AN IMPROVED FEED-FORWARD LINEARISATION OF OPTICAL TRANSMITTER FOR RADIO OVER FIBER SYSTEM

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requirements for the award of the degree of
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To the Beneficent, the Merciful for Your protect, blessing, strength and unlimited love

To my beloved parents, my beloved husband, my beloved children and my beloved siblings for their continous loves and support

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ABSTRACT

Radio over fiber (RoF) technology provides an efficient and cost effective solution to increase the capacity of mobile communication systems and the coverage of wireless broadband communication systems. This is due to the growing data traffic and bandwidth demands. However, the performance of an RoF system is limited by the linearity of the optical transmitter that contributes to major nonlinear distortions in the links. Meanwhile, in multichannel applications, high linearity is required to avoid a channel interference due to nonlinear distortions. The feedforward linearisation technique offers a number of advantages compared to other techniques such as a broadband distortion reduction at high frequencies and simultaneous reduction in all orders of distortion. Therefore, it is suitable for linearisation of the optical transmitter. But, the existing design uses many electronic components causing difficulty for the amplitude and phase matching to achieve the optimum distortion reduction and also generate the parasitic parameter at high frequency. This thesis aims to improve the performance of the optical feedforward transmitter by reducing the electrical component without decreasing the distortion reduction performance; thus reducing the difficulty for the amplitude and phase matching and the parasitic parameter at high frequency. System characterisation is carried out by the mathematical analysis using Volterra series approach and simulation using a commercial optical design software which is validated by the practical measurement. It shows that the IMD3 reduction is good for high frequency. More than 15 dB IMD3 reduction is achieved over the carrier frequency 1.2 to 2.4 GHz using the proposed system practically. In addition, the proposed system is simpler and less sensitive in the amplitude and phase matching to obtain the optimum distortion reduction since the distortion suppression is influenced by less electrical parameters compared to other works.

ABSTRAK

Teknologi isyarat radio melalui gentian (RoF) merupakan satu penyelesaian yang cekap dan kos efektif untuk meningkatkan kapasiti system perhubungan bergerak dan liputan sistem perhubungan jalur lebar wayarles. Ini disebabkan oleh lalu lintas data dan permintaan lebar jalur yang sentiasa bertambah. Walau bagaimanapun, prestasi sistem RoF telah dihadkan oleh kelinearan pemancar optik yang menyumbang kepada herotan tak linear yang besar dalam pautan-pautannya. Sementara itu, dalam aplikasi berbilang saluran, kelinearan yang tinggi diperlukan untuk mengelakkan gangguan saluran yang disebabkan oleh herotan tak linear. Teknik pelinearan suap depan mempunyai beberapa kebaikan berbanding dengan teknik-teknik lain, seperti pengurangan herotan jalur lebar pada frekuensi tinggi dan pengurangan serentak herotan dari semua tertib. Oleh sebab itu, teknik tersebut sesuai untuk linearisasi pemancar optik. Tetapi, reka bentuk yang ada menggunakan banyak komponen elektrik yang menyebabkan kesulitan daripada padanan amplitud dan fasa untuk mencapai pengurangan herotan yang optimum dan juga membangkitkan parameter parasit pada frekuensi tinggi. Tesis ini bertujuan untuk memperbaiki prestasi pemancar suap depan optik dengan mengurangkan komponen elektrik tanpa menurunkan prestasi pengurangan herotan; sehingga kesulitan daripada padanan amplitud dan fasa dan parameter parasit pada frekuensi tinggi dapat dikurangkan. Pencirian sistem dijalankan dengan analisis matematik menggunakan penghampiran siri Volterra dan simulasi menggunakan perisian reka bentuk optik komersial. Reka bentuk tersebut disahkan oleh pengukuran praktik. Didapati bahawa pengurangan IMD3 adalah baik pada frekuensi tinggi. Lebih daripada 15 dB pengurangan IMD3 telah dicapai pada frekuensi pembawa 1.2 hingga 2.4 GHz menggunakan sistem yang dicadangkan secara praktik. Tambahan pula, sistem yang dicadangkan adalah lebih ringkas dan kurang sensitif dalam padanan amplitud dan fasa untuk mendapatkan pengurangan herotan yang optimum, disebabkan penindasan herotan dipengaruhi oleh pengurangan parameter elektrik berbanding kajian-kajian lain.

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LIST OF SYMBOLS

C	-	coupling coefficient
e	-	electron charge
g	-	optical gain factor
g_i, g_t	-	intrinsic link gain
I, i	-	laser current
k	-	Boltzmann constant
m	-	optical modulation depth
N	-	carrier density
P, p	-	optical power
Q, q	-	photon density
R	-	resistance
r_d	-	responsivity of photodetection device
s_{md}	-	slope efficiency of modulation device
T	-	temperature
V	-	volume of active region
β	-	fraction of spontaneous emission
Γ	-	optical confinement factor
ε	-	gain compression parameter
λ	-	wavelength
τ_n	-	recombination lifetime
τ_p	-	photon lifetime

