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

NEO YUN SHENG

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Electrical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2018

To my parents and family…

ACKNOWLEDGEMENT

Here I would like to express my deepest gratitude to the many people who have made my PhD study possible. First of all, I would like to thank my supervisor, Prof. Dr Sevia Mahdaliza Idrus who has been patient and has given me a lot of guidance and encouragement to help me to keep the focus on my research. The completion of this thesis would not be possible without her help. Appreciation also goes my co-supervisor, Prof. Dr Mohd Fua'ad Rahmat who is always there to enlighten my research direction.

The acknowledgement also goes to the Ministry of Science, Technology, and Innovation Malaysia for the financial support through the EScience Funds Vot. 4S087. Big thanks to all students, researchers and respected staff of the Photonics Fabrication Laboratory, Faculty of Electrical Engineering, UTM for the support and help. My heartfelt appreciation also goes to Lightwave Devices Laboratory NICT Japan and Microwave Laboratory FKE UTM for the kind support in providing the facilities to conduct the experimental setup and measurements.

Last but not the least, I would like to thank my loving family for the love, care, and support they have given me along this PhD journey.

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 dikukuhkan 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 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 kekukuhan 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

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xii
	LIST OF FIGURES	xiii
	LIST OF SYMBOLS	xviii
	LIST OF ABBREVIATIONS	xix
	LIST OF APPENDICES	xxi
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

	1.8	Objectives	16
	1.9	Scope of Work	17
	1.10	Research Methodology	18
	1.11	Thesis Outline	22
2		**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 Lineariation	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	47
	2.8	Summary of the Optical Transmitter Linearization Works	53
	2.9	Adaptive Feedforward Linearization System for RF Power Amplifier	65
	2.9.1	Related Works	66
	2.10	Summary	69
3		**DESIGN CONSIDERATIONS AND MODELLING**	
	3.1	Introduction	70
	3.2	Laser Transmitter Design Considerations	71
	3.2.1	Gain	72
	3.2.2	Bandwidth	73
	3.2.3	Noise Figure	75
	3.2.4	Dynamic Range	76
	3.3	Mathematical Model for Laser Nonlinearities	78
	3.3.1	Static Nonlinearity	79
	3.3.2	Dynamic Nonlinearity	80
	3.4	Laser Rate Equations	82
	3.5	Laser Diode Modelling	85
	3.5.1	Volterra Series Analysis	85
	3.5.2	Numerical Integration	87
	3.6	Modulation Characteristics	91
	3.7	Summary	97
4		**SYSTEM MODELLING AND SIMULATION**	
	4.1	Introduction	99
	4.2	Feedforward Analysis	100
	4.3	Optical Feedforward Linearization System Model and Simulation	104
	4.4	Adaptive Optical Feedforward Linearization System Architecture	114

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 Signal Cancellation Loop 119
4.6.2 Error Cancellation Loop 123
4.7 Adaptive Optical Feedforward Linearization 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 System Simulation Result 139
4.9 Summary 146

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

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Growth of mobile-broadband subscriptions from 2012 to 2017	2
1.2	Basic RoF system configuration	4
1.3	Attenuation loss of electrical cables and optical fiber	6
1.4	Two-tone testing output spectrum of a nonlinear system	15
1.5	Research methodology flowchart	21
2.1	Block diagram representation of a third order nonlinear system	26
2.2	Block diagram representation of a predistortion system cascading with an optical transmitter	26
2.3	Block diagram of digital predistortion system	31
2.4	Block diagram of digital post-compensation system	36
2.5	Basic schematic of directly modulated optical injection-locked laser system. (PC: Polarization controller)	40
2.6	Block diagram of dual parallel modulation scheme	43
2.7	System architecture of optical feedforward linearization system	46
2.8	IMD3 suppression (8 MHz frequency spacing), Moon et. al. [88]	51
2.9	IMD3 suppression (1 MHz frequency spacing), Moon et. al. [98]	51
3.1	Block diagram of an intrinsic RoF link	71
3.2	Optical output versus current characteristic for a laser diode	73
3.3	Modulation response of a laser diode	74
3.4	Spurious free dynamic range	77

3.5	Volterra model block diagram	86
3.6	Laser rate equation model in MATLAB Simulink	88
3.7	Magnitude response, $\lvert H_1(\omega)\rvert$ for different bias currents	92
3.8	Phase response, $\arg(H_1(\omega))$ for different bias currents	92
3.9	IMD3/C magnitude response for different bias currents	93
3.10	IMD3/C frequency response for different bias currents	93
3.11	OptiSystem model for laser characterization	94
3.12	Fundamental signal magnitude against frequency for all 3 models	95
3.13	IMD3/C against frequency for all 3 models	95
3.14	Fundamental signal output power against modulation index	96
3.15	IMD3 product power against modulation index	97
4.1	Optical feedforward linearization system block diagram	100
4.2	Theoretical prediction of cancellation calculated based on Equation 4.14	104
4.3	Optical feedforward linearization system schematic in OptiSystem	105
4.4	LD1 main parameter configurations	105
4.5	LD1 physical parameter configurations	106
4.6	Result of cancellation at SCL output	107
4.7	Result of cancellation at ECL output (2.3 GHz)	108
4.8	Result of cancellation at ECL output (1.7 GHz)	108
4.9	Result of cancellation at ECL output (5.2 GHz)	109
4.10	Result of cancellation at ECL output (100MHz frequency spacing)	110
4.11	IMD3 suppression across different input frequencies	110
4.12	Simulink model for optical feedforward linearization system	112
4.13	OptiSystem and Simulink comparison (before feed-forward linearization)	112
4.14	OptiSystem and Simulink comparison (after feed-forward linearization)	113

4.15	OptiSystem and Simulink comparison at 1.7 GHz	113
4.16	Adaptive optical feedforward linearization system architecture	115
4.17	Interference cancellation	116
4.18	Block diagram of cancellation circuit in SCL	120
4.19	Block diagram of cancellation circuit in ECL	123
4.20	Term $\|1-\mu_{Б}.\sigma_{u_{Б}}{}^{2}.k/k_{ap}\|$ in geometric diagram	126
4.21	Simulink model for adaptive optical feedforward linearization system	132
4.22	System schematic for downconvertor module	133
4.23	Magnitude response of lowpass filter h(n)	135
4.24	Magnitude response of complex bandpass filter $\tilde{h}$(n)	135
4.25	Program flowchart of adaptive controller block	138
4.26	Convergence of α with LMS algorithm	139
4.27	Convergence of α with RLS algorithm	140
4.28	Re-convergence performance of α	141
4.29	Convergence of Б with LMS algorithm	141
4.30	Convergence of Б with RLS algorithm	142
4.31	Convergence of Б with deviated approximation of k	143
4.32	Re-convergence performance of Б	143
4.33	OFFLS output with loop parameters resulted from adaptive controller (1.7 GHz)	144
4.34	Convergence performances of LMS and RLS algorithms (2.3 GHz)	144
4.35	OFFLS output with loop parameters resulted from adaptive controller (2.3 GHz)	145
5.1	OFFLS setup configuration (NICT Japan)	149
5.2	OFFLS setup in Lightwave Devices Laboratory NICT Japan	150
5.3	Vaunix LMS-602D Lab Brick signal generator	151
5.4	FU-641SEA-1CNA2 laser diode module installed on Optilab ULDC	152
5.5	Sevensix Inc 12.5 Gb/s Optical Receiver	153

