$

$$i = k \mod \log_2 M$$

where $i$ is the location of the interleaved bit in a modulation symbol. The channel response for the $n$-th modulation symbol is assumed to be $\rho_n$. The received signal $y_n$ at the receiver is given as
Figure 3.8: A block diagram of Bit-interleaved coded OFDM.

\[ y_n = \rho_n x_n + n_n \]

where \( n_n \) is AWGN.

At the receiver, a demapper computes the maximum-likelihood (ML) soft metric of each interleaved bit based on the received signal. The ML soft metric is deinterleaved and sent to a Viterbi decoder. The Viterbi decoder chooses a sequence \( \hat{C} \) which satisfies [12]

\[ C = \max \Pr\{y_1, ..., y_N \mid C\} \]

(3.6)

where \( C \) is the set of all possible data sequence and \( N \) is the number of modulation symbols.

Figure 3.9 shows mappers for a 16-QAM modulator for bit-interleaved coded modulation and for trellis coded modulation. The mapping for each axis is a Gray mapping for bit-interleaved coded modulation. The mapping for trellis coded modulation is designed based on the set partition.

The bit-interleaved code modulation is a sub-optimal coding scheme for channel capacity in static channel environments. However, it provides frequency
diversity which is essential in wireless system designs that encounter multipath fading.

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<td>1110</td>
<td>1010</td>
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</tbody>
</table>

(b)

Figure 3.9: (a) Constellations of 16-QAM with Gray mapping.  
(b) Constellations of 16-QAM with set partitioning.
3.5 OFDM Advantages

OFDM has several advantages such as high data rate in mobile wireless channel and it is conveniently implemented using IFFT and FFT operations. However OFDM is a spectrally efficient modulation technique and it handles frequency selective channels well when combined with error as well as Correction coding. OFDM also has good tolerance to inter symbol interference (ISI).

3.6 OFDM Disadvantages

As OFDM has a lot of advantages it also has some disadvantages. The most effective disadvantage of OFDM is the complexity, where OFDM is a multicarrier modulation which is more complex than single-carrier modulation as well as OFDM Requires a more linear power amplifier.
CHAPTER 4

METOHODOLOGY

4.1 Introduction

This chapter shows the MATLAB/SIMULINK simulation model of this project and gives brief explanation of each block of the model and show the modeling of optical modulator (laser diode) and optical demodulator (photodiode) and what is the task of these block when we do run simulation.

4.2 Project methodology

The fist step to carry out this project is the understanding Radio Over Fiber Technology and the second is Study an OFDM modulation technique. The next step is mapping the simulation model of OFDM over Fiber for wireless systems. Simulate and evaluate QPSK-OFDM transmitted and received signal, power spectrum and BER. The software used for the simulation is MATLAB/SIMULINK software.

The methodology of this project is presented in the following flowchart
4.3 Blocks Used In Simulink

This section shows all blocks used in the whole system and explains in brief the task of each block.

4.3.1 Bernoulli Binary Generator

Bernoulli Binary Generator is using to generate Bernoulli-distributed random binary numbers. Figure 4.2 shows Bernoulli Binary Generator block.
4.3.2 Reed Solomon (RS) Double Error Correcting (15, 11) Code

It consists of inport, outport and Binary-Input RS Encoder. Figure 4.3 shows RS Double Error Correcting

![Figure 4.3: Reed Solomon (Rs) Double Error Correcting (15, 11) Code](image)

Inport creates an input port for a subsystem or an external input. Outport creates an output port for a subsystem or an external output. Binary-Input RS Encoder creates a Reed-Solomon code from binary vector data

4.3.3 QPSK Mapping

It consists of inport, outport, QPSK Modulator Baseband and Gain. Figure 4.4 shows QPSK Mapping and its parts.

![Figure 4.4: QPSK Mapping](image)
QPSK Modulator Baseband modulates using the quaternary phase shift keying method. Gain Multiply the input by a constant

### 4.3.3 Training

The Training block consists of PN Sequence Generator, Unipolar to Bipolar Converter and output. The Training block and its part are shown in Figure 4.5.

![Figure 4.5: Training](image)

PN Sequence Generator generates a pseudo noise sequence. Unipolar to Bipolar Converter maps a unipolar signal in the range \([0, M-1]\) into a bipolar signal

### 4.3.4 OFDM baseband modulator and add cyclic prefix

It consists of Multiport Selector, two Matrix Concatenation, Zero pad, IFFT, cyclic prefix. Figure 4.6 shows OFDM baseband modulator and add cyclic prefix block and Figure 4.7 shows its parts

![Figure 4.6: OFDM baseband modulator and add cyclic prefix](image)
Multiport Selector distributes arbitrary subsets of input rows or columns to multiple output ports. Matrix Concatenation concatenates inputs horizontally or vertically.

Zero pad block consists of input, output, zero pad and selector and they are shown in Figure 4.8

Zero Pad alters the input dimensions by zero-padding (or truncating) rows and/or columns. Selector selects input elements from a vector or matrix signal IFFT computes the IFFT (inverse fast fourier transform) of the input.

Cyclic prefix consists of input, output and selector and they are shown in Figure 4.9
4.3.6 Training Insertion

Training insertion consists of inport, outport, Multiport Selector, Matrix Concatenation and Frame Status Conversion as shown in Figure 4.10.

Frame Status Conversion specifies the frame status of the output as sample based or frame based.

4.3.7 Parallel To Serial Converter

It consists of inport, outport, Unbuffer, Complex to Real-Image. As shown in Figure 4.11.
Unbuffer unbuffers a frame input to a sequence of scalar outputs. Complex to Real-Image gives output the real and imaginary parts of a complex input signal.