LIST OF ABBREVIATIONS

1G	-	First Generation
2G	-	Second Generation
3G	-	Third Generation
4G	-	Fourth Generation
AM	-	Amplitude Modulation
AMPS	-	Advanced Mobile Phone Service
ASK	-	Amplitude Shift Keying
BER	-	Bit-Error Rate
BS	-	Base Station
CATV	-	Cable Television
CDMA	-	Code-Division Multiple Access
CMOS	-	Complementary Metal-Oxide-Semiconductor
CNR	-	Carrier to Noise Ratio
COTS	-	Commercial-Off-The-Shelf
CS	-	Central Station
CSO	-	Composite Second Order
CTB	-	Composite Triple Beat
CW	-	Continuous Wave
D/A	-	Digital-to-Analog Converter
DC	-	Direct Current
DCL	-	Distortion Cancellation Loop
DCS	-	Digital Cellular System
DFB	-	Distribution Feedback
DML	-	Directly Modulated Laser
DSP	-	Digital Signal Processing
DWDM	-	Dense Wavelength Division Multiplexing

EA	-	Electroabsorption
EAM	-	Electroabsorption Modulator
EDGE	-	Enhanced Data Rate for GSM Evolution
EMI	-	Electro-Magnetic Interference
EML	-	Electroabsorption Modulated Laser
EO	-	Electrical-to-Optical
ETC	-	Electronic Toll Collection
FDMA	-	Frequency-Division Multiple Access
FPGA	-	Field Programmable Gate Array
FWM	-	Four-Wave Mixing
GPRS	-	General Packet Radio Service
GSM	-	Global System for Mobile-Communications
HD	-	Harmonic Distortion
HSCSD	-	High Speed Circuit Switched Data
ICT	-	Information and Communication Technologies
IDA	-	Instantaneous Digital Adaptation
IMD3	-	Third order Intermodulation Distortion
IMDD	-	Intensity Modulation and Direct Detection
IIP3	-	Third-order Intercept Point
ISM	-	Industrial, Scientific, and Medical
ITS	-	Intelligent Transportation System
LD	-	Laser Diode
LED	-	Light-Emitting Diode
LUT	-	Look-Up Table
MQW	-	Multiquantum Well
MVDS	-	Multipoint Video Distribution Services
MZM	-	Mach Zehnder Modulator
NF	-	Noise Figure
NPR	-	Noise Power Ratio
NRZ	-	Non-Return-to-Zero
OFT	-	Optical Feedforward Transmitter
OMD	-	Optical Modulation Depth
OMI	-	Optical Modulation Index

OSNR	-	Optical Signal-to-Noise Ratio
OTDM	-	Optical Time Domain Multiplexing
PD	-	Photo Diode
PM	-	Phase Modulation
RAU	-	Remote Antenna Unit
RF	-	Radio Frequency
RIN	-	Relative Intensity Noise
RoF	-	Radio over Fiber
SCL	-	Signal Cancellation Loop
SCM	-	Sub-Carrier Multiplexing
SFDR	-	Spurious Free dynamic Range
SHD	-	Second Harmonic Distortion
SMF	-	Single-Mode Fiber
SNDR	-	Signal-to-Noise and Distortion Ratio
SOA	-	Semiconductor Optical Amplifier
TDMA	-	Time-Division Multiple Access
TETRA	-	Terrestrial Trunked Radio
THD	-	Third Harmonic Distortion
UWB	-	Ultra-Wideband
VCSEL	-	Vertical-Cavity Surface-Emitting Laser
VICS	-	Vehicle Information and Communication System
WCDMA	-	Wideband CDMA
WDM	-	Wavelength Division Multiplexing
WiMAX	-	Worldwide Interoperability for Microwave Access
WLAN	-	Wireless Local Area Network
WMAN	-	Wireless Metropolitan Area Network
WoF	-	Wireless-over Fiber
WPAN	-	Wireless Personal Area Networks
XGM	-	Cross-Gain Modulation

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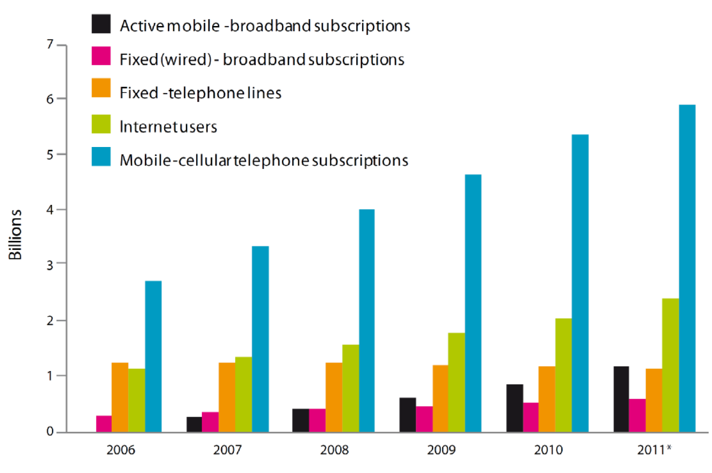
CHAPTER 1

INTRODUCTION

1.1 Radio over Fiber Technology

The fast growth of mobile-cellular telephone subscribers and mobile or fixed broadband internet users has triggered a traffic explosion and raised the demands for high broadband capacity and wide coverage network. Figure 1.1 shows the global ICT access from 2006 to 2011. It shows that the mobile-cellular subscriptions reached 5.9 billion in 2011 with a global penetration ratio of 87%. Meanwhile the mobile-broadband subscriptions have grown 45% annually over the last four years and today there are twice as many mobile-broadband as fixed broadband subscriptions[1].