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	Haphit 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

5.28	Before and after feedforward linearization (1.7 GHz, 1 MHz frequency spacing)	177
5.29	Adaptive OFFLS setup configuration	179
5.30	Adaptive OFFLS setup	181
5.31	Analog Devices EVAL-ADF4351EB1Z frequency synthesizer	182
5.32	Mini-Circuits ZAM-42 frequency mixer	183
5.33	Mini-Circuits ZFBP-400K+ bandpass filter	183
5.34	Adaptive controller system	186
5.35	Magnitude response of complex bandpass filter used in real time adaptive OFFLS	191
5.36	main () function program flowchart	194
5.37	edmaHwi () ISR function program flowchart	195
5.38	processbuffer () SWI function program flowchart	195
5.39	Convergence of α in real time adaptive OFFLS	198
5.40	RF spectrum at SCL output	199
5.41	Convergence of Б in real time adaptive OFFLS	200
5.42	RF spectrum at ECL output	200

LIST OF SYMBOLS

α	-	Signal Cancellation Loop Coefficient
Б	-	Error Cancellation Loop Coefficient
g	-	Optical Gain Coefficient
I_0	-	Laser Bias Current
I_{th}	-	Laser Threshold Current
$i(t)$	-	Time Varying Modulation Current
η_int	-	Internal Quantum Efficiency
m	-	Optical Modulation Depth
N	-	Carrier Density
N_t	-	Carrier Density for Transparency
S	-	Photon Density
V	-	Active Region Volume
β	-	Probability of Spontaneous Emission
Γ	-	Optical Confinement Factor
ε	-	gain compression parameter
τ_n	-	Injected Carriers' Lifetime
τ_p	-	Cavity Photons' Lifetime
gi	-	Intrinsic Link Gain
r_d	-	Responsivity of Photodetector
N_{link}	-	Intrinsic Link Noise
h	-	Planck's Constant

LIST OF ABBRIVIATIONS

3G	-	3rd generation
4G	-	4th generation
ACLR	-	adjacent channel power leakage ratio
ADC	-	analog to digital convertor
ACPR	-	adjacent channel power ratio
AM	-	amplitude modulation
ASK	-	amplitude shift keying
BS	-	base station
CAPEX	-	capital expenditure
CATV	-	community-antenna television
CoMP	-	coordinated multipoint
COTS	-	commercially-off-the-shelf
CS	-	central station
CTB	-	channel composite triple beat
DAC	-	digital to analog convertor
DAS	-	distributed antenna system
DFB	-	distributed feedback
DR	-	dynamic range
DSP	-	digital signal processor
EAM	-	electro-absorption modulator
ECL	-	error cancellation loop
EMI	-	electromagnetic Interference
EML	-	electroabsorption modulated laser
ETC	-	electronic toll collection system
EVM	-	error vector magnitude
HFC	-	hybrid fiber-coax
IMD3	-	third order intermodulation distortion

IM-DD	-	intensity modulation direct detection
ISM	-	Industrial, Scientific, and Medical
ITS	-	intelligent transport systems
LMS	-	least mean square
MB-OFDM	-	multi-band orthogonal frequency-division multiplexing
MIMO	-	multiple-input and multiple-output
MU	-	mobile unit
MZM	-	Mach-Zehnder modulator
NF	-	noise figure
OFFLS	-	optical feedforward linearization system
OMD	-	optical modulation depth
OPEX	-	operating expenditure
PHS	-	personal handy-phone system
PON	-	passive optical network
RAU	-	remote antenna unit
RIN	-	relative intensity noise
RLS	-	recursive least square
RoF	-	radio over fiber
RVC	-	road-to-vehicle communication systems
SCL	-	signal cancellation loop
SCM	-	sub-carrier multiplexing
SFDR	-	spurious free dynamic range
SHD	-	second harmonic distortion
SMF	-	single mode fiber
SNR	-	signal-to-noise ratio
THD	-	third harmonic distortion
UWB	-	ultra-wideband
VDSL	-	very high speed digital subscriber loop
VSA	-	vector spectrum analyzer
WDM	-	wavelength division multiplexing
WLAN	-	wireless local area networks
WLAN-AP	-	WLAN access point
WTU	-	wireless terminal unit

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Volterra Model of a Directly Modulater Laser	221
B	Mean-Squared Convergence of SCL Coefficient	224
C	Datasheet of Laser Transmitter Agilent 83430A	227
D	List of Publications	228

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].

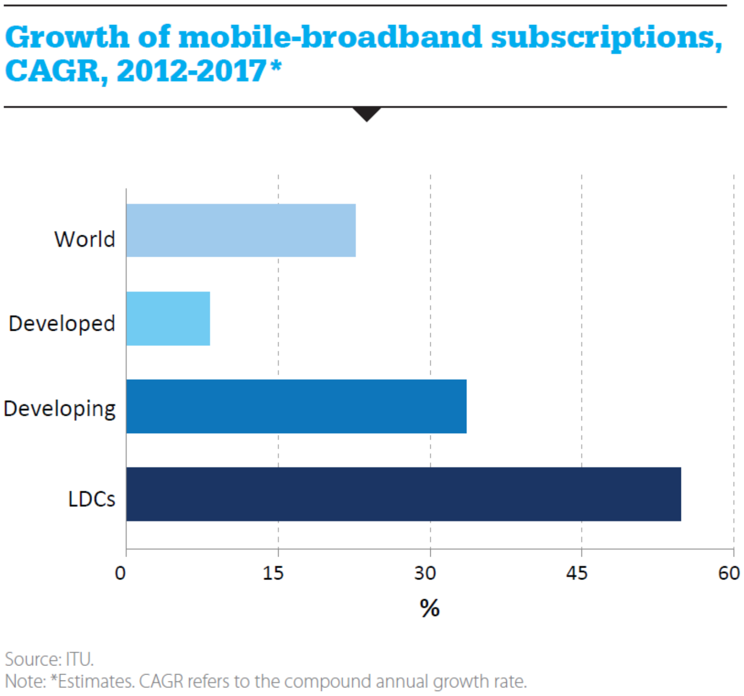

Figure 1.1 Growth of mobile-broadband subscriptions from 2012 to 2017 [1]

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].