4.3.8 Laser Diode

It consists of input, output, constants, gains and multiplexer based on the following equation [13]

\[
P_{\text{opt}} = -0.0045 + 0.32(I(t) - I_{\text{th}}) + 147.05(I(t) - I_{\text{th}})^2 - 12033(I(t) - I_{\text{th}})^3
\]  

(4.6)

Figure 4.12: laser diode

See the details of laser diode in Section 4.4

4.3.9 AWGN Channel and Optical Fiber Link

AWGN Channel adds white Gaussian noise to the input signal and it is shown in figure 4.13. And optical fiber link is presented by Gain.

Figure 4.13: AWGN Channel and Optical Fiber Link
4.3.9 Photodiode

This modeling of photo diode in details is existing in [13]

Figure 4.14: Photodiode

4.3.10 Serial To Parallel Converter

Serial To Parallel Converter consists of input, output, Buffer and Complex to Real-Image, and they are shown in Figure 4.15

Buffer buffers the input sequence to a smaller or larger frame size. Complex to Real-Image gives output the real and imaginary parts of a complex input signal
4.3.11 Training Separation

Training separation consists of import, outport, Multiport Selector, Matrix Concatenation as shown in Figure 4.16.
4.3.13 OFDM baseband demodulator and remove cyclic prefix:

It consists of Remove cyclic prefix, FFT, Selector, Frame Status Conversion and Multiport Selector as shown in Figure 4.17

FFT Computes the FFT of the input.

Figure 4.17: OFDM baseband demodulator and remove cyclic prefix

4.3.14 Channel Estimator

It consists of Step, two Enabled Subsystem, Two Frame Status Conversion, and Product as shown in Figure 4.18

Step is using to generate a step function. Enabled Subsystem represents a subsystem whose execution is enabled by external input
4.3.15 Channel Compensation

Channel compensation consists of Selector, Frame Status Conversion, and product as shown in Figure 4.19
4.3.16 Remove Zero

Remove Zero consists of inport, outport and selector as shown in Figure 4.20.

![Figure 4.20: Remove Zero](image)

4.3.16 QPSK Demodulator

It consists of inport, outport, QPSK Demodulator Baseband, Rounding Function and Gain as shown in Figure 4.21.

![Figure 4.21: QPSK DEMODULATOR](image)

QPSK Demodulator Baseband demodulates QPSK-modulated data. Rounding Function applies a rounding function to a signal.
4.3.17 Reed Solomon (RS) double error correcting (15, 11) decode

It consists of inport, outport, Terminator and Binary-Input RS Decoder as shown in Figure 4.22

Terminator is using to terminate an unconnected output port

![Figure 4.22: Reed Solomon (RS) double error correcting (15, 11) decode](image)

4.3.19 Error Rate Calculation

Error Rate Calculation is using to computes the bit error rate or symbol error rate of input data. Error Rate Calculation block is shown in Figure 4.23

![Figure 4.23: Error Rate Calculation](image)
4.4 Laser Diode Modeling

In general, a laser-diode exhibits a non-linear behaviour with memory which is called weak non-linearity. The Volterra series may be used to model the diode input/output characteristic. When the laser-diode is driven well above its threshold current, its input/output relationship can be modelled by a Volterra series of order 3 [14]. When the kernels of the Volterra series are taken as Dirac delta functions, then the system is modelled without memory. To simplify the analysis, a power series of order 3 can be used to adequately model the non-linear behaviour, because simple models can be used more readily for the analysis of wideband systems such as OFDM as well as narrow-band systems. For an ideal linear characteristic, the laser-diode input/output relationship is given by [14]

\[ P_{\text{opt}}(t) = r(I(t) - I_{\text{th}}) \] (4.1)

Where \( I(t) \) is the input current of the microwave signal including the DC bias, \( I_{\text{th}} \) is the diode threshold current, \( r \) is the “P-I” slope (i.e. the gradient of the output optical power vs. input electrical current curve) and \( P_{\text{opt}} \) is the output optical power of the laser-diode.

For the non-linear case the input/output relationship is assumed to be given by (2.4), where the terms \( a, b, c \) and \( d \) are constants [14]

\[ P_{\text{opt}}(t) = a + b(I(t) - I_{\text{th}}) + c(I(t) - I_{\text{th}})^2 + d(I(t) - I_{\text{th}})^3 \] (4.2)

For a bias current of 25.5 mA and a threshold current \( I_{\text{th}} \) of 19.5 mA, we can express the microwave input current as \( I(t) - I_{\text{th}} = B \cos(4\pi 10^9 t) + 0.006 \text{ Amps.} \), where \( B \) is the amplitude and the carrier frequency is 2 GHz. Then an expression for the instantaneous output electrical power is given by (3.4) assuming all other components have linear characteristics [2], where constant \( k_0 \) takes into account the cascaded gains and losses within the system. [14]

\[ P_{\text{e,out}}(t) = K_0 P_{\text{opt}}^2(t) \] (4.3)
Now we consider the AM/AM characteristic of Figure 2. Using curve fitting techniques we can fit a polynomial of degree 3 as shown in (4.4)

\[ P_y = 2.3 \times 10^3 P_x^3 - 670 P_x^2 + 0.95 P_x + 1.4 \times 10^{-6} \]  

