ADAPTIVE OPTICAL FEEDFORWARD LINEARIZATION OF OPTICAL TRANSCEIVER FOR RADIO OVER FIBER COMMUNICATION LINK

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To my parents and family...
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ABSTRACT

With the tremendous growth in numbers of mobile data subscribers and explosive demand for mobile data, the current wireless access network need to be augmented in order to keep up with the data speed promised by the future generation mobile network standards. Radio over fiber technology (RoF) is a cost effective solution because of its ability to support numerous numbers of simple structured base stations by consolidating the signal processing functions at the central station. RoF systems are analog systems where noise figure and spurious free dynamic range (SFDR) are important parameters in an RoF link. The nonlinearity of a laser transmitter is a major limiting factor to the performance of an RoF link, as it generates spurious spectral components, leading to intermodulation distortions (IMD), which limit the achievable SFDR of the analog RF wave transmissions. The device nonlinearity can be mitigated through various linearization schemes. The feedforward linearization technique offers a number of advantages compared to other techniques, as it offers good suppression of distortion products over a large bandwidth and supports high operating frequencies. On the other hand, feedforward linearization is a relatively sensitive scheme, where its performance is highly influenced by changing operating conditions such as laser aging, temperature effect, and input signal variations. Therefore, for practical implementations the feedforward system has to be real-time adaptive. This thesis aims to develop an adaptive optical feedforward linearization system for radio over fiber links. Mathematical analyses and computer simulations are performed to determine the most efficient algorithm for the adaptive controller for laser transmitter feedforward linearization system. Experimental setup and practical measurement are performed for an adaptive feedforward linearized laser transmitter and its performance is optimized. The adaptive optical feedforward linearization system has been modeled and simulated in MATLAB Simulink. The performances of two adaptive algorithms, which are related to the gradient signal method, such as least mean square (LMS) and recursive least square (RLS) have been compared. The LMS algorithm has been selected because of its robustness and simplicity. Finally, the adaptive optical feedforward linearization system has been set up with digital signal processor (DSP) as the control device, and practical measurement has been performed. The system has achieved a suppression of 14 dB in the third order IMD products over a bandwidth of 30 MHz, in a two-tone measurement at 1.7 GHz.
ABSTRAK

Dengan pertumbuhan yang besar dalam jumlah pelanggan data mudah alih dan permintaan yang meledak untuk data mudah alih, rangkaian akses tanpa wayar yang sedia ada perlu dikekalkan dalam usaha untuk bersaing dengan kelajuan data yang dijanjikan oleh piawaian rangkaian mudah alih untuk generasi masa depan. Isyarat radio melalui gentian (RoF) ialah satu penyelesaian yang berkesan dari segi kos kerana keupayaannya untuk menyokong bilangan stesen pangkalan yang berbezaan berstruktur ringkas yang banyak dengan menggabungkan fungsi pemprosesan isyarat di stesen pusat. Sistem RoF adalah sistem analog di mana angka hingar dan julat dinamik bebas isyarat yang tidak diingini (SFDR) adalah parameter penting dalam pautan RoF. Pemancar laser yang tidak linear adalah faktor utama yang mengehadkan prestasi pautan RoF, kerana ia menghasilkan komponen spektral palsu, yang menyebabkan herotan intermodulasi (IMD) yang mengehadkan SFDR yang boleh dicapai dalam penghantaran gelombang analog RF. Ketaklinearan peranti dapat dikurangkan melalui pelbagai skim pelinearan. Teknik pelinearan suapan depan menawarkan beberapa kelebihan berbanding dengan teknik yang lain, kerana ia menawarkan pengurangan yang baik terhadap produk herotan di bawah jalur lebar yang besar dan menyokong frekuensi operasi yang tinggi. Sebaliknya, pelinearan suapan depan merupakan satu skim yang agak sensitif, di mana prestasinya mudah dipengaruhi oleh perubahan keadaan operasi seperti penuaan laser, kesan suhu, dan variasi isyarat masukan. Oleh itu, untuk pelaksanaan praktikal, sistem pelinearan suapan depan harus mudah suai secara masa nyata. Tesis ini bertujuan untuk membangunkan sistem pelinearan suapan depan mudah suai optik untuk pautan RoF. Analisis matematik dan simulasi komputer dilakukan untuk menentukan algoritma yang paling cekap untuk sistem kawal mudah suai bagi sistem pelinearan suapan depan pemancar laser. Persediaan eksperimen dan pengukuran praktikal dilakukan untuk pemancar laser bersuapan depan linear dan prestasinya dioptimumkan. Sistem pelinearan optik bersuapan depan mudah suai telah dimodelkan dan disimulasikan dalam MATLAB Simulink. Prestasi dua algoritma mudah suai yang berkaitan dengan kaedah isyarat kecerunan, iaitu least mean square (LMS) dan recursive least square (RLS) telah dibandingkan. Algoritma LMS telah dipilih kerana kekuatannya dan keringkasannya. Akhirnya, sistem pelinearan optik bersuapan depan mudah suai telah dihasilkan dengan pemproses isyarat digit (DSP) sebagai peranti kawalan, dan pengukuran praktikal telah dilakukan. Sistem ini telah mencapai pengurangan sebanyak 14 dB terhadap produk IMD tertib ketiga ke atas jalur lebar 30 MHz, dalam pengukuran dua-nada pada 1.7 GHz.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td>ii</td>
<td></td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
<td></td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>iv</td>
<td></td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
<td></td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
<td></td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
<td></td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiii</td>
<td></td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xviii</td>
<td></td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xix</td>
<td></td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xx i</td>
<td></td>
</tr>
</tbody>
</table>

1 INTRODUCTION

1.1 Radio over Fiber Technology 1
1.2 Basic Radio over Fiber System Configuration 3
1.3 Benefits of RoF Technology 5
1.3.1 Low Attenuation Loss 6
1.3.2 Large Bandwidth 7
1.3.3 Immunity to Electromagnetic Interference 7
1.3.4 Easy Installation and Maintenance 8
1.3.5 Low RF Power Remote Antenna Units 8
1.3.6 Centralized Processing 9
1.4 Applications of RoF Technology 9
1.5 Limitations of RoF Technology 11
1.6 Motivation 14
1.7 Problem Statement 15
# LITERATURE REVIEW ON OPTICAL TRANSMITTER LINEARIZATION TECHNIQUES

2.1 Introduction 24

2.2 Analog Predistortion Linearization Technique 25
   2.2.1 Analog Predistortion Technique Principle 25
   2.2.2 Related Works on Analog Predistortion Linearization 27

2.3 Digital Predistortion Linearization Technique 30
   2.3.1 Digital Predistortion Technique Principle 31
   2.3.2 Related Works on Digital Predistortion Linearization 32