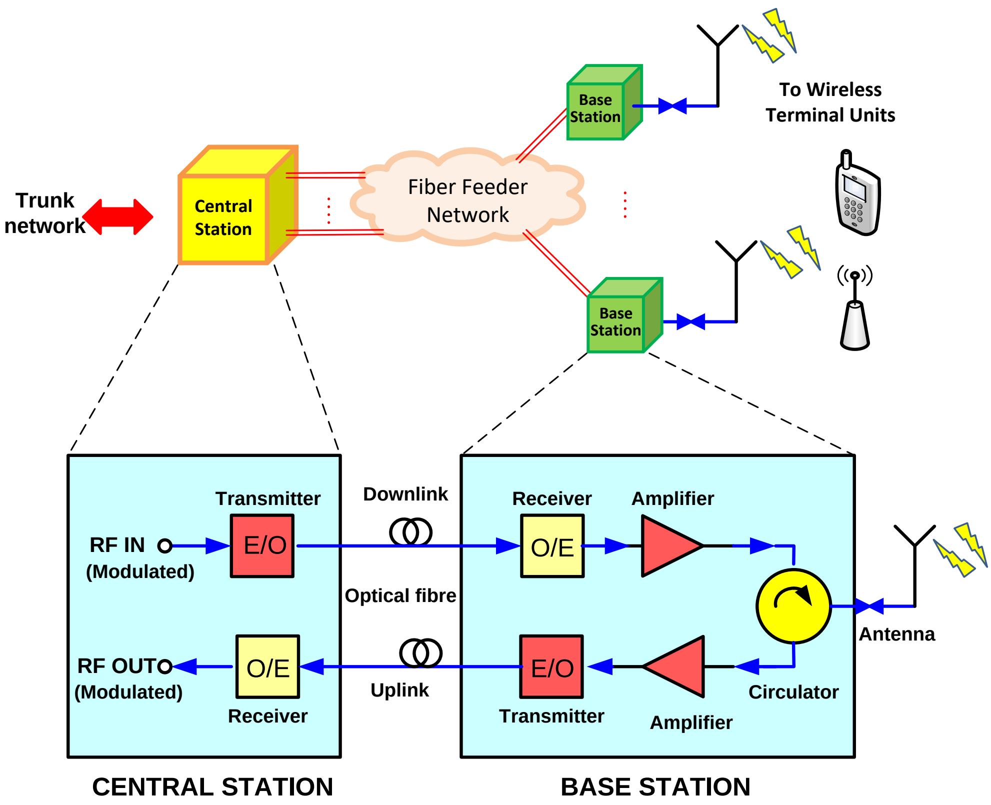

Figure 1.2 Basic RoF system configuration

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].

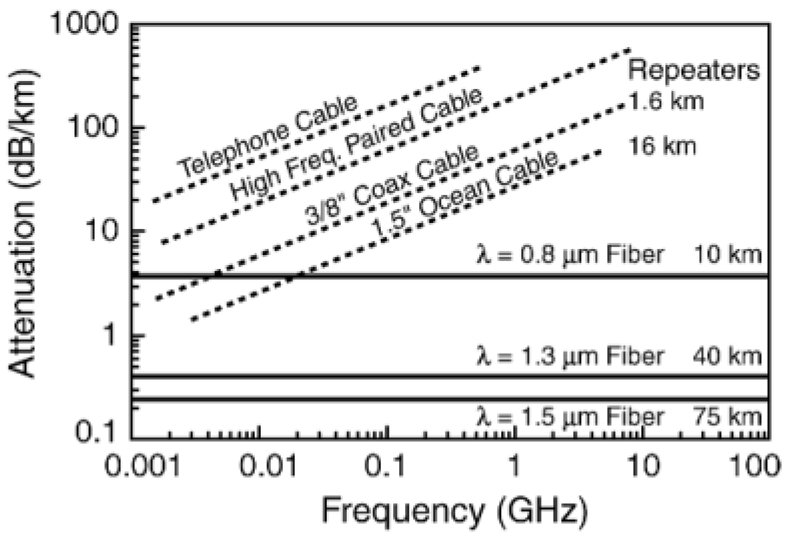

Figure 1.3 Attenuation loss of electrical cables and optical fiber [10]

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, ω_1 and ω_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.

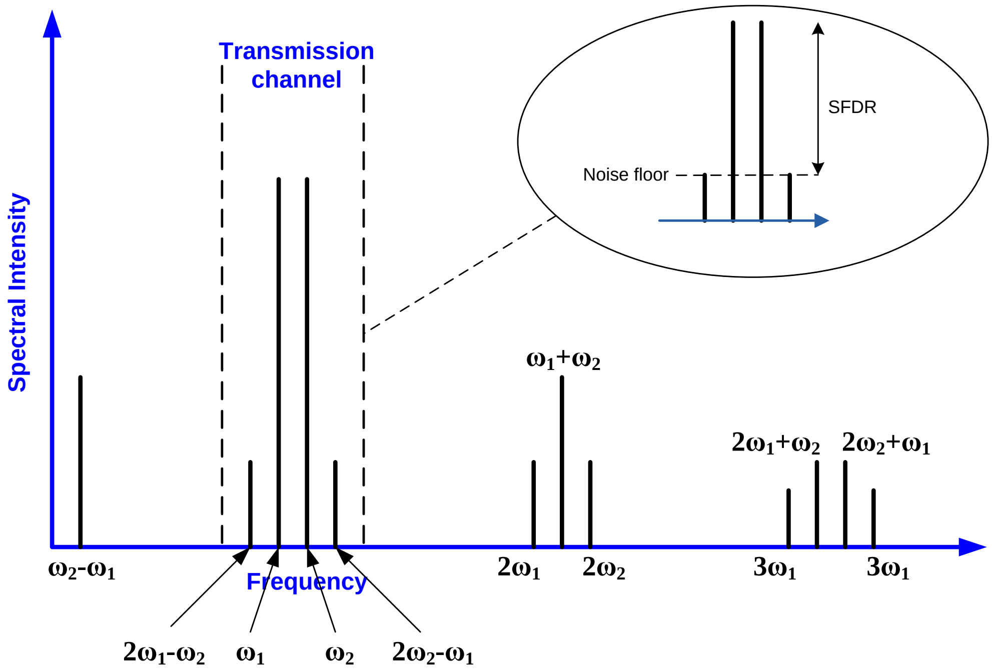

Figure 1.4 Two-tone testing output spectrum of a nonlinear system

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.