Note: * Estimate
Source: ITU World Telecommunication/ICT Indicators database

Figure 1.1 Statistics of ICT access in the world [1]

International internet bandwidth, a key factor for providing high-speed internet access to the growing number of internet users, has grown exponentially over the last five years, from 11,000 Gbit/s in 2006 to close to 80,000 Gbit/s in 2011 as shown in Figure 1.2 [1]. Therefore, the future network is encouraged to have a larger capacity to handle the ever-growing data traffic and also a wider coverage to serve broader areas. However there is a trade off between capacity and coverage.

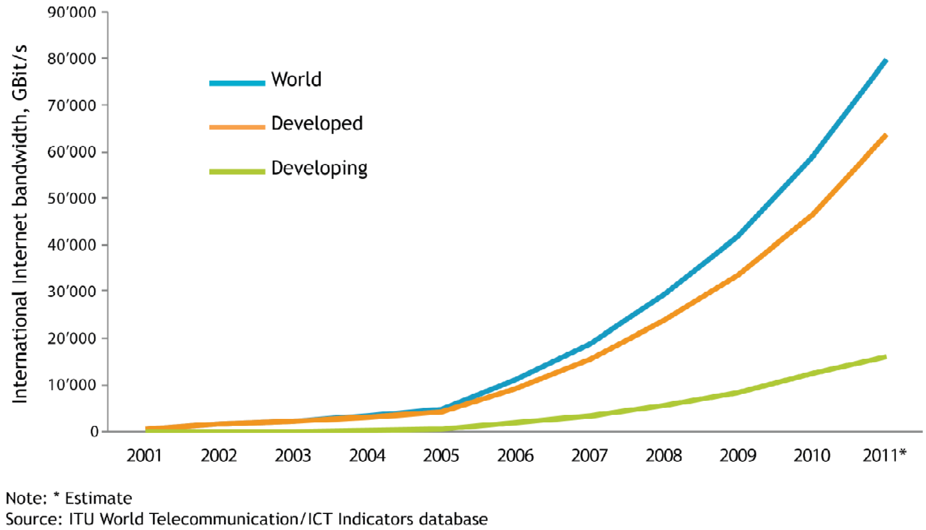


Figure 1.2 Statistics of internet bandwidth growth in the world [1]

The capacity of mobile communication system can be increased by converting the architectures into smaller cells, namely micro or pico cells, together with increasing the carrier frequency. A smaller cell allows more simultaneous mobile users, however the interconnection task will increase while the number of micro-cells in the network increases. Therefore, higher carrier frequency is necessary to overcome the congested ISM band frequencies since it offers a greater modulation bandwidth.

Unfortunately, the system cost will increase while the number of base stations (BSs) increases in the smaller cell and the BSs operate in higher frequencies. In order to overcome this problem, Radio-over-Fibre (RoF) technology has been considered as an attractive solution. In an RoF system, the radio system functionalities in BSs are centralized at the Central Station (CS) thereby making the BSs simpler and cheaper.

RoF technology is a technique to deliver radio signals through optical networks. A basic RoF system is described in Figure 1.3 [2]. In the downlink transmission, RF signals modulate the laser diode directly and result in intensity modulated optical signals at the CS. After that, they are transmitted through an optical fiber to the BS. At the BS, the signals are demodulated directly employing a photodiode (PD) for recovering the RF signals. Furthermore, they are amplified and radiated by an antenna. Based on modulation and detection perspective, RoF technology is known as intensity modulation and direct-detection (IMDD) that is the simplest method for optically distributing RF signals.

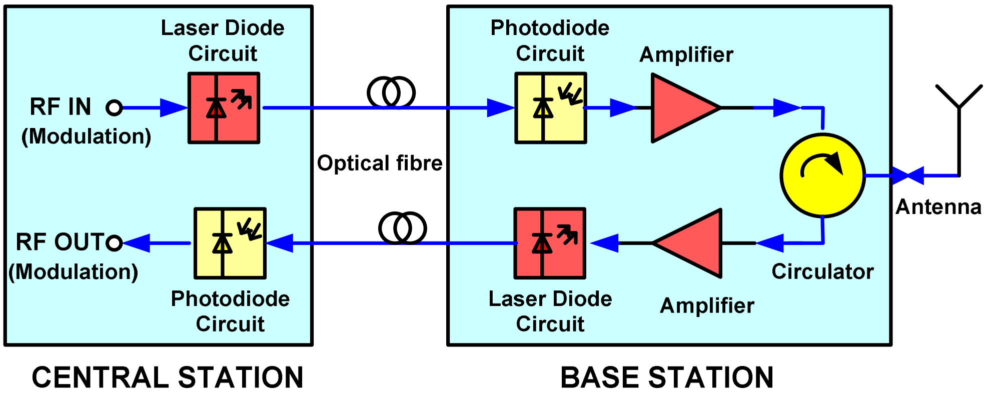


Figure 1.3 Basic RoF system

The opposite process is carried out in the uplink transmission. At the BS, RF signals from the antenna directly modulate the laser diode and then the resulting optical signals are transmitted through an optical fiber to the CS. At the CS, the intensity modulated optical signals are demodulated directly employing a PD for recovering the RF signals. After that, the signals are amplified and further processed.

1.1.1 Benefits of RoF Technology

RoF technology is the integration of the optical and radio networks. With a high transmission capacity, comparatively low cost and low attenuation, optical fiber provides an ideal solution for accomplishing these interconnections. In addition, a radio system enables the significant mobility, flexibility and easy access. Therefore, the system integration can meet the increasing demands of subscribers for voice, data, and multimedia services that require the access network to support high data rates at any time and any place inexpensively. Next, several key advantages of RoF technology are discussed further.