2.4 Digital Post-Compensation Linearization Technique 36
   2.4.1 Digital Post-Compensation Technique Principle 36
   2.4.2 Related Works on Digital Post-Compensation Linearization 37

2.5 Optical Injection Linearization Technique 39
   2.5.1 Optical Injection Technique Principle 39
   2.5.2 Related Works on Optical Injection Technique 41

2.6 Dual Parallel Modulation Technique 42
   2.6.1 Dual Parallel Modulation Technique Principle 42
   2.6.2 Related Works on Dual Parallel Modulation Technique 43

2.7 Feedforward Linearization Technique 44
   2.7.1 Feedforward Technique Principle 45
2.7.2 Related Works on Feedforward Linearization Technique

2.8 Summary of the Optical Transmitter Linearization Works

2.9 Adaptive Feedforward Linearization System for RF Power Amplifier
   2.9.1 Related Works

2.10 Summary

3 Design Considerations and Modelling

3.1 Introduction

3.2 Laser Transmitter Design Considerations
   3.2.1 Gain
   3.2.2 Bandwidth
   3.2.3 Noise Figure
   3.2.4 Dynamic Range

3.3 Mathematical Model for Laser Nonlinearities
   3.3.1 Static Nonlinearity
   3.3.2 Dynamic Nonlinearity

3.4 Laser Rate Equations

3.5 Laser Diode Modelling
   3.5.1 Volterra Series Analysis
   3.5.2 Numerical Integration

3.6 Modulation Characteristics

3.7 Summary

4 System Modelling and Simulation

4.1 Introduction

4.2 Feedforward Analysis

4.3 Optical Feedforward Linearization System Model and Simulation

4.4 Adaptive Optical Feedforward Linearization System Architecture
4.5 Adaptive Filter Theory 115
4.5.1 Least Mean Square Algorithm 117
4.5.2 Result Recursive Least Square Algorithm 118
4.6 Convergence Analysis 119
4.6.1 SignalCancellation Loop 119
4.6.2 Error Cancellation Loop 123
4.7 Adaptive Optical Feedforward Linearization 130
System Modelling 130
4.7.1 Signal Downconversion 130
4.7.2 Digital Quadrature Downconversion 133
4.7.3 Finding the ECL Constant 136
4.7.4 Program Flowchart 137
4.8 Adaptive Optical Feedforward Linearization 139
System Simulation Result 139
4.9 Summary 146

EXPERIMENTAL SETUP AND PRACTICAL MEASUREMENT
5.1 Introduction 147
5.2 OFFLS Setup in NICT Japan 148
5.2.1 Setup Configuration 148
5.2.2 Equipment and Components Specifications 151
5.2.3 Feedforward Loops Setup Procedures 156
5.2.4 Linearization Results 159
5.3 OFFLS Setup in FKE UTM 162
5.3.1 Setup Configuration 162
5.3.2 Equipment and Components Specifications 165
5.3.3 Feedforward Loops Setup Procedures 167
5.3.4 Linearization Results 171
5.4 Adaptive OFFLS Setup Configuration and Components 178
5.4.1 Setup Configuration 178
5.4.2 Components Specifications 182
5.4.3 Adaptive Controller System 184
5.5 Software Design 186
  5.5.1 McBSP Programming 187
  5.5.2 EDMA Programming 188
  5.5.3 Data Samples Processing 190
  5.5.4 Program Flow 193
5.6 Implementation Considerations 196
5.7 Adaptive OFFLS Adaptation and Linearization Results 198
5.8 Summary 202