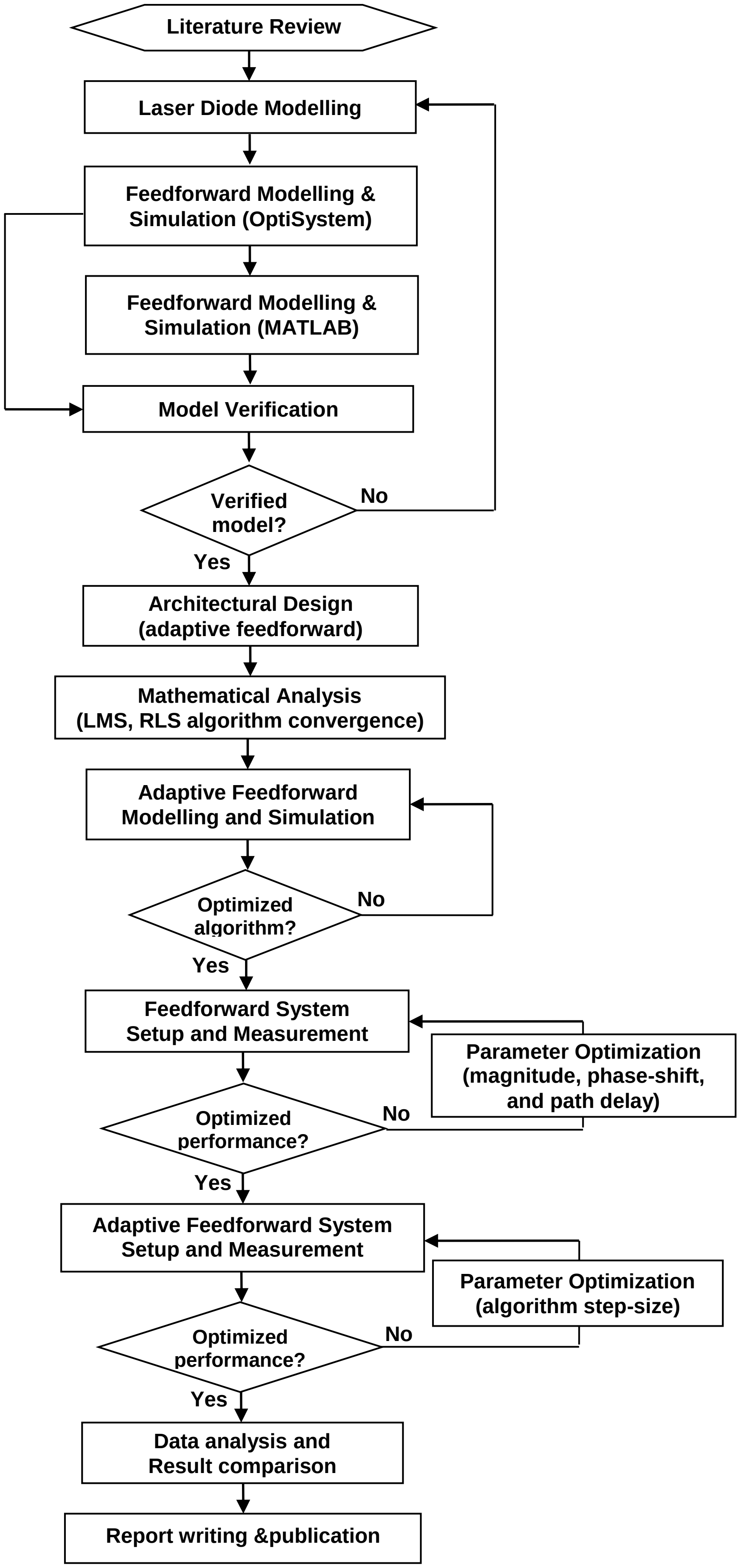

Figure 1.5 Research methodology flowchart

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.

REFERENCES

1. International Telecommunication Union, “ICT Facts & Figures 2017,” 2017.
2. P. Monteiro, A. Gameiro, and N. J. Gomes, “Background and Introduction,” in *Next Generation Wireless Communications Using Radio Over Fiber*, N. Gomes, P. Monteiro, and A. Gameiro, Eds. John Wiley & Sons, 2012.
3. C. Lim *et al.*, “Fiber-wireless networks and subsystem technologies,” *J. Light. Technol.*, vol. 28, no. 4, pp. 390–405, 2010.
4. A. Bhatia, H.-F. Ting, and M. A. Foster, “Linearization of phase-modulated analog optical links using a four-wave mixing comb source.,” *Opt. Express*, vol. 22, no. 25, pp. 30899–909, 2014.
5. V. J. Urick *et al.*, “Long-Haul Analog Photonics,” *J. Light. Technol.*, vol. 29, no. 8, pp. 1182–1205, Apr. 2011.
6. I. Frigyes, “Basic Microwave Properties of Optical Links: Insertion Loss, Noise Figure, and Modulation Transfer,” in *Radio Over Fiber Technologies for Mobile Communications Networks*, H. Al-Raweshidy and S. Komaki, Eds. USA: Artech House, Inc., 2002.
7. N. J. Gomes and D. Wake, “Introduction to Radio over Fiber,” in *Next Generation Wireless Communications Using Radio Over Fiber*, N. Gomes, P. Monteiro, and A. Gameiro, Eds. John Wiley & Sons, 2012.
8. M. Faugeron *et al.*, “High Optical Power, High Gain and High Dynamic Range Directly Modulated Optical Link,” *Light. Technol. J.*, vol. 31, no. 8, pp. 1227–1233, 2013.
9. P. Assimakopoulos, A. Nkansah, N. J. Gomes, and D. Wake, “Statistical distribution of EVM measurements for direct-modulation radio-over-fiber links transporting OFDM signals,” *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 4, pp. 1709–1717, 2013.
10. C. H. Cox, *Analog optical links: theory and practice*. Cambridge University Press, 2006.
11. S. Hunziker, “Low-Cost Fiber Optic Links for cellular Remote Antenna

Feeding," in *Radio Over Fiber Technologies for Mobile Communications Networks*, H. Al-Raweshidy and S. Komaki, Eds. USA: Artech House, Inc., 2002.

12. D. N. Hatfield, "The Challenge of Increasing Broadband Capacity," *Fed. Comm. LJ*, vol. 63, p. 43, 2010.
13. D. Wake, "Radio over Fiber Systems for Mobile Applications," in *Radio Over Fiber Technologies for Mobile Communications Networks*, S. Al- Raweshidy, H., and Komaki, Ed. USA: Artech House, Inc., 2002.
14. S. Eduard, *Broadband Circuits for Optical Fiber Communication*. John Wiley & Sons, 2005.
15. H. B. Kim, "Radio over Fiber based Network Architecture," Ph.D. dissertation, Tech. Berlin Univ., 2005.
16. Y. Pei *et al.*, "Complexity-reduced digital predistortion for subcarrier multiplexed radio over fiber systems transmitting sparse multi-band RF signals," *Opt. Express*, vol. 21, no. 3, pp. 3708–3714, 2013.
17. A. Attar, H. Li, and V. C. M. Leung, "Applications of fiber-connected distributed antenna systems in broadband wireless access," *2012 Int. Conf. Comput. Netw. Commun.*, pp. 623–627, 2012.
18. J. E. Mitchell, "Integrated wireless backhaul over optical access networks," *J. Light. Technol.*, vol. 32, no. 20, pp. 3373–3382, 2014.
19. A. J. Cooper, "Fibre/radio'for the provision of cordless/mobile telephony services in the access network," *Electron. Lett.*, vol. 26, no. 24, pp. 2054–2056, 1990.
20. T. S. Chu and M. J. Gans, "Fiber Optic Microcellular Radio," *IEEE Trans. Veh. Technol.*, vol. 40, no. 3, pp. 599–606, 1991.
21. J. S. Wu, J. Wu, and H. W. Tsao, "A radio-over-fiber network for microcellular system application," *IEEE Trans. Veh. Technol.*, vol. 47, no. 1, pp. 84–94, 1998.
22. H. S. Al-Raweshidy and R. Prasad, "Spread Spectrum Technique to Improve the Performance of Radio over Fibre for Microcellular GSM Networks," *Wirel. Pers. Commun.*, vol. 14, no. 2, pp. 133–146, 2000.
23. H. Kim and Y. C. Chung, "Passive optical network for CDMA-based microcellular communication systems," *J. Light. Technol.*, vol. 19, no. 3, pp. 301–311, 2001.

24. Y. Ebine, "Development of fiber-radio systems for cellular mobile communications," *Microw. Photonics, 1999. MWP'99. Int.*, pp. 249–252, 1999.

25. D. Wake, A Nkansah, and N. J. Gomes, "Radio Over Fiber Link Design for Next Generation Wireless Systems," *J. Light. Technol.*, vol. 28, no. 16, pp. 2456–2464, 2010.