1.1.1.1 Low Attenuation Loss

The distribution of RF signal electronically suffers from a significant loss at high carrier frequencies because of the impedance increment with frequency. As an alternative solution, optical fiber can be used to distribute RF signals at high frequencies due to its low attenuation loss. This loss varies depending on the fiber type and the operating wavelength. The comparison of attenuation loss between electronic and optical cables is shown in Figure 1.4. As can be seen, the 1.5 μm optical fiber has the lowest loss, followed by the 1.3 and 0.8 μm optical fiber. On the other hand, electronic cables have higher loss than optical fibers for any usable frequency [3].

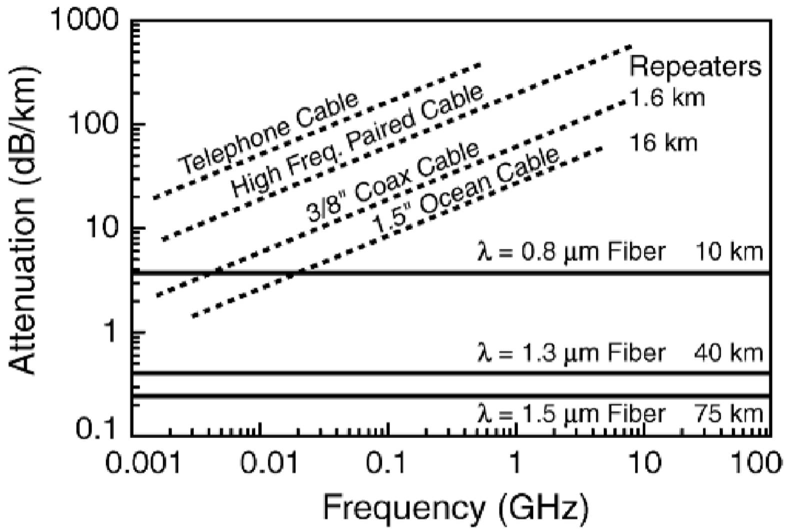


Figure 1.4 Comparison of attenuation loss for electronic and optical cables [3]

1.1.1.2 Large Bandwidth

In electronic systems, high speed signal processing is difficult to be realized because of the bandwidth limitation of the electrical cable. As a solution, optical fibers which provide a huge bandwidth due to their operation in very high frequencies (THz) are employed for high speed signal processing. Comparison of bandwidth for electronic and optical telecommunication medium can be seen in Table 1.

Table 1.1: Bandwidth of various telecommunication medium [4]

Types of Communication medium	Carrier Frequency	Bandwidth
Copper cable	1 MHz	100 KHz
Coaxial cable	100 MHz	10 MHz
Radio frequencies	500 KHz to 100 MHz	10 MHz
Microwave frequencies	200 GHz	20 GHz
Optical fiber cable	100 THz to 1000 THz	40 THz

The bandwidth limitation in electronic systems is an encumbrance in huge bandwidth usage of optical links while transforming electronic signals into optical signals and vise versa. To overcome this problem, Sub-Carrier Multiplexing (SCM) is employed in analog optical systems and RoF systems, meanwhile Optical Time Domain Multiplexing (OTDM) and Dense Wavelength Division Multiplexing (DWDM) are employed in digital optical systems. Those techniques are able to increase the utilization of the optical bandwidth. This makes RoF systems cost-effective.

1.1.1.3 Immunity to Electro-Magnetic Interference

RoF systems transmit RF signals as light through optical fibers that are immune to Electro-Magnetic Interference (EMI). Interferences emerge while an external source emits electromagnetic inductions or radiations which generate an electrical current as they cut across the conductors. Therefore EMI can be transpired in electronic cables as conductors but they cannot occur in optical fibers [5].

1.1.1.4 Easy Installation and Maintenance

The radio system functionalities in the expensive and complex equipments are concentrated at the CS thereby making the BSs or remote antenna units (RAU) simpler in RoF systems. This makes the system installation and maintenance of BS/RAU easier and reduces the maintenance cost. Easy installations and low maintenance costs of RAUs are very important requirements for mm-wave systems, because of the large number of the required RAUs [5]. In applications where RAUs are not easily accessible, the reduction in maintenance requirements leads to major operational cost savings. Smaller RAUs also lead to reduced environmental impact.

1.1.1.5 Reduced Power Consumption

In RoF systems, the complicated equipments in BS/RAU are moved into the CS thereby reducing the power consumption of BS/RAU [5]. Since there are plenty of BSs and RAUs in RoF systems, the reduction of power consumption is essential. Moreover, some RAUs are located in the unreachable area of the power grid.

1.1.1.6 Multi-Operator and Multi-Service Operation

RoF technology is capable of transporting all kinds of signals and services in a scenario of the broadband wired and wireless convergence. Multi-operator and multi-service operation can be transmitted simultaneously in an RoF system by employing effective multiplexing such as SCM/WDM, resulting in plenty of economic savings [6]. By using RoF technology, RF signals in any modulation format can be transmitted for a long distance and distributed through wireless access systems. Standards independence and multiservice operation are also facilitated.

1.1.1.7 Dynamic Resource Allocation

RoF systems are able to allocate the capacity dynamically due to the centralization of RF functionalties in the CS. WDM technique can be employed to allocate the optical wavelengths. For an instance during the peak time, an area can be allocated more capacity than during off times and the capacity can also be re-allocated to other areas. Conversely, it cannot occur while using the permanent allocation of capacity that dispose resources [6].