(4.4)

where \( P_x \) and \( P_y \) are the average input and output powers, respectively. In order to justify the existence of equation (2.4), the time average of equation (3.4) is determined over the photodiode response time \( T = 0.5 \text{ns} \), i.e. \( \frac{1}{T} \int P_{\theta,\text{out}}(t)dt \). Then, equating coefficients of the resulting equation with those of equation (4.4) for corresponding powers of \( P_x \) gives the coefficient values shown in (5.4). In determining (5.4), an overall amplification in the electrical front-end of 19 dB (i.e. \( k_0 \)) is assumed and \( P_x = 25 \Omega^2 \) (for a 50 Ohm termination) is used as in [5]. The coefficients in (5.4) are not unique.[14]

\[ [a \ b \ c \ d] = [-0.0045 \ 0.32 \ 147.05 \ -12033] \]  

(4.5)

Therefore, an expression for the final relationship between input current and output optical power of the laser-diode is shown in (6). Equation 6 is only valid for the power range over which measurements were taken i.e. -20 to 0 dBm.[14]

\[ P_{\text{opt}}(t) = a + b(I(t)-I_{\text{th}}) + c(I(t)-I_{\text{th}})^2 + d(I(t)-I_{\text{th}})^3 \]  

(4.6)

Based on equation the simulink model of laser diode will be as shown in Figure 4.24.
4.5 Simulation Model Of The Project

The simulation model of the project is presented in Figure 4.25. In figure 4.25 the blocks stated in Section 4.3 have been collected to present the whole simulation model and the parameters of each block are shown in appendix A

OFDM uses multiple sub-carriers to transmit low rate data streams in parallel.

The sub-carriers are modulated by using Quadrature Amplitude Modulation (QPSK) and are then carried on a high frequency microwave carrier.[5]

The transmitter converts the input data from a serial stream to parallel sets. Each set of data contains one symbol for each subcarrier.[8]

An inverse Fourier transform converts the frequency domain data set into samples of the corresponding time domain representation of this data.[8]
Figure 4.25: Simulation model of the project

The parallel to serial block converts this parallel data into a serial stream.[8]

The base band signal has been generated by Bernoulli binary generator block

Reed Solomon (RS) double error correcting (15, 11) code has been used as FEC code for base band signal to be sent to next stage.

Coherent QPSK modulation and training (pseudo noise sequence generation) blocks are used to provide input to OFDM symbol generation (IFFT add cyclic prefix block).

In OFDM symbol generation the transmitter first converts the input data from a serial stream to parallel sets. Each set of data contains one symbol for each subcarrier. An inverse Fourier transform converts the frequency domain data set into samples of the corresponding time domain representation of this data, Specifically, the IFFT is useful for OFDM because it generates samples of a waveform with
frequency components satisfying orthogonality conditions. Then add cyclic prefix means insert guard time between consecutive OFDM symbols which helps to combat against ISI.

Training insertion block identifies training pattern in OFDM symbol and place them at predefined position in OFDM symbol to facilitate training process. Then, the parallel to serial block converts this parallel data into a serial stream and creates the OFDM signal by sequentially outputting the time domain samples. The OFDM signal is used to modulate the Laser Diode. laser diode will convert the signal from electrical to optical signal. The optical signal will carried over single mode optical fiber link

The receiver performs the inverse of the transmitter to recover the baseband signal and transmitted to the corresponding wireless user. At the receiver the photodiode will convert the signal from optical to electrical signal.

The channel estimator and channel compensation blocks are used to characterise the fluctuating noisy channel of power line and hence to improve SER.

The symbol error rates (SERs) with and without RS FEC code can be observed in scope1 and scope2 respectively. It can be seen that SER is less with RS FEC code.
CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

In this chapter shows the results of the simulation model using MATLAB/SIMULINK software, version 7. The figures will show the QPSK-OFDM transmitted and received signal before and after the transmission over fiber and power spectrum before and after the transmission over fiber and constellation before and after channel estimation.

5.2 OFDM Transmitted and Received Signal

The figure shows OFDM transmitted and received signal of real part and image part, OFDM transmitted and received signals are close to each other.
Figure 5.1: OFDM transmitted signal

Transmitter generates a set of QPSK modulated tones; the phase of each tone is a multiple of 0.1.

Figure 5.2: OFDM received signal

At the receiver, each transmit tone phase is shifted proportionally to frequency offset, plus some frequency dependent phase modulation, due to “beating” between tones.
5.3 The constellation before and after channel estimation

A constellation diagram is a graphical representation of the complex envelope of each possible symbol state. The constellation before channel estimation is shown in Figure 5.3

![Figure 5.3: The constellation before channel estimation](image)

QPSK uses binary-level modulation of the single frequency carrier wave components, generating an output signal space, or constellation, with four message points. Each of these message points, or symbols, carries two bits of information.

By using two components of the carrier wave, QPSK is able to carry twice as much information in the same amount of bandwidth.
This QPSK constellation diagram shows symbols, each represented by two data bits that were first gray encoded. One can see that each adjacent symbol is represented by two data bits that vary by one bit.

The power efficiency is related to the minimum distance between the points in the constellation between the points in the constellation. The constellation after channel estimation is shown in Figure 5.4.

![Figure 5.4: The constellation after channel estimation](image)
5.4 power spectrum before the transmission over fiber

Figure 5.5 shows the OFDM transmitted spectrum over AWGN channel.

![OFDM Transmitted Spectrum](image)

**Figure 5.5:** OFDM transmitted spectrum

There is a severe out-of-band radiation outside this main lobe of the OFDM spectrum caused by the poor decay of the sinc function. Figure 5.5 figure shows the spectrum of an OFDM signal without guard interval.