6 CONCLUSIONS
  6.1 Conclusions 204
  6.2 Research Contributions 205
  6.3 Recommendations for Future works 206

REFERENCES 208
APPENDIX A 221
APPENDIX B 224
APPENDIX C 227
APPENDIX D 228
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Related works on analog predistortion linearization</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>technique</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>Related works on digital predistortion linearization</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>technique</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>Related works on digital post-compensation technique</td>
<td>57</td>
</tr>
<tr>
<td>2.4</td>
<td>Related works on optical injection technique</td>
<td>58</td>
</tr>
<tr>
<td>2.5</td>
<td>Related works on dual parallel modulation technique</td>
<td>58</td>
</tr>
<tr>
<td>2.6</td>
<td>Related works on feedforward linearization technique</td>
<td>59</td>
</tr>
<tr>
<td>2.7</td>
<td>Quantitative comparisons of various linearization</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>techniques</td>
<td></td>
</tr>
<tr>
<td>2.8</td>
<td>Advantages and disadvantages of various linearization</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>techniques</td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Laser parameters</td>
<td>91</td>
</tr>
<tr>
<td>5.1</td>
<td>Components or equipment replacement</td>
<td>165</td>
</tr>
<tr>
<td>5.2</td>
<td>OFFLS IMD3 suppression results comparison</td>
<td>174</td>
</tr>
<tr>
<td>5.3</td>
<td>OFFLS IMD3 suppression results comparison (1.7 GHz)</td>
<td>177</td>
</tr>
<tr>
<td>5.4</td>
<td>ADC channels assignments</td>
<td>192</td>
</tr>
<tr>
<td>5.5</td>
<td>IMD3 suppression results comparison between OFFLS and</td>
<td>201</td>
</tr>
<tr>
<td></td>
<td>adaptive OFFLS</td>
<td></td>
</tr>
<tr>
<td>5.6</td>
<td>Adaptive OFFLS IMD3 suppression results comparison</td>
<td>202</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Growth of mobile-broadband subscriptions from 2012 to 2017</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Basic RoF system configuration</td>
<td>4</td>
</tr>
<tr>
<td>1.3</td>
<td>Attenuation loss of electrical cables and optical fiber</td>
<td>6</td>
</tr>
<tr>
<td>1.4</td>
<td>Two-tone testing output spectrum of a nonlinear system</td>
<td>15</td>
</tr>
<tr>
<td>1.5</td>
<td>Research methodology flowchart</td>
<td>21</td>
</tr>
<tr>
<td>2.1</td>
<td>Block diagram representation of a third order nonlinear system</td>
<td>26</td>
</tr>
<tr>
<td>2.2</td>
<td>Block diagram representation of a predistortion system cascading with an optical transmitter</td>
<td>26</td>
</tr>
<tr>
<td>2.3</td>
<td>Block diagram of digital predistortion system</td>
<td>31</td>
</tr>
<tr>
<td>2.4</td>
<td>Block diagram of digital post-compensation system</td>
<td>36</td>
</tr>
<tr>
<td>2.5</td>
<td>Basic schematic of directly modulated optical injection-locked laser system. (PC: Polarization controller)</td>
<td>40</td>
</tr>
<tr>
<td>2.6</td>
<td>Block diagram of dual parallel modulation scheme</td>
<td>43</td>
</tr>
<tr>
<td>2.7</td>
<td>System architecture of optical feedforward linearization system</td>
<td>46</td>
</tr>
<tr>
<td>2.8</td>
<td>IMD3 suppression (8 MHz frequency spacing), Moon et. al. [88]</td>
<td>51</td>
</tr>
<tr>
<td>2.9</td>
<td>IMD3 suppression (1 MHz frequency spacing), Moon et. al. [98]</td>
<td>51</td>
</tr>
<tr>
<td>3.1</td>
<td>Block diagram of an intrinsic RoF link</td>
<td>71</td>
</tr>
<tr>
<td>3.2</td>
<td>Optical output versus current characteristic for a laser diode</td>
<td>73</td>
</tr>
<tr>
<td>3.3</td>
<td>Modulation response of a laser diode</td>
<td>74</td>
</tr>
<tr>
<td>3.4</td>
<td>Spurious free dynamic range</td>
<td>77</td>
</tr>
</tbody>
</table>
3.5 Volterra model block diagram
3.6 Laser rate equation model in MATLAB Simulink
3.7 Magnitude response, $|H_1(\omega)|$ for different bias currents
3.8 Phase response, $\arg(H_1(\omega))$ for different bias currents
3.9 IMD3/C magnitude response for different bias currents
3.10 IMD3/C frequency response for different bias currents
3.11 OptiSystem model for laser characterization
3.12 Fundamental signal magnitude against frequency for all 3 models
3.13 IMD3/C against frequency for all 3 models
3.14 Fundamental signal output power against modulation index
3.15 IMD3 product power against modulation index
4.1 Optical feedforward linearization system block diagram
4.2 Theoretical prediction of cancellation calculated based on Equation 4.14
4.3 Optical feedforward linearization system schematic in OptiSystem
4.4 LD1 main parameter configurations
4.5 LD1 physical parameter configurations
4.6 Result of cancellation at SCL output
4.7 Result of cancellation at ECL output (2.3 GHz)
4.8 Result of cancellation at ECL output (1.7 GHz)
4.9 Result of cancellation at ECL output (5.2 GHz)
4.10 Result of cancellation at ECL output (100MHz frequency spacing)
4.11 IMD3 suppression across different input frequencies
4.12 Simulink model for optical feedforward linearization system
4.13 OptiSystem and Simulink comparison (before feedforward linearization)
4.14 OptiSystem and Simulink comparison (after feedforward linearization)
4.15 OptiSystem and Simulink comparison at 1.7 GHz
4.16 Adaptive optical feedforward linearization system architecture
4.17 Interference cancellation
4.18 Block diagram of cancellation circuit in SCL
4.19 Block diagram of cancellation circuit in ECL
4.20 Term $|1 - \mu \cdot \sigma_w \cdot \frac{2 \cdot k/k_{ap}}{}}$ in geometric diagram
4.21 Simulink model for adaptive optical feedforward linearization system
4.22 System schematic for downconvertor module
4.23 Magnitude response of lowpass filter $h(n)$
4.24 Magnitude response of complex bandpass filter $h^*(n)$
4.25 Program flowchart of adaptive controller block
4.26 Convergence of $\alpha$ with LMS algorithm
4.27 Convergence of $\alpha$ with RLS algorithm
4.28 Re-convergence performance of $\alpha$
4.29 Convergence of $B$ with LMS algorithm
4.30 Convergence of $B$ with RLS algorithm
4.31 Convergence of $B$ with deviated approximation of $k$
4.32 Re-convergence performance of $B$
4.33 OFFLS output with loop parameters resulted from adaptive controller (1.7 GHz)
4.34 Convergence performances of LMS and RLS algorithms (2.3 GHz)
4.35 OFFLS output with loop parameters resulted from adaptive controller (2.3 GHz)
5.1 OFFLS setup configuration (NICT Japan)
5.2 OFFLS setup in Lightwave Devices Laboratory NICT Japan
5.3 Vaunix LMS-602D Lab Brick signal generator
5.4 FU-641SEA-1CNA2 laser diode module installed on Optilab ULDC
5.5 Sevensix Inc 12.5 Gb/s Optical Receiver
<p>| 5.6 | Analog Devices AD8341-EVAL vector modulator | 154 |
| 5.7 | Amplifiers | 154 |
| 5.8 | API Technologies model 6805 RF phase shifter | 155 |
| 5.9 | Hapht Ltd. model FCLW-2102-135061-50 2x2 50:50 optical coupler | 155 |
| 5.10 | Mini-Circuits ZAPD-4+ RF power splitter/combiner | 156 |
| 5.11 | Tektronix MDO4104-6 oscilloscope/ spectrum analyser | 156 |
| 5.12 | LD1 output before feedforward linearization (10 MHz frequency spacing) | 159 |
| 5.13 | Cancellation result at SCL output | 160 |
| 5.14 | LD1 output after feedforward linearization system (10 MHz frequency spacing) | 160 |
| 5.15 | LD1 output before feedforward linearization system (1 MHz frequency spacing) | 161 |
| 5.16 | LD1 output after feedforward linearization system (1 MHz frequency spacing) | 161 |
| 5.17 | OFFLS setup configuration (FKE UTM) | 163 |
| 5.18 | OFFLS setup in Microwave Laboratory FKE UTM | 164 |
| 5.19 | Newport F-VDL-2-6-FA-S optical delay line | 167 |
| 5.20 | Cancellation of 2 signals in anti-phase | 168 |
| 5.21 | Cancellation of two 2-tone signals with a delay difference of Δt | 169 |
| 5.22 | LD1 output before feedforward linearization (10 MHz frequency spacing) | 171 |
| 5.23 | LD1 output after feedforward linearization (10 MHz frequency spacing) | 172 |
| 5.24 | LD1 output before feedforward linearization (1 MHz frequency spacing) | 173 |
| 5.25 | LD1 output after feedforward linearization (1 MHz frequency spacing) | 173 |
| 5.26 | Before feedforward linearization (1.7 GHz, 10 MHz frequency spacing) | 176 |
| 5.27 | After feedforward linearization (1.7 GHz, 10 MHz frequency spacing) | 176 |</p>
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.28</td>
<td>Before and after feedforward linearization (1.7 GHz, 1 MHz frequency spacing)</td>
</tr>
<tr>
<td>5.29</td>
<td>Adaptive OFFLS setup configuration</td>
</tr>
<tr>
<td>5.30</td>
<td>Adaptive OFFLS setup</td>
</tr>
<tr>
<td>5.31</td>
<td>Analog Devices EVAL-ADF4351EB1Z frequency synthesizer</td>
</tr>
<tr>
<td>5.32</td>
<td>Mini-Circuits ZAM-42 frequency mixer</td>
</tr>
<tr>
<td>5.33</td>
<td>Mini-Circuits ZFBP-400K+ bandpass filter</td>
</tr>
<tr>
<td>5.34</td>
<td>Adaptive controller system</td>
</tr>
<tr>
<td>5.35</td>
<td>Magnitude response of complex bandpass filter used in real time adaptive OFFLS</td>
</tr>
<tr>
<td>5.36</td>
<td>main() function program flowchart</td>
</tr>
<tr>
<td>5.37</td>
<td>edmaHwi() ISR function program flowchart</td>
</tr>
<tr>
<td>5.38</td>
<td>processbuffer() SWI function program flowchart</td>
</tr>
<tr>
<td>5.39</td>
<td>Convergence of α in real time adaptive OFFLS</td>
</tr>
<tr>
<td>5.40</td>
<td>RF spectrum at SCL output</td>
</tr>
<tr>
<td>5.41</td>
<td>Convergence of β in real time adaptive OFFLS</td>
</tr>
<tr>
<td>5.42</td>
<td>RF spectrum at ECL output</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