1.1.2 Applications of RoF Technology

Various applications that distribute RF signals through short as well as long transmission link, such as cellular communication systems, wireless data communication systems, CATV distribution system, etc, can be realized using RoF technology. In the following subsection, its applications are discussed.

1.1.2.1 Mobile Communication Network

One of the important application of RoF technology is the mobile communication system. It has evoluted into a higher speed and larger capacity system as shown in Figure 1.5. Larger capacity and higher speed can be achieved by converting the architectures into smaller cells together with increasing the carrier frequency. Using RoF technology, it can be realized in an effective cost because of the simplification of the BSs .

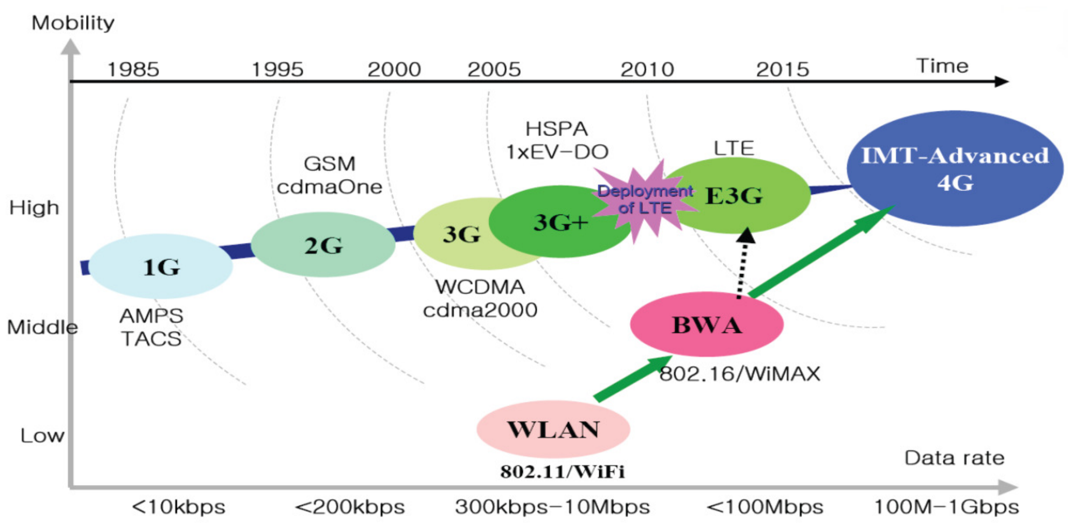


Figure 1.5 Evolution of wireless technology [7]

Mobile communication technology has evoluted rapidly ever since the first generation (1G) with analog traffic channels and FDMA for multiple access that has improved by Advanced Mobile Phone Service (AMPS) to overcome the spectral congestion. Second generation (2G) systems have been developed to address the demands for greater capacity, better-quality signals and higher data-rates to support the digital services with GSM and CDMA one. In order to support the increased throughput data rates that are required for modern mode applications, new data-centric standards have been developed and they can be overlaid upon the existing 2G infrastructures. There are three TDMA upgrades viz. High Speed Circuit Switched Data (HSCSD), General Packet Radio Service (GPRS), Enhanced Data Rate for GSM Evolution (EDGE) and one CDMA upgrade IS-95B have been categorized as 2.5G standards. To support multimedia transmissions, third generation (3G) standards, high-speed mobile technology have been developed, namely Wideband CDMA standards which are based on backward compatibility with GSM and IS-136/PDC and CDMA 2000 standards which are based on backward compatibility with IS-95. Furthermore, in order to solve the still-remaining problems of 3G systems and provide a wide variety of new services such as high-quality voice, high-definition video, and high-data-rate wireless channels, Fourth Generation (4G) standards were developed. Table 1.2 describes the comparison of performance between mobile communication technologies [8, 9, 10].

Tabel 1.2: Comparison of the mobile communication technologies

Technology	1G	2G	2.5G	3G	4G
Standard	AMPS	GSM IS-54TDMA IS-95CDMA	GPRS EDGE 1xRTT	WCDMA/ CDMA2000/ EDVO/ LTE	Single Unified Standard
RF Band	800 MHz	900, 1800, 1900 MHz	900, 1800, 1900 MHz	0.9, 1.8, 1.9 & 2.1 GHz	2-8 GHz
Data Rate	1.9 Kbps	14.4 Kbps	14.4 Kbps	2 Mbps	200 Mbps

1.1.2.2 Broadband Wireless Network

Another essential application of RoF technology is the broadband wireless data communication system. Using the technology, the complexity of the system can be reduced by using a centralized architecture that incorporates a simplified Remote Antenna Unit (RAU) which can be located closer to the customer.

Broadband wireless data communication systems can be categorized into mobile and fixed wireless. The two broadband mobile wireless network technologies are the third Generation (3G) and Fourth Generation (4G) networks which have been discussed in the previous subsection. Meanwhile the emerging fixed wireless networks are shown in Figure 1.6 based on their coverage, namely ZigBee, WiFi-802.11n and WiMAX.