Figure 5.6 shows OFDM received spectrum. The guard interval slightly modifies the spectral shape by introducing ripples into the main lobe and reducing the ripples in the side lobe. The side lobes of the complete OFDM spectrum show a steeper decay and the spectrum comes closer to a rectangular shape.

The decay may still not be sufficient to fulfill the network planning requirements. These are especially strict for broadcasting systems, where side lobe reduction in the order of $-70$ dB is mandatory. In that case, appropriate steps must be taken to reduce the out-of-band radiation.
5.5 Comparison between Theoretical and Simulation BER

Figure 5.7 shows Comparison between Theoretical and Simulation BER. Both of Theoretical and Simulation BER are close to each other.

At the receiver the signal is filtered by the FFT stage, thus making the receiver only see noise within the signal bandwidth.

Increasing the cyclic prefix duration improves the BER performance for the OFDM system. The BER performance is in all cases improved by increasing the OFDM symbol length.
Figure 5.7: Comparison between Theoretical and Simulation BER

5.6 OFDM Over Fiber Transmitted and Received Power Spectrum

Figures 5.8 and 5.9 show OFDM over fiber transmitted and received power spectrum. For transmitted power spectrum in Figure 5.8 it the same like transmitted power spectrum before sending the signal over fiber. For received power spectrum in Figure 5.9 it became different with received signal before sending over fiber.
The result in Figure 5.9 indicates that the photodiode can be used as an optical demodulator with laser diode as optical modulator but the photodiode is working better with Mach-Zehnder optical modulator.

Figure 5.8: OFDM transmitted spectrum over fiber

Figure 5.9: OFDM received spectrum over fiber
5.7 OFDM over fiber Transmitted and Received Signal

Figures 5.10 and 5.11 show OFDM over fiber transmitted and received signal. For transmitted signal in Figure 5.10 it the same like transmitted signal before sending the signal over fiber. For received signal in Figure 5.11 it became different with received signal before sending over fiber.

The result in Figure 5.11 indicates to the photodiode can used as optical demodulator with laser diode as optical modulator but the photodiode is working better with Mach-Zehnder optical modulator.

![Figure 5.10: OFDM over fiber Transmitted Signal](image1)

![Figure 5.11: OFDM over fiber Received Signal](image2)
CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

In today's modern world, the interconnection and interfacing of differing technologies are becoming commonplace. The increasing demand for high-capacity multimedia services in real-time demands wireless broadband access. Therefore, gaining an understanding of how these interconnects and interfaces interact is critical to successful system design. In order to meet this demand, a fiber based wireless access scheme using radio-over-fiber (ROF) technology is used and is discussed in this project.

The system identification technique has been devised for a concatenated fiber-wireless channel, and has proposed various compensation schemes to equalize the time varying linear wireless plus static nonlinear optical channel. Also, it has been focused on supporting both cellular OFDM and IEEE 802.11 signals over the fiber-wireless channel. As well as performed various experimental studies on the ROF approach and have been working with optical and electrical signal processing for performance improvement.
As a conclusion that covers the determination made by studies the projected impact of implementing ROF schemes is substantial. The deployment of optical fiber technology in wireless networks provides grate results obtained from the first part OFDM over AWGN channel which were close for expected results. The results of transmit QPSK-OFDM signal over fiber were good specially in the transmitter part but it still need to improve and as a result, the photodiode can used as optical demodulator with laser diode as optical modulator but it is working better with Mach-Zehnder optical modulator. Overall, the project offered vast learning opportunity in the OFDM and Radio over Fiber technology and how to simulate using MATLAB/SIMULINK software. The studying of OFDM modulation and radio over fiber technology became very important because both of them have been developed to support some important future wireless systems. Finally this project was transmitting of QPSK-OFDM baseband signal over fiber and it is able to improve to transmit radio signal over fiber.

6.2 Future of work and recommendations

The future work is to complement and extend the results further, it is recommended to add IQ modulator to the system, which will convert from baseband to RF signal then carried over optical fiber link. It is also recommended to enhance the BER for the signal transmitted over fiber by using Mach-Zehnder as optical modulator and photodiode as optical demodulator or modify the photodiode design to works well with laser diode. most highly recommendation is to develop OFDM modulation and radio over fiber technology to support the 4th generation cellular systems. Finally, Based on the results and calculations which made in this project, it should be in the interest to design an effective compensation technique so that a good quality and availability of the service is provided.
References


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16. SONG B., GUAN Y. and ZHANG W. "An efficient training sequences strategy for channel estimation in OFDM systems with transmit diversity"
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APPENDIX A

The goal of putting this appendix is to show the important parameters of each block used in SIMULINK in the whole system, starting from the binary data and OFDM transmitter and going to AWGN channel and OFDM receiver.

![Source Block Parameters: Bernoulli Random Bi...](image)
Encode the message in the input vector using an (N,K) Reed-Solomon encoder with the narrow-sense generator polynomial. The input must be a frame-based column vector with an integer multiple of N*K(ceil(log2(N+1))) bits. Each group of N*K(ceil(log2(N+1))) input bits represents one message word to be encoded.

The optional 'Primitive polynomial' parameter is a row vector that represents the binary coefficients of the primitive polynomial in order of descending powers. When such a user-defined Primitive polynomial is provided, the number of input bits must be an integer multiple of K times the order of the Primitive polynomial instead.

The optional 'Generator polynomial' parameter is a row vector that represents the coefficients of the generator polynomial in order of descending powers. Each coefficient is an element of the Galois field defined by the primitive polynomial.