\( \alpha \) - Signal Cancellation Loop Coefficient
\( \beta \) - Error Cancellation Loop Coefficient
\( g \) - Optical Gain Coefficient
\( I_0 \) - Laser Bias Current
\( I_{th} \) - Laser Threshold Current
\( i(t) \) - Time Varying Modulation Current
\( \eta_{int} \) - Internal Quantum Efficiency
\( m \) - Optical Modulation Depth
\( N \) - Carrier Density
\( N_t \) - Carrier Density for Transparency
\( S \) - Photon Density
\( V \) - Active Region Volume
\( \beta \) - Probability of Spontaneous Emission
\( \Gamma \) - Optical Confinement Factor
\( \varepsilon \) - gain compression parameter
\( \tau_n \) - Injected Carriers’ Lifetime
\( \tau_p \) - Cavity Photons’ Lifetime
\( g_i \) - Intrinsic Link Gain
\( r_d \) - Responsivity of Photodetector
\( N_{\text{link}} \) - Intrinsic Link Noise
\( h \) - Planck’s Constant
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3G</td>
<td>3rd generation</td>
</tr>
<tr>
<td>4G</td>
<td>4th generation</td>
</tr>
<tr>
<td>ACLR</td>
<td>adjacent channel power leakage ratio</td>
</tr>
<tr>
<td>ADC</td>
<td>analog to digital convertor</td>
</tr>
<tr>
<td>ACPR</td>
<td>adjacent channel power ratio</td>
</tr>
<tr>
<td>AM</td>
<td>amplitude modulation</td>
</tr>
<tr>
<td>ASK</td>
<td>amplitude shift keying</td>
</tr>
<tr>
<td>BS</td>
<td>base station</td>
</tr>
<tr>
<td>CAPEX</td>
<td>capital expenditure</td>
</tr>
<tr>
<td>CATV</td>
<td>community-antenna television</td>
</tr>
<tr>
<td>CoMP</td>
<td>coordinated multipoint</td>
</tr>
<tr>
<td>COTS</td>
<td>commercially-off-the-shelf</td>
</tr>
<tr>
<td>CS</td>
<td>central station</td>
</tr>
<tr>
<td>CTB</td>
<td>channel composite triple beat</td>
</tr>
<tr>
<td>DAC</td>
<td>digital to analog convertor</td>
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<tr>
<td>DAS</td>
<td>distributed antenna system</td>
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<tr>
<td>DFB</td>
<td>distributed feedback</td>
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<td>DR</td>
<td>dynamic range</td>
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<td>DSP</td>
<td>digital signal processor</td>
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<tr>
<td>EAM</td>
<td>electro-absorption modulator</td>
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<td>ECL</td>
<td>error cancellation loop</td>
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<tr>
<td>EMI</td>
<td>electromagnetic Interference</td>
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<td>EML</td>
<td>electroabsorption modulated laser</td>
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<tr>
<td>ETC</td>
<td>electronic toll collection system</td>
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<tr>
<td>EVM</td>
<td>error vector magnitude</td>
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<tr>
<td>HFC</td>
<td>hybrid fiber-coax</td>
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<tr>
<td>IMD3</td>
<td>third order intermodulation distortion</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>IM-DD</td>
<td>intensity modulation direct detection</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific, and Medical</td>
</tr>
<tr>
<td>ITS</td>
<td>intelligent transport systems</td>
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<tr>
<td>LMS</td>
<td>least mean square</td>
</tr>
<tr>
<td>MB-OFDM</td>
<td>multi-band orthogonal frequency-division multiplexing</td>
</tr>
<tr>
<td>MIMO</td>
<td>multiple-input and multiple-output</td>
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<tr>
<td>MU</td>
<td>mobile unit</td>
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<tr>
<td>MZM</td>
<td>Mach-Zehnder modulator</td>
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<tr>
<td>NF</td>
<td>noise figure</td>
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<td>OFFLS</td>
<td>optical feedforward linearization system</td>
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<tr>
<td>OMD</td>
<td>optical modulation depth</td>
</tr>
<tr>
<td>OPEX</td>
<td>operating expenditure</td>
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<tr>
<td>PHS</td>
<td>personal handy-phone system</td>
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<td>PON</td>
<td>passive optical network</td>
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<tr>
<td>RAU</td>
<td>remote antenna unit</td>
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<td>RIN</td>
<td>relative intensity noise</td>
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<td>RLS</td>
<td>recursive least square</td>
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<tr>
<td>RoF</td>
<td>radio over fiber</td>
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<td>RVC</td>
<td>road-to-vehicle communication systems</td>
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<td>SCL</td>
<td>signal cancellation loop</td>
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<tr>
<td>SCM</td>
<td>sub-carrier multiplexing</td>
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<tr>
<td>SFDR</td>
<td>spurious free dynamic range</td>
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<td>SHD</td>
<td>second harmonic distortion</td>
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<tr>
<td>SMF</td>
<td>single mode fiber</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
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<td>THD</td>
<td>third harmonic distortion</td>
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<tr>
<td>UWB</td>
<td>ultra-wideband</td>
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<tr>
<td>VDSL</td>
<td>very high speed digital subscriber loop</td>
</tr>
<tr>
<td>VSA</td>
<td>vector spectrum analyzer</td>
</tr>
<tr>
<td>WDM</td>
<td>wavelength division multiplexing</td>
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<tr>
<td>WLAN</td>
<td>wireless local area networks</td>
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<tr>
<td>WLAN-AP</td>
<td>WLAN access point</td>
</tr>
<tr>
<td>WTU</td>
<td>wireless terminal unit</td>
</tr>
</tbody>
</table>
# LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Volterra Model of a Directly Modulator Laser</td>
<td>221</td>
</tr>
<tr>
<td>B</td>
<td>Mean-Squared Convergence of SCL Coefficient</td>
<td>224</td>
</tr>
<tr>
<td>C</td>
<td>Datasheet of Laser Transmitter Agilent 83430A</td>
<td>227</td>
</tr>
<tr>
<td>D</td>
<td>List of Publications</td>
<td>228</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Radio over Fiber Technology

The proliferation of smart devices and mobile broadband subscribers has increased the demand for multimedia services and operations, such as social media, online games, video calls, and high definition video streams. Those are the activities that are only accessible on a personal computer a couple of years back, but now the end-users can perform them anywhere, anyhow and anytime. This means that wide coverage and high capacity are the essential requirements for the future data communication systems. While the 3rd generation (3G) wireless access network is still responsible in carrying most of the mobile data traffics globally, the 4th generation (4G) system has already been highly sought after.