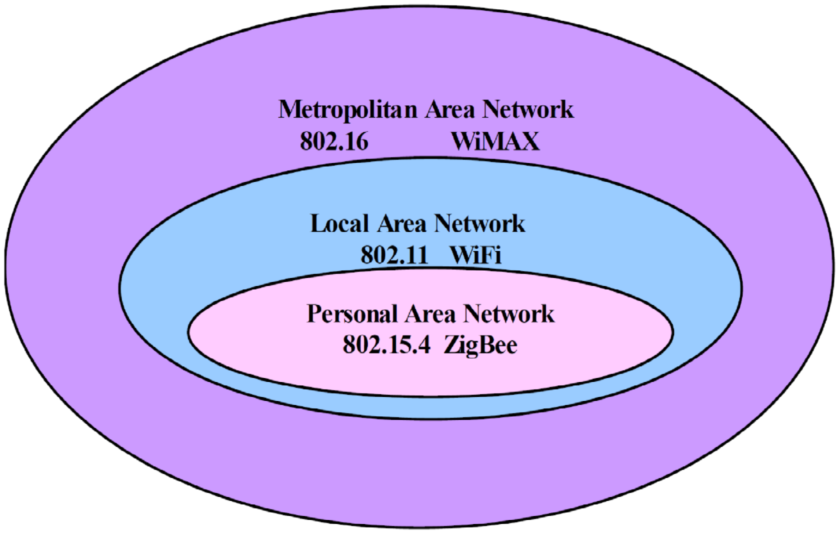


Figure 1.6 Types of wireless data network [11]

ZigBee is a Wireless Personal Area Networks (WPAN) technology based on IEEE 802.15.4 standard that is simpler and cheaper than other WPANs such as Bluetooth. It is able to provide low data rate wireless communications with high-precision ranging and localization by employing UWB technologies for a low-power and low cost solution. WiFi is a Wireless Local Area Network (WLAN) technology based on IEEE 802.11 standard, which consists of 802.11a, 802.11b, 802.11g and the newest standard, 802.11n that promises both higher data rates and increased reliability. Meanwhile the technology of Wireless Metropolitan Area Network (WMAN) based on IEEE 802.16 standards is known as WiMAX. WiMAX allows higher data rates over longer distances, efficient use of bandwidth, and it avoids

Tabel 1.3: Comparison of the broadband wireless technologies

Technology	ZigBee	WiFi	WiMax	3G	4G
Standard	IEEE 802.15.4	IEEE 802.11 a/b/g/n	IEEE 802.16 a/d/e	WCDMA/ CDMA2000/ EDVO/LTE	Single Unified Standard
RF Band	2.4 GHz	5/2.4/2.4/ 2.4 &5GHz	10-66/2-11 2-6 GHz	0.9, 1.8, 1.9 & 2.1 GHz	2-8 GHz
Data Rate	250 Kbps	54/11/54/ 600 Mbps	75 Mbps	2 Mbps	200 Mbps
Coverage	70 – 100 m	100 m	50 km	6 miles	30 miles

1.1.2.3 Video Distribution Services

RoF systems have been used for video (TV) broadcast employing cellular terrestrial transmission system known as Multipoint Video Distribution Services (MVDS). Recently, the services have been equipped by the service interactive using a return channel. While operating in 40 GHz, the maximun cell size of MVDS is about 5 km which can serve a small town. RoF systems can be used to increase the coverage and simplify remote transmitters that are usually located on a mast or a tall building [14]. Moreover, wireles cable TV (CATV) can be implemented using an RoF system that can provide seamless services between indoor and outdoor environments [15].

1.1.2.4 Intelligent Transport Systems

Another potential application of RoF is Intelligent Transport Systems (ITS) that provide continuous mobile communications on major roads. It intends to provide traffic informations, improve transportation efficiency, reduce burden on drivers, and contribute to the improvement of the environment [16]. Various ITS services such as electronic toll collection (ETC) system, vehicle information and communication system (VICS), TV and radio broadcasting system, and mobile phone system can be integrated using RoF technology. It is able to enlarge the coverage by increasing the number of BSs while simplifying the BSs and reducing its cost.

1.1.3 Performance Limitation of RoF

RoF technology that is known as the intensity modulation and direct-detection (IMDD) is fundamentally an analogue transmission system. Therefore, signal impairments such as noise and distortion are important in this system and they tend to limit the Noise Figure (NF) and Spurious Free Dynamic Range (SFDR) of the system. SFDR is the figure of merit that summarize the overall performance for mobile communication and wireless broadband network. The SFDR that is required in a radio over fiber system is influenced by the radio environment such as wireless standard specification and coverage range as well as the specific signal transport approach, and it can vary from 95 to 115 dB-Hz [17].

In RoF systems, the SFDR is mainly limited by the performance of the optical transmitter that is characterized by the application bandwidth, distortion and noise. Distortions can be caused by many factors. Static distortion occurs when the nonlinearities of the light-versus current (LI) are present. These nonlinearities are caused by spatial hole burning, gain compression, finite carrier transport times, and leakage currents. Dynamic distortion occurs when the nonlinearities of the devices cause different frequency components to mix together through the interaction of photons, electrons in the laser cavity. As a result of these nonlinearities in the device, it is possible for multiple frequencies from separate channels to interfere and mix with each other to produce new frequency components.

The application bandwidth determines the type of distortion that will affect the system. A narrow band system will be primarily affected by IMD3. The key figure of merit for such narrow band application is the spurious free dynamic range (SFDR), which is the range of inputs over which the output signal is unaffected by either noise or distortion. In contrast, a broadband system can be affected by IMD3 as well as second order harmonic and other intermodulation distortion products. The key figures of merit for broadband systems are the composite second order distortion and the composite triple beat (CTB) distortion.