Parameters

Codeword length N:
16

Message length K:
11

Specify primitive polynomial

Primitive polynomial:
[1 0 1 1]

Specify generator polynomial

Generator polynomial:
isgenpoly(7,3)

Output data type: double

[OK]  [Cancel]  [Help]  [Apply]
Source Block Parameters: PN Sequence Generator

Generate a pseudonoise (PN) sequence using a linear feedback shift register whose configuration is specified by the Generator polynomial parameter.

The generator polynomial parameter values represent the shift register connections. Enter these values as either a binary vector or a descending ordered polynomial to indicate the connection points.

For the binary vector representation the first and last elements of the vector must be 1. For the descending ordered polynomial representation the last element of the vector must be 0.

The initial states parameter is a binary vector that represents the starting state of the shift register.

The shift parameter is a scalar integer that produces an offset in the PN sequence. As a result, the block outputs the sequence from a future instant in time. Alternatively, one can specify the mask parameter as a binary vector corresponding to the same shift.

Parameters:

Generator polynomial:

\[ [1|0|0|0|0|1] \]

Initial states:

\[ [0|0|0|0|1] \]

Shift (or mask):

0

Sample time:

1.6e-5/2/31

- Frame-based outputs
- Samples per frame:

31

- Reset on nonzero input
- Output data type: double
**Function Block Parameters: Unipolar to Bipolar Converter**

Convert a unipolar signal in the range $[0, M-1]$, where $M$ is the M-ary number, into a bipolar signal.

**Parameters**

- **M-ary number:**
  - 3

- **Polarity:** Positive

- **Output data type:** Same as input

**Function Block Parameters: QPSK Modulator Baseband**

Modulate the input signal using the quaternary phase shift keying method.

The input can be either bits or integers. In case of sample-based bit input, the input width must be two. In case of frame-based bit input, the input width must be an integer multiple of two. The bits can be either binary-mapped or Gray-mapped into symbols.

For sample-based integer input, the input must be a scalar. For frame-based integer input, the input must be a column vector.

In case of frame-based input, the width of the output frame equals the product of the number of symbols and the Samples per symbol value.

In case of sample-based input, the output sample time equals the symbol period divided by the Samples per symbol value.

**Parameters**

- **Input type:** Bit

- **Constellation ordering:** Gray

- **Phase offset (rad):** $\pi/4$

- **Samples per symbol:** 1

[OK] [Cancel] [Help] [Apply]
**Function Block Parameters: Matrix Concatenation**

**Concatenate**
Concatenate input signals of the same data type to create a contiguous output signal. Select vector or matrix mode.

In vector mode, all input signals must be either vectors or one-row \([1 \times M]\) matrices or one-column \([M \times 1]\) matrices or a combination of vectors and either one-row matrices or one-column matrices. The output is a vector if all inputs are vectors. The output is a one-row or one-column matrix if any of the inputs are one-row or one-column matrices, respectively.

Matrix mode treats vector inputs as one-column matrices. The output is always a matrix.

**Parameters**
- **Number of inputs:** 3
- **Mode:** Vertical matrix concatenation

**Function Block Parameters: Matrix Concatenation**

**Concatenate**
Concatenate input signals of the same data type to create a contiguous output signal. Select vector or matrix mode.

In vector mode, all input signals must be either vectors or one-row \([1 \times M]\) matrices or one-column \([M \times 1]\) matrices or a combination of vectors and either one-row matrices or one-column matrices. The output is a vector if all inputs are vectors. The output is a one-row or one-column matrix if any of the inputs are one-row or one-column matrices, respectively.

Matrix mode treats vector inputs as one-column matrices. The output is always a matrix.

**Parameters**
- **Number of inputs:** 2
- **Mode:** Horizontal matrix concatenation
**Function Block Parameters: Zero Pad**

**Zero Pad (mask) (link)**

Append or prepend zeros to the input along specified dimensions. Truncation will occur if the specified number of output rows and/or columns is less than the corresponding input signal dimensions.

**Parameters**

- **Pad signal at**: End
- **Pad along**: Columns and rows
- **Number of output rows**: User-specified
- **Specified number of output rows**: 64
- **Number of output columns**: User-specified
- **Specified number of output columns**: 2
- **Action when truncation occurs**: None

**Function Block Parameters: Selector**

**Selector**

Select or reorder specified elements of an input vector or matrix. If "Use index as starting value" option is not checked:

- For vector input: \( y = u(\text{elements}) \)
- For matrix input: \( y = u(\text{rows, columns}) \)

Otherwise:

- For vector input: \( y = u(\text{element:element+outdim-1}) \)
- For matrix input: \( y = u(\text{row:row+outdim(1)-1, column:column+outdim(2)-1}) \)

Where `outdim` is the value specified in the "Output port dimensions" parameter. The source of elements (E) or row (R) and column (C) indices may be the block's dialog (internal) or an input port (external).

**Parameters**

- **Input type**: Matrix
- **Index mode**: One-based
- **Source of row indices (R)**: Internal
- **Rows**: [1:64:1:15]
- **Source of column indices (C)**: Internal
- **Columns**: [1 for all columns]
- **-1**: Use index as starting value

[Apply] [OK] [Cancel] [Help]
Function Block Parameters: IFFT

Outputs the inverse fast Fourier transform (IFFT) of a real or complex input by computing radix-2 decimation-in-time (DIT) or decimation-in-frequency (DIF), depending on block options. Outputs are real if you select 'Input is conjugate symmetric' option; otherwise, outputs are complex.