As the number of mobile data subscriber has been showing tremendous growth, it can be foreseen that in the future, with that mass number of users, the current access network technology will be unable to provide the data speed as promised by the future generation networks. Figure 1.1 illustrates the global statistics for the growth of mobile-broadband subscriptions for the past 5 years, presented by ITU facts and figures of 2017. The data shows that mobile-broadband subscriptions
have grown more than 20% annually in the last five years and are expected to reach 4.3 billion globally by end 2017 [1].

Figure 1.1 Growth of mobile-broadband subscriptions from 2012 to 2017 [1]

The frequency spectrum within a mobile cell, such as the Industrial, Scientific, and Medical (ISM) band is necessarily shared by all the users covered within that area. Spectral congestion is bound to happen when massive data traffics are handled. An automatic solution is to decrease the mobile cell size, to reduce the number of users per cell and improve the frequency spectral reusability. This can be achieved by the deployment of microcell or picocell architecture, which divides the conventional macrocell into several microcells or picocells. However, smaller mobile cells require a larger number of base stations (BS) per network area. This increases operating cost. Furthermore, the interference between cells is an issue as the cell size becomes small. Therefore, intercell interference cancellation needs to be applied. This requires cooperation among the BSs, which adds to the complexity of the BSs functionalities [2].
The radio over fiber (RoF) technology is able to provide a cost effective solution to the smaller cells configuration by consolidating the processing functions of the BSs onto a central station (CS). A CS is connected to multiple BSs through a fiber feeder network. As opposed to digital signals which are usually deployed in mainstream optical communication technologies, the digitally modulated RF waveforms are going to be transmitted between the BSs and CS in an RoF system. This implies that RF signal processing functions such as modulations, demodulations, coding, and routing are all being performed at the CS instead of BSs. The BSs are only remote antenna units (RAU) with functions of optoelectronics and electro-optics conversion and signal amplifications. As a result, the BS structure is significantly simplified, thus bringing about massive savings in operating and maintenance cost. By consolidating the signal processing functions at the CS, the transportation of the RF signals becomes transparent. This enables the interconnection task between the BSs to be performed easily.

### 1.2 Basic Radio over Fiber System Configuration

Figure 1.2 shows a basic RoF system configuration, where a CS is connected to a BS through an optical link. During transmission, the information-bearing RF signals are converted to optical domain through an electro-optical (E/O) convertor at the transmitter side. The resulting optical signal is carried over the optical link to the receiver side. At the receiver side, the optical signal is converted back to electrical domain by an opto-electrical (O/E) convertor. Both the CS and BS contain a pair of transmitter and receiver; thus, enabling bi-directional communications with each other. The transmission direction from the CS to the BS is called downlink; whereas, the opposite transmission direction is called uplink. At the BS, the received RF signals are amplified and fed to the antenna to be radiated to end users, such as mobile units (MU) and wireless terminal units (WTU). Meanwhile, at the CS side, the received RF signals are downconverted to baseband data to be handled by higher layer protocol, before entering the trunk network [2][3].
The most common method for the E/O and O/E conversion in the above context is intensity modulation of an optical source and direct detection by a photodetector. This method is referred to as intensity modulation direct detection (IM-DD). There are other methods such as phase and frequency modulations and interferometric demodulation [4][5], but IM-DD method is the most popular because of its simplicity. The IM-DD method is impractical for high frequency millimeter-wave signal transmission because of fiber dispersions and coherent mixing of the sidebands of modulated light. Instead, the millimeter-wave signals are preferably optically generated at the receiver side through remote heterodyning [6]. As millimeter-wave signal transmission is beyond the scope of this project, it is not further discussed.

There are 2 ways of modulating RF signals onto an optical carrier in IM-DD systems, which are direct intensity modulation and external modulation. For the
direct intensity modulation method, the RF signal modulates the input current of a laser diode to change the intensity of its emitted photons. Direct intensity modulation is easy and cost effective, but it has limited modulation bandwidth due to modulation cut-off frequency of a laser diode. Therefore, external modulation is normally used for RF frequencies higher than 10 GHz. For the external modulation method, the light emitted from a continuous wave laser diode is modulated by an external light intensity modulator, such as Mach-Zehnder modulator (MZM) and electro-absorption modulator (EAM) [6][7].

The current research of RoF technology is focusing on the higher end of the radio frequency spectrum, which means that external intensity modulation is prevalent nowadays. Despite that, direct intensity modulation of laser diode at lower frequencies, such as the ISM band is an interesting subject because of its simplicity and cost effectiveness [8][9]. Moreover, most of the widely deployed mobile and local area wireless standards are still operating at lower frequency microwave bands. Hence, the discussion for the remaining of this thesis will focus on the directly modulated IM-DD link.

1.3 Benefits of RoF Technology

The advantages of RoF technology compared to other existing remote antenna feeding technologies, such as RF signals over transmission lines and digital baseband over fiber, are discussed in this section.
1.3.1 Low Attenuation Loss

An optical fiber has lower attenuation loss compared to a transmission line. Figure 1.3 compares attenuation loss among various types of electrical cables and optical fiber at three common wavelengths [10]. The optical fiber has attenuation loss of 0.25 dB/km and 0.4 dB/km at optical wavelength 1.5 μm and 1.3 μm respectively, and the attenuation maintains the same value over the frequency range. Meanwhile, even the highest performing ocean cable has a higher loss than the optical fiber. The advantage of optical fiber is more pronounced as the frequency increases. Through RoF technology, RF signals can be transmitted at a long distance with minimum use of repeaters. This results in a massive savings in operating expenditure (OPEX) and capital expenditure (CAPEX) [11].

![Figure 1.3 Attenuation loss of electrical cables and optical fiber [10]](image-url)
1.3.2 Large Bandwidth

The next advantage of optical fibers is in term of bandwidth. The analog bandwidth of a coaxial cable used in cable television networks is roughly 1 GHz [12]. A single mode fiber (SMF) has a combined bandwidth of 50 THz over the 3 low-loss windows (850 nm, 1300 nm and 1550 nm) [13]. The 1550 nm window alone can already provide a bandwidth of 11 THz [14]. While most of today’s core networks have already been dominated by optical fibers, the RoF technology brings the bandwidth offered by the fiber even closer to the end users. In order to fully utilize the bandwidth of the optical fiber, multiplexing schemes such as sub-carrier multiplexing (SCM) and wavelength division multiplexing (WDM) have been carried out. Optical fiber is principally transparent to all types of radio interface format and protocol [15]. Therefore, a single fiber channel can be shared by multi-operators and multi-services such as 3G or 4G networks, wireless local area networks (WLAN), and passive optical network (PON) services [16]. The sharing of network infrastructure among different services will lead to another massive savings in OPEX and CAPEX.