The performance of the optical transmitter is also limited by the noise in the laser device, which is characterized by the relative intensity noise (RIN) and the linewidth. Both types of noise are related to the random carrier and photon fluctuations within the laser cavity. The linewidth is related to the phase noise and the RIN is related to the amplitude noise due to these random fluctuations.

1.2 Motivation

RoF system is potential to many important applications as highlighted above such as mobile communication system, wireless broadband communication system, video distribution system and ITS with many benefits such as cost effective, managable as well as low-loss, wide-bandwidth, EMI immunity, etc. However, the performance of an RoF system is limited by the nonlinearity of the optical transmitter. In multichannel systems, high linearity is required to avoid channel interference due to the nonlinear distortion.

For example, if two modulation frequencies, ω_1 and ω_2, are transmitted within a channel, the second order distortions are $2\omega_1$, $2\omega_2$, $\omega_2 \pm \omega_1$ while the third order distortions are $3\omega_1$, $3\omega_2$, $2\omega_1 \pm \omega_2$, and $2\omega_2 \pm \omega_1$ as shown in Figure 1.7. If the transmission channel is carefully chosen, harmonic distortions ($2\omega_1$, $2\omega_2$, $3\omega_1$, $3\omega_2$, . . .) are of little concern since they generally do not fall within the channel. However, the third order intermodulation (IMD3) products at $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$ usually lie within the channel and they must be carefully considered [18].

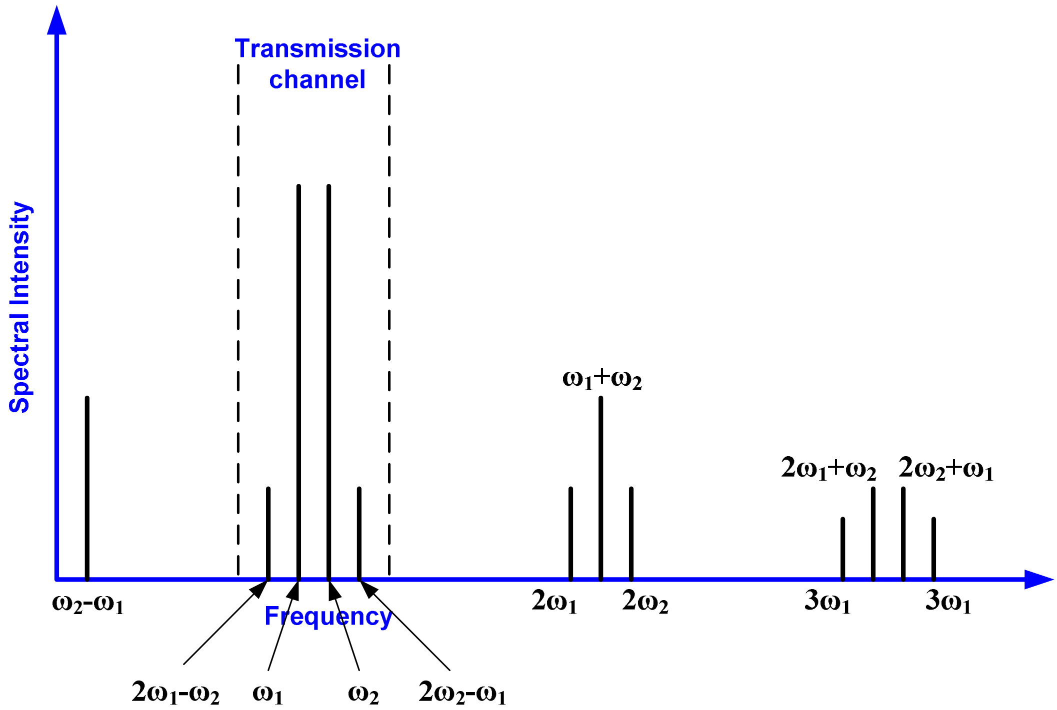


Figure 1.7 RF spectrum of nonlinear distortion

1.3 Problem Statement

The nonlinearity of the laser transmitter is a significant cause of performance degradation in multichannel RoF systems, while the application has stringent constraint on the system linearity. Many efforts have been done to improve the linerity using various linearisation techniques, however it still has the remaining problems. Predistortion technique might be a simpler approach but it has some restrictions since it exhibits device dependency and difficulty to suppress all order of distortions simultaneously [19-20]. In order to overcome the device dependency, feedback technique has been proposed by some researchers. Besides being a promising approach due to its cost effectiveness and simplicity, this technique is device-independent that can operate smoothly regardless of various device parameters. However, the feedback technique exhibits a limited operating bandwidth due to potential instability of the feedback loop at high frequency [21]. Likewise, the dual parallel modulation technique also suffers from narrow bandwidth

[22]. Feed-forward linearisation technique offers a number of advantages compared to other techniques such as broadband distortion reduction at high frequency and reduction in all orders of distortion simultaneously [23,24]. However, in the feed-forward system, amplitude and phase matching are relatively complicated and sensitive, but critical for the optimum distortion reduction. Therefore the improved design of feed-forward linearisation for the optical transmitter is proposed to reduce its complexity and sensitivity without decreasing the performances.

1.4 Research Objectives

This research has several objectives based on the problems that were stated in the previous section. The main objectives are as follows:

(i) To determine the ability of an existing feed-forward linearisation technique for reducing the nonlinear distortion of an RoF optical transmitter system using Volterra series approach.