26. A. Saadani *et al.*, "Digital Radio over Fiber for LTE-Advanced: Opportunities and Challenges," *Opt. Netw. Des. Model. (ONDM), 2013 17th Int. Conf.*, pp. 194–199, 2013.

27. T. Niiho, M. Nakaso, K. Masuda, H. Sasai, K. Utsumi, and M. Fuse, "Transmission performance of multichannel wireless LAN system based on radio-over-fiber techniques," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 980–989, 2006.

28. H. Sasai, T. Niiho, K. Tanaka, K. Utsumi, and S. Morikura, "Radio-over-fiber transmission performance of OFDM signal for dual-band wireless LAN systems," *MWP 2003 - Proceedings, Int. Top. Meet. Microw. Photonics*, pp. 139–142, 2003.

29. Y. Li, H. Ji, X. Li, and V. Leung, "Dynamic channel selection with reinforcement learning for cognitive WLAN over fiber," *Int. J. Commun. Syst.*, vol. 25, no. 8, pp. 1077–1090, 2012.

30. H. Ogawa, D. Polifko, and S. Banba, "Millimeter-wave fiber optics systems for personal radio communication," *IEEE Trans. Microw. Theory Tech.*, vol. 40, no. 12, pp. 2285–2293, 1992.

31. R. Waterhouse and D. Novak, "Realizing 5G: microwave photonics for 5G mobile wireless systems," *IEEE Microw. Mag.*, vol. 16, no. 8, pp. 84–92, 2015.

32. D. Novak *et al.*, "Radio-Over-Fiber Technologies for Emerging Wireless Systems," *IEEE J. Quantum Electron.*, vol. 52, no. 1, pp. 1–11, 2016.

33. M. Zhu, L. Zhang, J. Wang, L. Cheng, C. Liu, and G.-K. Chang, "Radio-over-fiber access architecture for integrated broadband wireless services," *J. Light. Technol.*, vol. 31, no. 23, pp. 3614–3620, 2013.

34. C. Liu, J. Wang, L. Cheng, M. Zhu, and G.-K. Chang, "Key Microwave-Photonics Technologies for Next-Generation Cloud-Based Radio Access Networks," *J. Light. Technol. Vol. 32, Issue 20, pp. 3452-3460*, vol. 32, no. 20, pp. 3452–3460, 2014.

35. M. Sauer, A. Kobyakov, and J. George, "Radio over fiber for picocellular

network architectures," *J. Light. Technol.*, vol. 25, no. 11, pp. 3301–3320, 2007.

36. N. J. Gomes *et al.*, "Radio-over-fiber transport for the support of wireless broadband services [Invited]," *J. Opt. Netw.*, vol. 8, no. 2, p. 156, Feb. 2009.
37. T. Darcie, "Subcarrier multiplexing for multiple-access lightwave networks," *J. Light. Technol.*, vol. 5, no. 8, pp. 1103–1110, 1987.
38. J. A. Chiddix, H. Laor, D. M. Pangrac, L. D. Williamson, and R. W. Wolfe, "AM video on fiber in CATV systems: need and implementation," *IEEE J. Sel. Areas Commun.*, vol. 8, no. 7, pp. 1229–1239, 1990.
39. P. K. Tang, L. C. Ong, A. Alphones, B. Luo, and M. Fujise, "PER and EVM Measurements of a Radio-Over-Fiber Network for Cellular and WLAN System Applications," *J. Light. Technol.*, vol. 22, no. 11, pp. 2370–2376, Nov. 2004.
40. Y. Okamoto, R. Miyamoto, and M. Yasunaga, "Radio-on-fiber access network systems for road-vehicle communication," in *ITSC 2001. 2001 IEEE Intelligent Transportation Systems. Proceedings (Cat. No.01TH8585)*, pp. 1050–1055.
41. M. Fujise, "Radio over Fiber Multiple-Service Wireless Communication Systems," in *Radio over Fiber Technologies for Mobile Communications Networks*, H. Al- Raweshidy and S. Komaki, Eds. USA: Artech House, Inc., 2002.
42. C. H. Cox, E. I. Ackerman, G. E. Betts, and J. L. Prince, "Limits on the performance of RF-over-fiber links and their impact on device design," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 906–920, Feb. 2006.
43. W. Way, "Optical Fiber-Based Microcellular Systems: An Overview (Special Issue on Fiber-optic Microcelluler Radio Communication System and Their Technologies)," *IEICE Trans. Commun.*, vol. 76, no. 9, pp. 1091–1102, 1993.
44. D. Wake and R. E. Schuh, "Measurement and simulation of W-CDMA signal transmission over optical fibre," *Electron. Lett.*, vol. 36, no. 10, p. 901, 2000.
45. B. Jalali and A. R. Shah, "Adaptive equalisation for broadband predistortion linearisation of optical transmitters," *IEE Proc. - Optoelectron.*, vol. 152, no. 1, pp. 16–32, Feb. 2005.
46. J. Yao, "Microwave Photonics," *J. Light. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.
47. J. K. Cavers, "Adaptation behavior of a feedforward amplifier linearizer," *IEEE Trans. Veh. Technol.*, vol. 44, no. 1, pp. 31–40, 1995.

48. S. R. O'Connor, J. Thomas R. Clark, and D. Novak, "Wideband Adaptive Feedforward Photonic Link," *J. Light. Technol. Vol. 26, Issue 15, pp. 2810-2816*, vol. 26, no. 15, pp. 2810–2816, 2008.
49. L. Roselli *et al.*, "Analog laser predistortion for multiservice radio-over-fiber systems," *J. Light. Technol.*, vol. 21, no. 5, pp. 1211–1223, May 2003.
50. R. Sadhwani and B. Jalali, "Adaptive CMOS Predistortion Linearizer for Fiber-Optic Links," *J. Light. Technol. Vol. 21, Issue 12, pp. 3180-*, vol. 21, no. 12, p. 3180, 2003.
51. Y. Shen, B. Hraimel, X. Zhang, G. E. R. Cowan, K. Wu, and T. Liu, "A Novel Analog Broadband RF Predistortion Circuit to Linearize Electro-Absorption Modulators in Multiband OFDM Radio-Over-Fiber Systems," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3327–3335, Nov. 2010.
52. G. C. Wilson *et al.*, "Predistortion of electroabsorption modulators for analog CATV systems at 1.55 μm," *J. Light. Technol.*, vol. 15, no. 9, pp. 1654–1662, 1997.
53. F.-C. Lin and D. M. Holburn, "Linearisation for analogue optical links using integrated CMOS predistortion circuits," in *Proc. SPIE 5837, VLSI Circuits and Systems II*, 2005, pp. 121–129.
54. Shingo Tanaka, N. Taguchi, T. Kimura, and Y. Atsumi, "A predistortion-type equi-path linearizer designed for radio-on-fiber system," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 938–944, Feb. 2006.
55. R. Zhu, X. Zhang, B. Hraimel, D. Shen, and T. Liu, "Broadband Predistortion Circuit Using Zero Bias Diodes for Radio Over Fiber Systems," *IEEE Photonics Technol. Lett.*, vol. 25, no. 21, pp. 2101–2104, Nov. 2013.
56. R. Zhu, Zichen Xuan, Ye Zhang, X. Zhang, and D. Shen, "Novel broadband analog predistortion circuit for radio-over-fiber systems," in *2015 IEEE MTT-S International Microwave Symposium*, 2015, pp. 1–4.
57. R. Zhu, "Broadband Linearization Technologies for Broadband Radio-over-Fiber Transmission Systems," PhD Thesis, Concordia University, 2015.
58. S. Nadarajah, X. N. Fernando, and R. Sedaghat, "Adaptive digital predistortion of laser diode nonlinearity for wireless applications," in *CCECE 2003 - Canadian Conference on Electrical and Computer Engineering. Toward a Caring and Humane Technology (Cat. No.03CH37436)*, vol. 1, pp. 159–162.
59. Z. Xuan, "Digital Predistortion for Broadband Radio-over-Fiber Transmission

Systems," Masters Thesis, Concordia University, 2015.