1.3.3 Immunity to Electromagnetic Interference

Unlike copper cables, optical fibers are immune to Electromagnetic Interference (EMI), because they are made of glass and do not conduct electricity. Moreover, RoF system transmits signals in the form of light instead of microwave. Hence, it is assured that electrical noises from the surroundings will not cause any interference to RoF system transmissions.
1.3.4 Easy Installation and Maintenance

In RoF systems, the signal processing functions of the BSs are consolidated at the CS. Hence, the expensive equipment are centralized at the CS. The BS is only a remote antenna unit with no processing functions. As the BS is structurally simple, it can be made smaller, lighter, more compact, and less power consuming. This effectively reduces installation and maintenance costs. In addition, this can reduce the negative aesthetic effect that might be caused by the presence of large BSs [2]. Furthermore, RoF systems can provide the flexibility for upgrading and reconfiguring when network augmentation is needed for wireless services. For instance, if a wireless link is to be upgraded, only the central processing entity at the CS needs to be updated; whereas, hardware replacement is not needed at the BSs [17]. This flexibility is expected to bring about substantial upgrading cost savings in the long term.

1.3.5 Low RF Power Remote Antenna Units

RoF technology permits the use of low RF power RAUs because of smaller cell sizes. Low RF power RAUs are more environmental friendly and less likely to cause human health issues. As there have been growing concerns about the effect of electromagnetic radiation on public health, the distributed coverage by multiple RAUs instead of a single large BS can help to smoothen the radiation density pattern [2]. Meanwhile, the mobile devices at the end user side can also have more battery lifetime.
1.3.6 Centralized Processing

The beauty of the RoF technology lies within its centralized processing feature. Firstly, centralized processing at the CS facilitates cooperation between the BSs; thereby, permitting coordinated multipoint (CoMP) transmission and multiple-input and multiple-output (MIMO) technology to be carried out [18]. Consequently, the cell planning tasks become easier. Furthermore, the network resources and capacity can be allocated dynamically according to the populations in each area. This can avoid allocating permanent capacity, which would be a waste of resources as traffic loads vary frequently and by large margins [13].

1.4 Applications of RoF Technology

The RoF technology was first demonstrated on the distribution of second-generation cordless telephony services back in 1990 [19]. Since then, the RoF technology has been actively researched. Until the present time, the deployment of RoF technology can be found in various applications such as mobile communication systems, wireless local area network (WLAN), broadband wireless access systems, video distribution systems and intelligent transport systems.

The distributed antenna system (DAS) is a network of geographically distributed antenna nodes connected to a central unit via a transport medium that provides wireless service within an area, where the transport medium will be optical fibers in the RoF context. For the 2G and 3G mobile communication networks, the DAS system has been applied for the realization of microcellular networks and to overcome blind area issues [20][21][22][23][24]. The main motivation behind those applications is to reduce cost and power consumption. As for 4G and beyond networks, the spatially distributed feature of DAS has been exploited to further
improve the cell throughput by the use of distributed MIMO [25]. CoMP transmission enables inter-cell interference cancellation to enhance the spectral efficiency [26][18].

Meanwhile, the RoF technology has niche applications in WLAN systems. The WLAN technology has been popular because of high speed access to the internet. The proliferation of WLAN access points (WLAN-AP) can cause serious signal interference problem if the wireless channels are not properly allocated. As a solution, the RoF techniques have been applied in WLAN systems, where a CS containing all the processing functions of a conventional WLAN-AP is fiber-connected to a distributed set of RAUs [27][28], so that centralized processing and cognitive radio techniques can be carried out to enable dynamic channel allocations [17][29].

Other than that, RoF can support the future broadband wireless access systems for in-building high speed personal networks [30][3]. In such systems, mm-wave carrier frequencies and significantly small cells (picocells/ femtocells) are deployed, where the unlicensed spectrum in the 60 GHz region has been of particular interests [31][32][33][34]. Due to the large available bandwidth at the mm-wave region, data rates of multi-Gbps can be easily achieved to support applications of Gbps signal transmissions. Meanwhile, applications of in-building picocellular network with WLAN standards in lower microwave frequencies (2.4 and 5 GHz) can also be found in the literature [35][36].

The concept of RoF has already been applied in the video distribution systems for community-antenna television (CATV) in the late 80’s [37]. Subcarrier multiplexing technique is used to carry multiple radio frequencies from different TV channels from the distribution center to the neighbourhood; thereby, extending the reach of the distribution network through optical fibers. The TV signals are then distributed to individual homes through conventional coaxial cables; thus, leading to a hybrid fiber-coax (HFC) network [38][14]. The HFC network has the advantage of
low loss, which it saves electrical amplifier, accommodates more users, and provides better signal quality [7].

Intelligent transport systems (ITS) have the aims of communicating people, vehicles, and the road to realize a safer, more efficient, and more comfortable traffic environment. The ITS provides various services such as road-to-vehicle communication systems (RVC), vehicle information and communication system (VIC), electronic toll collection system (ETC), and personal handy-phone system (PHS) [39]. In order to provide seamless and extended coverage of the services, numerous BSs need to be installed. The RoF technology is introduced so that the BSs can be made simple and low cost, and easy installation can be made along the road [40]. Furthermore, the RoF systems can support multiple ITS services concurrently through the transmission of integrated broadband radio signals at 36 to 37 GHz mm-wave band [41]. Moreover, the RoF systems provide diversity reception between adjacent cells to support rapid handover functions needed for moving vehicles.

1.5 Limitations of RoF Technology

RoF system is essentially an analog system, as it involves modulating an RF waveform that is modulated with information signal onto an optical signal, instead of the information signal like most optical communication systems do. Hence, the performance of an RoF link can be characterized using typical analog RF links performance parameters [10], where gain, bandwidth, noise figure (NF) and dynamic range (DR) are the important parameters.

On the other hand, an RoF link consists of various sources of signal impairments. Each part of the link has their own share of contributions. For example, in a directly modulated IM-DD link, there are thermal noise and shot noise from the
photodiode, relative intensity noise (RIN) and nonlinear distortions from the laser diode, dispersions and nonlinearities from the optical fiber, and signal losses throughout the link.