Computes the IFFT along the vector dimension for sample-based vector inputs, which must have a power-of-2 length. Computes the IFFT along each column for all other inputs, where the columns must be a power-of-2 length.

Parameters:
- Twiddle factor computation: [Table lookup]
- Optimize table for: [Speed]
- [Input is in bit-reversed order]
- [Input is conjugate symmetric]
- [Skip scaling]
Select or reorder specified elements of an input vector or matrix.
If "Use index as starting value" option is not checked
- $y = u(\text{elements})$ for vector input
- $y = u(\text{rows, columns})$ for matrix input
Otherwise
- $y = u(\text{element, element} + \text{outdim}-1)$ for vector input
- $y = u(\text{row, row} + \text{outdim}[1], \text{column, column} + \text{outdim}[2]-1)$ for matrix input
where outdim is the value specified in the "Output port dimensions" parameter.
The source of element (E) or row (R) and column (C) indices may be
the block’s dialog (internal) or an input port (external).

Parameters

- **Input type:** Matrix
- **Index mode:** One-based
- **Source of row indices (RI):** Internal
- **Rows [1 for all rows]:** [33.04, 1.04]
- **Source of column indices (CI):** Internal
- **Columns [1 for all columns]:** [1]
- **Use index as starting value**

---

Output specified rows or columns to one or more output ports. The number of output
ports is determined by the number of index vectors, each specified as a separate
vector entry in a cell array. Indices are 1-based and need not be unique.

Parameters

- **Select:** Columns
- **Indices to output:** (1, 2)
- **Invalid index:** Clip Index

---
**Function Block Parameters: Complex to Real-Imag**

Complex to Real-Imag

Output the real and/or imaginary components of the input

**Parameters**

Output: Real and imag

Sample time (-1 for inherited): -1

**Function Block Parameters: Multipath Rayleigh Fading Channel**

Multipath Rayleigh fading channel for complex baseband signals.

Multiplies the input signal with samples of a Rayleigh distributed complex random process. The spectrum of the Rayleigh process is given by the Jakes PSD.

The number of paths equals the length of either the 'Delay vector' or 'Gain vector' parameters.

**Parameters**

Maximum Doppler shift (Hz)

200

Sample time:

0.5/100

Delay vector (s):

[0 3e-6]

Gain vector (dB):

[0 -6]

Normalize gain vector to 0 dB overall gain

Initial seed:

336497248

[OK] [Cancel] [Help] [Apply]
Function Block Parameters: AWGN Channel

AWGN Channel (mask) (link)

Add white Gaussian noise to the input signal. The input and output signals can be real or complex. This block supports multichannel input and output signals as well as frame-based processing.

When using either of the variance modes with complex inputs, the variance values are equally divided among the real and imaginary components of the input signal.

Parameters

Initial seed:
32368

Mode: Signal to noise ratio (Es/No)

Es/No (dB):
28

Input signal power (watts):
30/(5.5e5*11/1.15^2.4)*1.08

Symbol period (s):
80e-6

OK Cancel Help Apply

Function Block Parameters: Buffer

Buffer (mask) (link)

Convert scalar samples to a frame output at a lower sample rate. You can also convert a frame to a smaller or larger size with optional overlap. For calculation of sample delay, see the rebuffer_delay function.

Parameters

Output buffer size (per channel):
160

Buffer overlap:
0

Initial conditions:
0

OK Cancel Help Apply
Function Block Parameters: FFT

FFT

Outputs the complex fast Fourier transform (FFT) of a real or complex input by computing radix-2 decimation-in-time (DIT) or decimation-in-frequency (DIF), depending on block options. Uses half-length and double-length algorithms for real inputs where possible.

Computes the FFT along the vector dimension for sample-based vector inputs, which must have a power-of-2 length. Computes the FFT along each column for all other inputs, where the columns must be a power-of-2 length.

Parameters

- Twiddle factor computation: Table lookup
- Optimize table for: Speed
- Output in bit-reversed order

[OK] [Cancel] [Help] [Apply]
Function Block Parameters: Multiport Selector

Output specified rows or columns to one or more output ports. The number of output ports is determined by the number of index vectors, each specified as a separate vector entry in a cell array. Indices are 1-based and need not be unique.

Parameters

Select: **Columns**

Indices to output:

\{1,2\}

Invalid index: **Clip Index**

OK  Cancel  Help  Apply

Function Block Parameters: Selector2

Select or reorder specified elements of an input vector or matrix.

If 'Use index as starting value' option is not checked

\[ y = u(\text{elements}) \text{ for vector input} \]

\[ y = u(\text{rows,columns}) \text{ for matrix input} \]

Otherwise

\[ y = u(\text{element,element+outdim-1}) \text{ for vector input} \]

\[ y = u(\text{row,row+outdim(1)}\text{,column,column+outdim(2)-1}) \text{ for matrix input} \]

where outdim is the value specified in the "Output port dimensions" parameter.

The source of element (E) or row (R) and column (C) indices may be the block's dialog (internal) or an input port (external).

Parameters

Input type: **Matrix**

Index mode: **One-based**

Source of row indices (R): **Internal**

Rows \{1 for all rows\}:

\[ [1,15,17,31] \]

Source of column indices (C): **Internal**

Columns \{1 for all columns\}:

-1

Use index as starting value

OK  Cancel  Help  Apply
Function Block Parameters: Product

Product
Multiply or divide inputs. Choose element-wise or matrix product and specify one of the following:
a) * or / for each input port (e.g., "*/")
b) scalar specifies the number of input ports to be multiplied
Scalar value of "1" for element-wise product causes all elements of a single input vector to be multiplied.
If / is specified with matrix product, compute the inverse of the corresponding input.