60. L. Ding *et al.*, "A Robust Digital Baseband Predistorter Constructed Using Memory Polynomials," *IEEE Trans. Commun.*, vol. 52, no. 1, pp. 159–165, Jan. 2004.

61. X. Zhang, R. Zhu, D. Shen, and T. Liu, "Linearization Technologies for Broadband Radio-Over-Fiber Transmission Systems," *Photonics*, vol. 1, no. 4, pp. 455–472, Nov. 2014.

62. H. Moon and R. Sedaghat, "FPGA-Based adaptive digital predistortion for radio-over-fiber links," *Microprocess. Microsyst.*, vol. 30, no. 3, pp. 145–154, 2006.

63. A. S. Karar, Y. Jiang, J. C. Cartledge, J. Harley, D. J. Krause, and K. Roberts, "Electronic precompensation of the nonlinear distortion in a 10 Gb/s 4-ary ASK directly modulated laser," in *36th European Conference and Exhibition on Optical Communication*, 2010, pp. 1–3.

64. L. C. Vieira, N. J. Gomes, and A. Nkansah, "An experimental study on digital predistortion for radio-over-fiber links," in *Asia Communications and Photonics Conference and Exhibition*, 2010, pp. 126–127.

65. L. C. Vieira, N. J. Gomes, A. Nkansah, and F. van Dijk, "Behavioral modeling of radio-over-fiber links using memory polynomials," in *2010 IEEE International Topical Meeting on Microwave Photonics*, 2010, pp. 85–88.

66. L. C. Vieira and N. J. Gomes, "Experimental demonstration of digital predistortion for orthogonal frequency-division multiplexing-radio over fibre links near laser resonance," *IET Optoelectron.*, vol. 9, no. 6, pp. 310–316, Dec. 2015.

67. A. Hekkala *et al.*, "Predistortion of Radio Over Fiber Links: Algorithms, Implementation, and Measurements," *IEEE Trans. Circuits Syst. I Regul. Pap.*, vol. 59, no. 3, pp. 664–672, Mar. 2012.

68. H. Chen *et al.*, "Experimental investigation on multi-dimensional digital predistortion for multi-band radio-over-fiber systems," *Opt. Express*, vol. 22, no. 4, p. 4649, Feb. 2014.

69. Y. Bao, Z. Li, J. Li, X. Feng, B. Guan, and G. Li, "Nonlinearity mitigation for high-speed optical OFDM transmitters using digital pre-distortion," *Opt. Express*, vol. 21, no. 6, p. 7354, Mar. 2013.

70. P. W. Berenguer *et al.*, "Nonlinear Digital Pre-distortion of Transmitter

Components," *J. Light. Technol. Vol. 34, Issue 8, pp. 1739-1745*, vol. 34, no. 8, pp. 1739–1745, 2016.

71. Y. Pei, J. Li, K. Xu, Y. Dai, J. Yuefeng, and J. Lin, "Digital Multi-Channel Post-Linearization for Uplink in Multi-Band Radio-Over-Fiber Systems," in *Optical Fiber Communication Conference*, 2014, p. M3D.4.
72. H.-J. Park, S.-Y. Jung, and S.-K. Han, "Blind post processed nonlinearity mitigation in multiband OFDM radio over fiber optical transmission," 2016, p. 97720L.
73. J. Pan and C.-H. Cheng, "Wiener–Hammerstein Model Based Electrical Equalizer for Optical Communication Systems," *J. Light. Technol.*, vol. 29, no. 16, pp. 2454–2459, Aug. 2011.
74. D. Lam, A. M. Fard, and B. Jalali, "Digital broadband linearization of analog optical links," in *IEEE Photonics Conference 2012*, 2012, pp. 370–371.
75. D. Lam, A. M. Fard, B. Buckley, and B. Jalali, "Digital broadband linearization of optical links," *Opt. Lett.*, vol. 38, no. 4, p. 446, Feb. 2013.
76. H. J. Park *et al.*, "Distortion Mitigation in Multiband OFDM RoF Transmission Employing Blind Post Equalizer," *IEEE Photonics Technol. Lett.*, vol. 28, no. 23, pp. 2708–2711, Dec. 2016.
77. Xue Jun Meng, Tai Chau, and M. C. Wu, "Improved intrinsic dynamic distortions in directly modulated semiconductor lasers by optical injection locking," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1172–1176, Jul. 1999.
78. E. K. Lau, Liang Jie Wong, and M. C. Wu, "Enhanced Modulation Characteristics of Optical Injection-Locked Lasers: A Tutorial," *IEEE J. Sel. Top. Quantum Electron.*, vol. 15, no. 3, pp. 618–633, 2009.
79. Sang-Hoon Lee, Jeung-Mo Kang, In-Hyuk Choi, and Sang-Kook Han, "Linearization of DFB laser diode by external light-injected cross-gain modulation for radio-over-fiber link," *IEEE Photonics Technol. Lett.*, vol. 18, no. 14, pp. 1545–1547, Jul. 2006.
80. A. Kaszubowska, P. Anandarajah, and L. P. Barry, "Improved performance of a hybrid radio/fiber system using a directly modulated laser transmitter with external injection," *IEEE Photonics Technol. Lett.*, vol. 14, no. 2, pp. 233–235, Feb. 2002.
81. L. Chrostowski, Xiaoxue Zhao, and C. J. Chang-Hasnain, "Microwave

performance of optically injection-locked VCSELs," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 788–796, Feb. 2006.

82. Hyun-Do Jung and Sang-Kook Han, "Nonlinear distortion suppression in directly modulated DFB-LD by dual-parallel modulation," *IEEE Photonics Technol. Lett.*, vol. 14, no. 7, pp. 980–982, Jul. 2002.

83. Hyun-Do Jung, Duk-Ho Jeon, and Sang-Kook Han, "Linearity enhancement of an electroabsorption modulated laser by dual-parallel modulation," *IEEE Photonics Technol. Lett.*, vol. 14, no. 4, pp. 462–464, Apr. 2002.

84. S.-K. Kim, W. Liu, Q. Pei, L. R. Dalton, and H. R. Fetterman, "Nonlinear intermodulation distortion suppression in coherent analog fiber optic link using electro-optic polymeric dual parallel Mach-Zehnder modulator," *Opt. Express*, vol. 19, no. 8, p. 7865, Apr. 2011.