NF is a measurement of the degradation of the signal-to-noise ratio (SNR) caused by components in an RF signal chain. The NF of an RoF link is affected by noise sources like thermal noise, shot noise and laser RIN, combining with the effect of link loss. For a directly modulated link, the NF generally increases linearly with the link loss [42]. Thermal noise dominates in low optical power RoF links, and as the optical power increases, the shot noise and laser RIN start taking over. The shot noise and laser RIN are caused by the statistical fluctuations of the photocurrent in the photodiode and the optical power output from the laser diode respectively. Increasing the optical power and photocurrent results in increase in both shot noise and laser RIN. The laser RIN will increase faster than the shot noise due to its direct square relationship with the photocurrent. As a result, the laser RIN will emerge as the dominant noise source when the optical power reaches a certain level [6][7].

In order to improve the SNR of an RIN limited RoF link, the RF signals have to be pre-amplified. Ideally, the SNR of an RoF link can be made to be large by increasing the pre-amplifier gain. However, for a practical RoF link, increasing the input RF signal level will eventually drive the modulation device to its nonlinear region; thus, leading to the occurrence of nonlinear distortions. Nonlinear distortions impose a limit on the SNR of an RoF link, and the dynamic range parameter defines the maximum achievable SNR. The spurious free dynamic range (SFDR) of the system is defined as the ratio of the maximum input signal power at which the distortion products exceed the noise floor to the minimum signal power at which its output becomes distinguishable from the noise floor. In simple terms, SFDR is the maximum achievable output SNR at which the distortion products exceed the noise floor.
Each RoF service has its specifications in terms of signal quality to be met in order to provide satisfying service. For example, AM-VSB signal for CATV requires CNR > 45 dB and distortion level > 50 dBc [38]. GSM picocellular and microcellular networks need input dynamic range (DR) varying from 40-55 dB to 80-90 dB respectively [43]. The UMTS standard requires an adjacent channel power leakage ratio (ACLR) of -45 dBc (downlink) and -30 dBc (uplink) [44]. On the other hand, the laser diode produces harmonic and intermodulation distortions when modulated with high level signals, especially during the transmission of multiple channels. These distortion products result in constellation degradation in multilevel modulation signals, which eventually leads to degraded bandwidth efficiency due to constraint in modulation depth, channel spacing, and choices of modulation scheme [45]. The effect of the distortion products can be mitigated through linearization techniques, as will be discussed in the later sections.

Other than the laser diode, the photodiode and optical fiber also have nonlinear properties. However, both the photodiode nonlinearity and fiber nonlinearity only cause problem when the optical power level is high: photodiode in the range of a few milliwatts, and optical fiber in the range of a few tens of milliwatts. Therefore, the effects of these two nonlinearities are normally neglected in most RoF links [7].

Furthermore, fiber dispersion is an important signal impairment to be considered. The chromatic dispersion in a single mode fiber (SMF) causes different wavelengths to travel at different speeds, due to the variation of refractive index across the wavelengths [14]. This results in the lower and upper sidebands of an intensity modulated optical signal to be out of phase with respect to the optical carrier, leading to RF power fading at the receiver [5][46]. This problem normally occurs in millimeter-wave frequencies transmissions. Single-sideband modulation techniques or optical generation techniques have been deployed as a solution to the problem [6][7]. Other than that, fiber dispersion causes in-band linear distortions due to power differences of frequencies within the bandwidth. Those distortions can be mitigated by an equalizer in the receiver [6][14].
In general, the performance of the optical transmitter defines the SFDR of an RoF link. Hence, the nonlinearity of the optical transmitter is considered as a major limiting factor on the system performance for most applications. The only way to compensate this nonlinearity is to perform linearization techniques on the optical transmitter. This project will focus on improving the performance of RoF systems on the transmitter side through the application of an effective linearization scheme, namely feedforward system.

1.6 Motivation

The RF input signals of RoF links usually are composed of multiple frequency components. The nonlinearity of the optical transmitters causes spurious emissions, such as harmonic distortions and intermodulation distortions to appear at the output spectra. For systems with less than one octave bandwidth, the harmonic distortions and even-order intermodulation distortions are generally not taken into considerations, as they do not fall within the operating bandwidth. On the other hand, some of the odd-order intermodulation distortions fall in-band and mix with the fundamental signals. The third order intermodulation distortion (IMD3) product has the highest magnitude. Hence, the IMD3 product level is always used to define the SFDR of a narrowband system.

In order to evaluate the linearity performance of a nonlinear system, it is a common practice to use a two-tone signal as the testing input and observe the fundamental signals and distortions at the output. Figure 1.4 shows the two-tone testing output spectrum of a nonlinear system. The 2 main tones, $\omega_1$ and $\omega_2$ are accompanied by second and third order distortion products at the harmonic frequencies and linear combinations of the main tone frequencies. The IMD3 products at $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$ are particularly close to the main tones and fall
within the transmission channel. Therefore, it is essential to suppress the IMD3 products in order to enhance the SFDR of narrowband systems.

![Two-tone testing output spectrum of a nonlinear system](image)

Figure 1.4 Two-tone testing output spectrum of a nonlinear system

1.7 Problem Statement

Radio over fiber links suffers from performance degradation due to nonlinear distortions generated by optical transmitter. In order to meet the stringent requirement for the services of interests, linearization techniques have to be applied to improve the optical transmitter linearity. Several distortion-compensation techniques have been considered. Feedforward linearization is seen as the most effective, since it can offer good suppression of distortion products over a large bandwidth at high operating frequencies. Furthermore, it can suppress all orders of nonlinearities regardless of their characteristics, and even reduce laser relative intensity noise (RIN). However, feedforward is a relatively sensitive scheme, as it
requires cancellations between two signals which are almost identical. Hence, the
gain, phase shift, and path delay parameters in the system have to be properly
adjusted to facilitate the error cancellation mechanism. The optimum parameters are
usually searched iteratively. However, the balance in magnitude and phase
adjustments is bounded to disruption by parameter drifts and process variations, such
as temperature effect, laser aging, and input signal variations. Therefore, for practical
implementation, a feedforward system needs to be real-time adaptive. However, the
reported works on adaptive feedforward linearization system in the electro-optics
domain has been lacking compared to its deployment in RF amplifier linearization.
Hence, this research will focus on developing an adaptive optical feedforward
linearization system for radio over fiber links.

1.8 Objectives

The main objective of this research is to develop an adaptive optical
feedforward linearization system for radio over fiber links. The specific objectives of
the research are listed below:

1. To determine the most efficient algorithm for the adaptive controller for laser
   transmitter feedforward linearization system through mathematical analysis and
   computer simulation.
2. To perform set-up and practical measurement for the adaptive optical
   feedforward linearization system to suppress laser diode’s third order
   intermodulation distortion products, and optimize the system performance.
3. To demonstrate and evaluate a novel real-time adaptive feedforward
   linearization system which improves radio over fiber transceiver systems’
   spurious free dynamic range.
1.9 Scope of Work

This research focuses on improving the SFDR performance of a directly modulated IM-DD RoF link. Among the impairments of an RoF link, the nonlinearity of the optical transmitter is considered as the main limitation on the achievable SFDR. A number of linearization techniques can be applied to compensate for the optical transmitter nonlinearity. Among those candidates, the feedforward linearization technique has been selected based on literature review on reported techniques and comparisons on their performances.