Main

Number of inputs

Multiplication: Element-wise(*)

Sample time (-1 for inherited):

-1

OK Cancel Help Apply

Function Block Parameters: Frame Status Conversion5

Frame Status Conversion (mask) (link)
Specify the frame status of the output signal.

Parameters

[Inherit output frame status from Ref input port]

Output signal: Frame-based

OK Cancel Help Apply
Function Block Parameters: Selector2

Selector
Select or reorder specified elements of an input vector or matrix.
If "Use index as starting value" option is not checked
  \[ y = u(\text{elements}) \] for vector input
  \[ y = u(\text{rows}, \text{columns}) \] for matrix input
Otherwise
  \[ y = u(\text{element} \cdot \text{element} + \text{outdim} - 1) \] for vector input
  \[ y = u(\text{row} \cdot \text{row} + \text{outdim}(1), \text{column} \cdot \text{column} + \text{outdim}(2) - 1) \] for matrix input
where \text{outdim} is the value specified in the "Output port dimensions" parameter.
The source of element (E) or row (R) and column (C) indices may be
the block's dialog (internal) or an input port (external).

Parameters

Input type: [Matrix]
Index mode: [One-based]
Source of row indices (R): [Internal]
Rows [1 for all rows]: [1:15, 17:31]
Source of column indices (C): [Internal]
Columns [1 for all columns]: [-1]

[Use index as starting value]

OK  Cancel  Help  Apply

Function Block Parameters: Gain

Gain
Element-wise gain \( y = K \cdot u \) or matrix gain \( y = K \cdot u \) or \( y = u \cdot K \).

Option

Gain: [0.75]
Multiplication: [Element-wise(K \cdot u)]
Sample time [-1 for inherited]: [-1]

OK  Cancel  Help  Apply
Function Block Parameters: Binary-Output RS Decoder

Binary-Output RS Decoder (mask) (link)

Attempt to decode the input received signal using an \((N,K)\) Reed-Solomon decoder with the narrow-sense generator polynomial. The input must be a frame-based column vector with an integer multiple of \(N \times \text{ceil}(\log_2(N+1))\) bits. Each group of \(N \times \text{ceil}(\log_2(N+1))\) input bits represents one received word to be decoded.

The optional 'Primitive polynomial' parameter is a row vector that represents the binary coefficients of the primitive polynomial in order of descending powers. When such a user-defined Primitive polynomial is provided, the number of input bits must be an integer multiple of \(N\) times the order of the Primitive polynomial instead.

The optional 'Generator polynomial' parameter is a row vector that represents the coefficients of the generator polynomial in order of descending powers. Each coefficient is an element of the Galois field defined by the primitive polynomial.

The number of corrected errors can be sent to a second output port by checking the 'Output number of corrected errors' check box. A decoding failure occurs when a certain received word in the input contains more than \((N-K)/2\) symbol errors. This is indicated by a value of -1 in the corresponding position in the second output vector.

Parameters

Codeword length \(N\):
[16]

Message length \(K\):
[11]

Specify primitive polynomial

Primitive polynomial:
[1 0 1 1]

Specify generator polynomial

Generator polynomial:
[s gen poly7 3]

Output number of corrected errors

Output data type: double
Function Block Parameters: QPSK Modulator Baseband1

Modulate the input signal using the quaternary phase shift keying method.

The input can be either bits or integers. In case of sample-based bit input, the input width must be two. In case of frame-based bit input, the input width must be an integer multiple of two. The bits can be either binary-mapped or Gray-mapped into symbols.

For sample-based integer input, the input must be a scalar. For frame-based integer input, the input must be a column vector.

In case of frame-based input, the width of the output frame equals the product of the number of symbols and the Samples per symbol value.

In case of sample-based input, the output sample time equals the symbol period divided by the Samples per symbol value.

Parameters

- Input type: Bit
- Constellation ordering: Gray
- Phase offset (rad): $\pi/4$
- Samples per symbol: 1

[OK] [Cancel] [Help] [Apply]
Modulate the input signal using the quaternary phase shift keying method.

The input can be either bits or integers. In case of sample-based bit input, the input width must be two. In case of frame-based bit input, the input width must be an integer multiple of two. The bits can be either binary-mapped or Gray-mapped into symbols.

For sample-based integer input, the input must be a scalar. For frame-based integer input, the input must be a column vector.

In case of frame-based input, the width of the output frame equals the product of the number of symbols and the Samples per symbol value.

In case of sample-based input, the output sample time equals the symbol period divided by the Samples per symbol value.

Parameters

Input type: Bit
Constellation ordering: Gray
Phase offset (rad): π/4
Samples per symbol: 1
Function Block Parameters: Error Rate Calculation

Compute the error rate of the received data by comparing it to a delayed version of the transmitted data. The block output is a three-element vector consisting of the error rate, followed by the number of errors detected and the total number of symbols compared. This vector can be sent to either the workspace or an output port.

The delays are specified in number of samples, regardless of whether the input is a scalar or a vector. The inputs to the 'Tx' and 'Rx' ports must be sample-based scalars or frame-based column vectors.

The 'Stop simulation' option stops the simulation upon detecting a target number of errors or a maximum number of symbols, whichever comes first.

Parameters:

- Receive delay:
- Computation delay:
- Computation mode: Entire frame
- Output data: Pot
- Reset port
- Stop simulation
- Target number of errors:
- Maximum number of symbols:

OK Cancel Help Apply

Sink Block Parameters: Display

Numeric display of input values.