85. B. Buxton and R. Vahldieck, "Noise and intermodulation distortion reduction in an optical feedforward transmitter," in *1994 IEEE MTT-S International Microwave Symposium Digest (Cat. No.94CH3389-4)*, pp. 1105–1108.

86. R. G. Randall, "A Broadband DSP Based Feedforward Amplifier Linearizer," M.Sc. thesis, Univ. Calgary, 2001.

87. T. Ismail, C.-P. Liu, J. E. Mitchell, and A. J. Seeds, "High-Dynamic-Range Wireless-Over-Fiber Link Using Feedforward Linearization," *J. Light. Technol.*, vol. 25, no. 11, pp. 3274–3282, Nov. 2007.

88. Y.-T. Moon, J. W. Jang, W.-K. Choi, and Y.-W. Choi, "Simultaneous noise and distortion reduction of a broadband optical feedforward transmitter for multi-service operation in radio-over-fiber systems," *Opt. Express*, vol. 15, no. 19, p. 12167, 2007.

89. M. Nazarathy, J. Berger, A. J. Ley, I. M. Levi, and Y. Kagan, "Progress in externally modulated AM CATV transmission systems," *J. Light. Technol.*, vol. 11, no. 1, pp. 82–105, Jan. 1993.

90. D. Hassin and R. Vahldieck, "Feedforward linearization of analog modulated laser diodes-theoretical analysis and experimental verification," *IEEE Trans. Microw. Theory Tech.*, vol. 41, no. 12, pp. 2376–2382, 1993.

91. L. S. Fock and R. S. Tucker, "Reduction of distortion in analogue modulated semiconductor lasers by feedforward compensation," *Electron. Lett.*, vol. 27, no. 8, p. 669, 1991.

92. L. S. Fock and R. S. Tucker, "Simultaneous reduction of intensity noise and

distortion in semiconductor lasers by feedforward compensation," *Electron. Lett.*, vol. 27, no. 14, p. 1297, 1991.

93. D. Hassin and R. Vahldieck, "Improved feedforward linearization of laser diodes-simulation and experimental results," in *1993 IEEE MTT-S International Microwave Symposium Digest*, 1993, pp. 727–730.

94. T. Ismail and A. Seeds, "Nonlinear distortion reduction in directly modulated semiconductor laser using feedforward linearisation," in *London Communication Symposium*, 2003.

95. T. Ismail, J. Mitchell, and A. Seeds, "Linearity Enhancement of a Directly Modulated Uncooled DFB Laser in a Multi-Channel Wireless-over-Fibre Systems," in *IEEE MTT-S International Microwave Symposium Digest, 2005.*, pp. 7–10.

96. Sang-Hyun Park and Young-Wan Choi, "Significant suppression of the third intermodulation distortion in transmission system with optical feedforward linearized transmitter," *IEEE Photonics Technol. Lett.*, vol. 17, no. 6, pp. 1280–1282, Jun. 2005.

97. Joon-Jae Lee, Sang-Hyun Park, and Young-Wan Choi, "Enhanced ACPR of W-CDMA Signals in Optical Feedforward Transmitter by Optimization," in *2005 International Topical Meeting on Microwave Photonics*, 2005, pp. 59–62.

98. Yon-Tae Moon, Tae-Kyeong Lee, Seok Lee, and Young-Wan Choi, "Compact feedforward optical transmitter without adaptive vector modulator," in *2008 International Topical Meeting on Microwave Photonics jointly held with the 2008 Asia-Pacific Microwave Photonics Conference*, 2008, pp. 124–126.

99. Y.-T. Moon, W.-K. Choi, and Y.-W. Choi, "Dispersion penalty analysis using light injection method in the feedforward optical transmitter for WDM/SCM radio-over-fiber systems," *Opt. Commun.*, vol. 281, no. 23, pp. 5851–5854, 2008.

100. Y.-T. Moon *et al.*, "Systematic design and realization of the optical feedforward transmitter based on microwave circuit modeling," *Microw. Opt. Technol. Lett.*, vol. 51, no. 1, pp. 192–195, Jan. 2009.

101. S. Alifah, S. M. Idrus, and N. M. Kassim, "Better Performance of Optical Transmitter Using Feedforward Linearisation System for Multi Service Operation in Radio over Fiber Links," in *2008 IEEE PhotonicsGlobal@Singapore*, 2008, pp. 1–4.

102. S. Alifah, S. M. Idrus, and N. M. Kassim, “Simultaneous Noise Reduction and Linearity Improvement of Optical Feedforward Transmitter for Radio over Fiber Systems,” in *2008 International Symposium on High Capacity Optical Networks and Enabling Technologies*, 2008, pp. 97–101.

103. S. Alifah, S. M. Idrus, and N. M. Kassim, “Wideband linearisation technique for radio over fiber laser transmitter,” in *2009 14th OptoElectronics and Communications Conference*, 2009, pp. 1–2.

104. D. Novak and T. R. Clark, “Broadband Adaptive Feedforward Photonic Linearization for High Dynamic Range Signal Remoting,” in *MILCOM 2007 - IEEE Military Communications Conference*, 2007, pp. 1–6.

105. S. R. O’Connor, T. R. Clark, and D. Novak, “Wideband adaptive feedforward linearized RF photonic link,” in 2008 I*nternational Topical Meeting on Microwave Photonics jointly held with the 2008 Asia-Pacific Microwave Photonics Conference*, 2008, pp. 94–97.

106. D. Novak, T. Clark, S. O’Connor, D. Oursler, and R. Waterhouse, “High performance, compact RF photonic transmitter with feedforward linearization,” in *2010 - MILCOM 2010 MILITARY COMMUNICATIONS CONFERENCE*, 2010, pp. 880–884.

107. M. Obermann and J. Long, “Feed forward distortion minimization circuit,” 1991.

108. S. Narahashi and T. Nojima, “Extremely low-distortion multi-carrier amplifier-self-adjusting feed-forward (SAFF) amplifier,” in *ICC 91 International Conference on Communications Conference Record*, pp. 1485–1490.

109. S. J. Grant, J. K. Cavers, and P. A. Goud, “A DSP controlled adaptive feedforward amplifier linearizer,” in *Proceedings of ICUPC - 5th International Conference on Universal Personal Communications*, vol. 2, pp. 788–792.

110. A. M. Smith and J. K. Cavers, “A wideband architecture for adaptive feedforward linearization,” in *VTC ’98. 48th IEEE Vehicular Technology Conference. Pathway to Global Wireless Revolution (Cat. No.98CH36151)*, vol. 3, pp. 2488–2492.

111. G. Zhao, F. M. Ghannouchi, F. Beauregard, and A. B. Kouki, “Digital implementations of adaptive feedforward amplifier linearization techniques,” in *1996 IEEE MTT-S International Microwave Symposium Digest*, vol. 2, pp. 543–546.

112. Jiunn-Tsair Chen, Huan-Shang Tsai, and Young-Kai Chen, "The optimal RLS parameter tracking algorithm for a power amplifier feedforward linearizer," *IEEE Trans. Circuits Syst. II Analog Digit. Signal Process.*, vol. 46, no. 4, pp. 464–468, Apr. 1999.