The performance of a feedforward linearization system relies heavily on the matching of gain and phase-shift parameters; hence, an adaptive mechanism plays an important role in its practical implementation. The adaptation methods available include adaptation by power minimization and adaptation by gradient signal [47], with reference to the techniques derived from RF power amplifier’s adaptive feedforward linearization. The implementation of adaptation using power minimization has been reported for external modulated optical transmitter [48], but the method of adaptation using gradient signal has never been carried out in optical feedforward linearization systems.

Compared to the power minimization method, the gradient adaptation method has the advantages that deliberate misadjustment is not needed during adaptation [47]. Moreover, digital signal processing functions can also be carried out to condition the gradient signal, which provides more robustness in this method. Therefore, the adaptive feedforward system developed in this project will be based on the gradient signal method.

Specifically, the scope of this research involves step by step measures to implement an adaptive optical feedforward linearization system and examine on the system’s performance. This involves mathematical analysis, computer simulations,
and practical measurements. The details of these conducts will be discussed in the following section. The practical measurements in this research are subjected to a few practical limitations:

i) The operating frequency is limited from 1.7 GHz to 2.3 GHz due to the limitations of the available commercial-off-the-shelf components.

ii) As the research is only focussing on improving the nonlinearity at the optical transmitter part, the measurement only involves a short distance optical fiber link.

iii) Characterizations of the optical feedforward linearization system performance are carried out with two-tone test signals instead of real-time wireless data channels.

iv) This research is focussing on the reduction of optical transmitter’s nonlinear distortions, while the analysis of noises such as laser RIN and photodiode shot noise are not included in the scope. Throughout the simulation and experimental works in this research, the noise floor is considered to be constant at the thermal noise level at $T_0 = 290 \, K$ [10], which is approximately $-174$ dBm, as given by $k_B T_0 B$, where $k_B$ is Boltzmann’s constant, and $B$ is the noise bandwidth (taken as 1 Hz herein).

1.10 Research Methodology

This section will cover all the issues of the approach considerations towards this project as shown in Figure 1.5. The 6 phases of the research design are as follows:

i) Literature Review

The literature review is started from the basic principle, benefits, applications, and limitations of RoF systems to discover the background and problems for this
research. Then, the investigation on the current researches and technologies of optical domain linearization techniques is carried out. The research progress on the feedforward linearization technique will be continued herein. The reported works for optical feedforward linearization systems are studied to get a good insight on the considerations for practical measurement. Next, the reported works for adaptive feedforward linearization system for power amplifiers are reviewed to identify the available control strategies and algorithms.

ii) Model and Simulation (Laser Diode and Optical Feedforward Linearization System)

The laser diode is first modeled in MATLAB Simulink based on laser rate equations. The model is used to determine the modulation characteristics of a typical laser diode. The characterization results are validated with commercial software for optical communication system modeling, OptiSystem 13.0. Next, the optical feedforward linearization system is modeled and simulated using OptiSystem 13.0 to characterize its performance. The optical feedforward linearization system model is also developed in Simulink. Simulations are carried out in Simulink and the results are compared to the results obtained in OptiSystem for model verification.

iii) System Design and Mathematical Analysis

The adaptive control system design starts with the consideration of system architecture based on the review from previous works. Both the power minimization and gradient signal method have distinctively different architectures. The latter has been adapted for this research. There are 2 algorithms which are related to the gradient signal method, namely the least mean square (LMS) and recursive least square (RLS) algorithm. Mathematical analysis is performed to analyze the convergence of both the LMS and RLS algorithm.
iv) Model and simulation (Adaptive Optical Feedforward Linearization System)

The adaptive optical feedforward linearization system is modeled in Simulink by integrating an adaptive controller block to the previously modeled optical feedforward linearization system. The adaptive controller block is programmed with either LMS or RLS algorithm. Simulations are carried out. The performances of both algorithms are optimized and then compared in terms of convergence speed and tracking ability. From the simulation results, the algorithm which performs better is determined and will be implemented in the practical measurement.

v) System Implementation and Measurement

Firstly, the appropriate components are selected by carefully studying their specifications. The prototype development is started from the setup of a manually controlled optical feedforward linearization system. The system parameters are optimized and performance characterization for the optical feedforward linearization system is done. Due to the limitation in operating frequencies for the available commercially-off-the-shelf (COTS) RF components, the measurement will be limited to the highest achievable frequencies at the 2.3 GHz region. Next, additional circuitries are introduced. The adaptive algorithm chosen from the simulation phase is implemented; thus, completing the setup of an adaptive optical feedforward linearization system. System measurement and performance characterization are done using the developed prototype. The practical demonstration and measurement have been conducted in the Lightwave Devices Laboratory National Institute of Information and Communication Technology (NICT) Japan, Photonics Fabrication Laboratory and Microwave Laboratory of the Faculty of Electrical Engineering Universiti Teknologi Malaysia (FKE UTM).

vi) Data Analysis

Finally, comparison is done between the results obtained from practical measurement and simulation. The problems and limitations on the design are identified and further implications, suggestions and any recommendations are illuminated.
Figure 1.5 Research methodology flowchart
1.11 Thesis Outline

The flow of the thesis is discussed in this section. The thesis starts off in Chapter 1 with the background introduction of this research. An overview of the RoF system's basic configuration, benefits, applications, and limitations has been presented. Next, the motivation, problem statement, objectives, scope of work, and methodology of this research are discussed. This is followed by an overview of the thesis outline at the end of this chapter.

Chapter 2 focuses on the literature review for the reported works on various optical transmitter linearization techniques, such as, analog predistortion, digital predistortion, digital post-compensation, dual-parallel, optical injection, and feedforward linearization. The principle and basic architecture of those linearization techniques are discussed. This is followed by a summary of the related works on their experiment or simulation setup details and achieved improvements. Next, comparisons between the linearization techniques in terms of their qualitative and quantitative performance, advantages, and disadvantages are presented. One section is also dedicated to the adaptive feedforward linearization system for RF power amplifier. The related works are reviewed in consideration on the system architectures and algorithms to be adapted in optical feedforward linearization systems.

Chapter 3 mainly discusses on the design considerations of a laser transmitter and the modeling of laser diode. First, the important parameters for RoF system performance characterization, and some general means for improving those performance criteria are discussed. Next, the types of laser diode nonlinearities and their mathematical models are focused. Then, the bases for laser diode modeling, i.e. the laser rate equations are explored. Laser diode modeling based on laser rate equations are discussed afterwards. Finally, based on the laser model simulation results, the laser diode modulation characteristics are analyzed.
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