Parameters:

- Format: short
- Decimation:
- Floating display

OK Cancel Help Apply
Modulate the input signal using the quaternary phase shift keying method.

The input can be either bits or integers. In case of sample-based bit input, the input width must be two. In case of frame-based bit input, the input width must be an integer multiple of two. The bits can be either binary-mapped or Gray-mapped into symbols.

For sample-based integer input, the input must be a scalar. For frame-based integer input, the input must be a column vector.

In case of frame-based input, the width of the output frame equals the product of the number of symbols and the Samples per symbol value.

In case of sample-based input, the output sample time equals the symbol period divided by the Samples per symbol value.

Parameters

- **Input type**: Bit
- **Constellation ordering**: Gray
- **Phase offset (rad)**: \( \pi/4 \)
- **Samples per symbol**: 1

[OK] [Cancel] [Help] [Apply]
Function Block Parameters: QPSK Modulator BasebandZ

Modulate the input signal using the quaternary phase shift keying method.

The input can be either bits or integers. In case of sample-based bit input, the input width must be two. In case of frame-based bit input, the input width must be an integer multiple of two. The bits can be either binary-mapped or Gray-mapped into symbols.

For sample-based integer input, the input must be a scalar. For frame-based integer input, the input must be a column vector.

In case of frame-based input, the width of the output frame equals the product of the number of symbols and the Samples per symbol value.

In case of sample-based input, the output sample time equals the symbol period divided by the Samples per symbol value.

Parameters

Input type: Bit

Constellation ordering: Gray

Phase offset (radians): pi/4

Samples per symbol: 1
Function Block Parameters: Error Rate Calculation

Error Rate Calculation (mask) (link)

Compute the error rate of the received data by comparing it to a delayed version of the transmitted data. The block output is a three-element vector consisting of the error rate, followed by the number of errors detected and the total number of symbols compared. This vector can be sent to either the workspace or an output port.

The delays are specified in number of samples, regardless of whether the input is a scalar or a vector. The inputs to the 'TX' and 'RX' ports must be sample-based scalars or frame-based column vectors.

The 'Stop simulation' option stops the simulation upon detecting a target number of errors or a maximum number of symbols, whichever comes first.

Parameters:

Receive delay:

Computation delay:

Computation mode: Entire frame

Output data: Port

Reset port

Start simulation

Target number of errors:

Maximum number of symbols:

OK  Cancel  Help

Apply

Sink Block Parameters: Display1

Display

Numeric display of input values.

Parameters:

Format: Short

Decimation: 1

Floating display

OK  Cancel  Help

Apply
Source Block Parameters: PN Sequence Generator

Generate a pseudonoise (PN) sequence using a linear feedback shift register whose configuration is specified by the Generator polynomial parameter.

The generator polynomial parameter values represent the shift register connections. Enter these values as either a binary vector or a descending ordered polynomial to indicate the connection points.

For the binary vector representation the first and last elements of the vector must be 1. For the descending ordered polynomial representation the last element of the vector must be 0.

The initial states parameter is a binary vector that represents the starting state of the shift register.

The shift parameter is a scalar integer that produces an offset in the PN sequence. As a result, the block outputs the sequence from a future instant in time. Alternatively, one can specify the mask parameter as a binary vector corresponding to the same shift.

Parameters

- Generator polynomial: [1 0 0 0 0 1]
- Initial states: [0 0 0 0 1]
- Shift (or mask): 0
- Sample time: 16:0/2/31
- Frame-based outputs
- Samples per frame: 31
- Reset on nonzero input
- Output data type: double

Function Block Parameters: Unipolar to Bipolar Converter

Convert a unipolar signal in the range [0, M-1], where M is the M-ary number, into a bipolar signal.

Parameters

- M-ary number: 2
- Polarity: Positive
- Output data type: Same as input

[Buttons: OK, Cancel, Help, Apply]
Function Block Parameters: Product

Product
Multiply or divide inputs. Choose element-wise or matrix product and specify one of the following:
- "\cdot" or "\cdot/" for each input port (e.g., "x*x")
- Scalar specifies the number of input ports to be multiplied
Scalar value of "\cdot" for element-wise product causes all elements of a single input vector to be multiplied.
If / is specified with matrix product, compute the inverse of the corresponding input.

Main Signal Data Types
Number of inputs:

Multiplication: Element-wise (\cdot)
Sample time (-1 for inherited):

OK Cancel Help Apply

Function Block Parameters: Frame Status Conversion

Frame Status Conversion [mask] (link)
Specify the frame status of the output signal.

Parameters
- Inherit output frame status from Ref input port
Output signal: Frame-based

OK Cancel Help Apply

Function Block Parameters: Math Function

Math
Mathematical functions including logarithmic, exponential, power, and modulus functions. When the function has more than one argument, the first argument corresponds to the top (or left) input port.

Main Signal Data Types

Function: reciprocal
Output signal type: auto
Sample time (-1 for inherited):

OK Cancel Help Apply
**Block Parameters: Enable**

Enable Port:
Place this block in a subsystem to create an enabled subsystem.

Parameters:
- States when enabling: held
- [ ] Show output port
- [x] Enable zero crossing detection

**Function Block Parameters: Frame Status Conversion4**

Frame Status Conversion (mask) (link)
Specify the frame status of the output signal.

Parameters:
- [ ] Inherit output frame status from Ref input port
- Output signal: Frame-based

[OK] [Cancel] [Help] [Apply]