113. Youngoo Yang *et al.*, "Digital controlled adaptive feedforward amplifier for IMT-2000 band," in *2000 IEEE MTT-S International Microwave Symposium Digest (Cat. No.00CH37017)*, vol. 3, pp. 1487–1490.

114. Young Yun Woo, Youngoo Yang, Jaehyok Yi, Joongjin Nam, Jeong Hyeon Cha, and Bumman Kim, "Feedforward amplifier for WCDMA base stations with a new adaptive control method," in *2002 IEEE MTT-S International Microwave Symposium Digest (Cat. No.02CH37278)*, pp. 769–772.

115. Sanggee Kang, Myungsun Song, Huimin Yi, and Sungyong Hong, "Adaptive control method for a feedforward amplifier," in *2004 IEEE 59th Vehicular Technology Conference. VTC 2004-Spring (IEEE Cat. No.04CH37514)*, vol. 2, pp. 1182–1186.

116. Sanggee Kang, Unghee Park, Kyunghee Lee, and Seongyoung Hong, "Adaptive feedforward amplifier using digital controller," in *The 57th IEEE Semiannual Vehicular Technology Conference, 2003. VTC 2003-Spring.*, vol. 3, pp. 2076–2079.

117. Kwok-Po Chan and K.-K. M. Cheng, "Novel DSP algorithms for adaptive feed-forward power amplifier design," in *IEEE MTT-S International Microwave Symposium Digest, 2003*, pp. 1323–1326.

118. W. Zhu, Q. Kaiyu, Y. Kai, Z. Man, C. Changwei, and Z. Xilin, "An Adaptive Control Method for Microwave Linear Power Amplifier," in *2006 International Conference on Communications, Circuits and Systems*, 2006, pp. 2573–2576.

119. A. Gokceoglu, A. ghadam, and M. Valkama, "Steady-State Performance Analysis and Step-Size Selection for LMS-Adaptive Wideband Feedforward Power Amplifier Linearizer," *IEEE Trans. Signal Process.*, vol. 60, no. 1, pp. 82–99, Jan. 2012.

120. C. H. Lee, *Microwave photonics*. CRC press, 2013.

121. W. S. C. Chang, *RF photonic technology in optical fiber links*. Cambridge University Press, 2007.

122. V. A. Thomas, M. El-Hajjar, and L. Hanzo, "Millimeter-Wave Radio Over

Fiber Optical Upconversion Techniques Relying on Link Nonlinearity," *IEEE Commun. Surv. Tutorials*, vol. 18, no. 1, pp. 29–53, 2016.

123. E. I. Ackerman and C. H. Cox, "RF fiber-optic link performance," *IEEE Microw. Mag.*, vol. 2, no. 4, pp. 50–58, 2001.
124. S. Kotsopoulos and K. Ioannou, *Handbook of Research on Heterogeneous Next Generation Networking*. IGI Global, 2009.
125. G. Morthier and P. Vankwikelberge, *Handbook of distributed feedback laser diodes*. Artech House, 2013.
126. S. Narayanan, "Application of Volterra series to intermodulation distortion analysis of transistor feedback amplifiers," *IEEE Trans. Circuit Theory*, vol. 17, no. 4, pp. 518–527, 1970.
127. E. Bedrosian and S. O. Rice, "The output properties of Volterra systems (nonlinear systems with memory) driven by harmonic and Gaussian inputs," *Proc. IEEE*, vol. 59, no. 12, pp. 1688–1707, 1971.
128. R. Tucker and D. Pope, "Circuit modeling of the effect of diffusion on damping in a narrow-stripe semiconductor laser," *IEEE J. Quantum Electron.*, vol. 19, no. 7, pp. 1179–1183, Jul. 1983.
129. G. P. Agrawal, "Optical Transmitters," in *Fiber-Optic Communication Systems*, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2011, pp. 79–127.
130. T. K. Biswas and W. F. McGee, "Volterra series analysis of semiconductor laser diode," *IEEE Photonics Technol. Lett.*, vol. 3, no. 8, pp. 706–708, Aug. 1991.
131. M. Schetzen, *The Volterra and Wiener theories of nonlinear systems*. Wiley, 1980.
132. OptiSystem 13.0 documentation 2014, "OptiSystem Component Library," Optiwave Systems Inc.
133. W. Way, "Large signal nonlinear distortion prediction for a single-mode laser diode under microwave intensity modulation," *J. Light. Technol.*, vol. 5, no. 3, pp. 305–315, 1987.
134. S. S. Haykin, *Adaptive Filter Theory*. Prentice Hall, 2002.
135. Vaunix Technology, *Lab Brick® LMS Signal Generators*. LMS Signal Generators datasheet.
136. Mitsubishi Electric Corportation, *1.55um EA modulator integrated DFB-LD module (7 Pin package with K connector, 10Gb/s digital application)*. FU-641SEA-1MX datasheet.
137. Optilab LLC, *Universal Laser Diode Controller*. ULDC datasheet, 2010.

138. Agere Systems Inc., *R2860D Digital Receiver OC-192/STM-64*. R2860D Digital Receiver datasheet, 2001.
139. Analog Devices, *1.5 GHz to 2.4 GHz RF Vector Modulator*. AD8341 Datasheet, 2012.
140. SHF Communication Technologies AG, *Datasheet SHF 806 E*. SHF 806E datasheet, 2009.
141. Mini-Circuits, *Connectorized Amplifier ZX60-4016E+*. ZX60-4016E+ datasheet, 2012.
142. Mini-Circuits, *DC Pass Power Splitter/Combiner ZAPD-4+*. ZAPD-4+ datasheet, 2014.
143. Picometrix, "Photodetector Model D-100," Newport User's Manual, 2009.
144. Thorlabs inc, *PDA8GS Amplified Fiber Optic Photo Detector*. PDA8GS Spec Sheet, 2010.
145. Mini-Circuits, *Coaxial Amplifier ZKL-2R5+*. ZKL-2R5+ datasheet, 2013.
146. Analog Devices, *Wideband Synthesizer with Integrated VCO*. ADF4351 datasheet, 2012.
147. Mini-Circuits, *Coaxial Frequency Mixer ZAM-42*. ZAM-42 datasheet, 2009.
148. Mini-Circuits, *Coaxial Bandpass Filter ZFBP-400K+*. ZFBP-400K+ datasheet, 2011.
149. Texas Instruments, *TMS320C6713 Floating-Point Digital Signal Processor*. TMS320C6713 datasheet (SPRS186), 2005.
150. Spectrum Digital Inc., *TMS320C6713 DSK Technical Reference*. 2004.
151. Texas Instruments, *5–6K Interface Board*. 5-6K Interface Board EVM User's Guide (SLAU104), 2004.
152. Texas Instruments, *14-Bit, 2 MSPS, Dual-Channel, Differential/Single-Ended, Ultralow-Power Analog-to-Digital Converters*. ADS7945 datasheet (SBAS539), 2011.
153. Texas Instruments, *ADS794xEVM and ADS794xEVM-PDK*. ADS794xEVM User's Guide (SBAU194), 2011.
154. Texas Instruments, *Quad, Serial Input 14-Bit Multiplying Digital-to-Analog Converter*. DAC8803 datasheet (SBAS340), 2006.
155. Texas Instruments, *DAC8803/14 EVM*. DAC8803/14 EVM User's Guide (SLAU184), 2006.