(ii) To design an improved optical feed-forward transmitter system with less sensitive parameters that may deteriorate the system performances

(iii) To verify the performance of the proposed feed-forward linearisation technique by the computer simulation and experimental results.

1.5 Project Scope

The research project focuses on the study of the feed-forward linearisation technique to reduce the nonlinear distortion of optical transmitters in RoF systems; which focuses on the design, analysis and practical measurement of the proposed system. Due to the limitation of the research equipment and facility, this project will focus on a certain properties of the system.

1. The research is considering utilization of a directly modulated semiconductor laser (DML) to transmit the optical signal through the single mode fiber

(SMF) in the RoF system. DML is simpler to implement and less expensive than the external modulation, therefore attractive for many applications.

2. Performance analysis is carried out to calculate harmonic distortion (HD) and intermodulation distortion (IMD) reduction employing Volterra Series analysis as well as the effects of amplitude and phase matching in its loop on the achievement of nonlinear distortion reduction.
3. Software simulation is carried out to validate the calculation of HD and IMD reduction using Optical System Design Software Optisystem 10.
4. Practical measurement is carried out to revalidate the calculation of HD and IMD reduction at 2.4 GHz operating frequency.

1.6 Research Methodology

This section will cover all the issues of the approach considerations towards this project as shown in Figure 1.8.

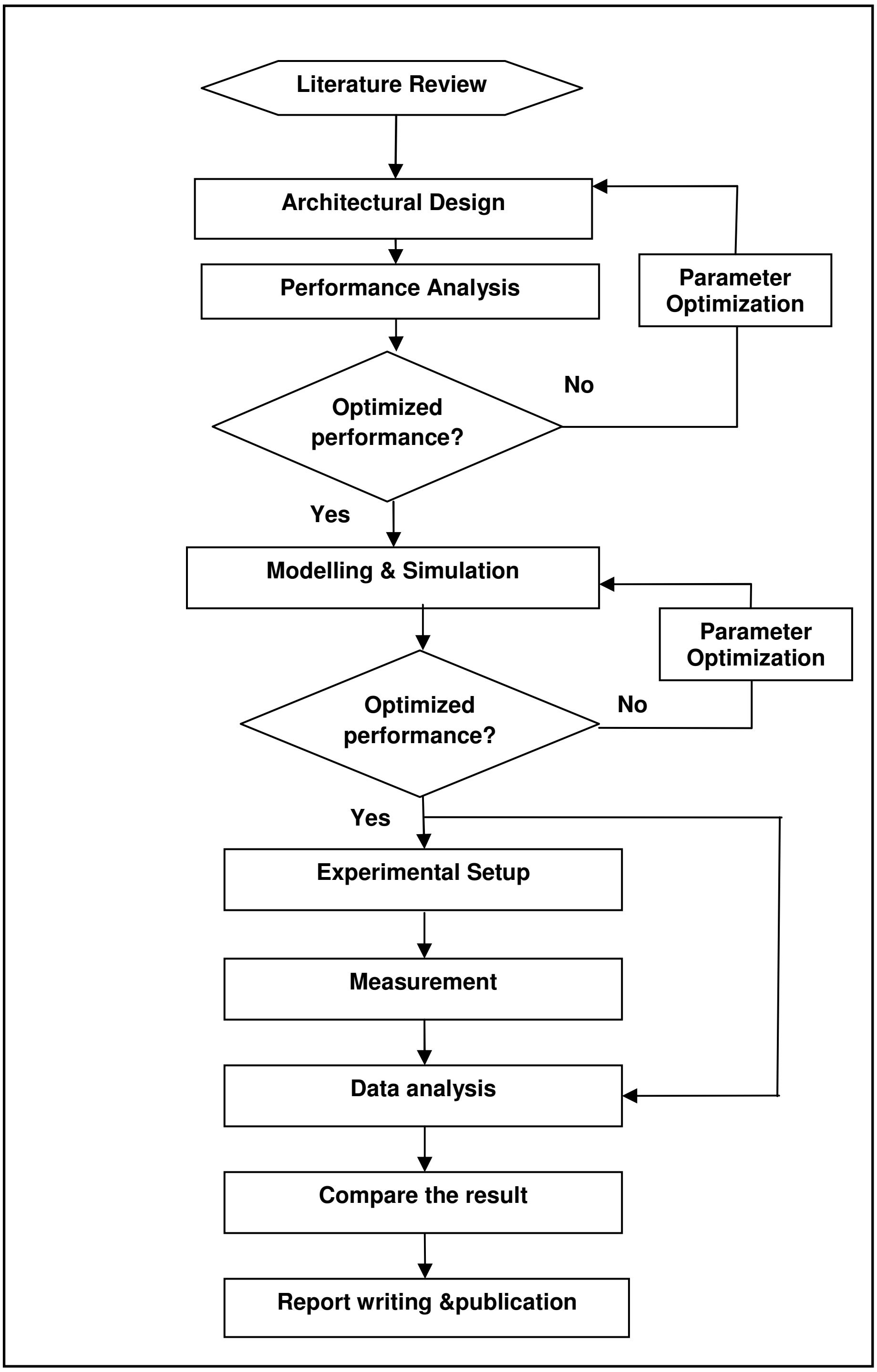


Figure 1.8 Flowchart of the research methodology

1.6.1 Literature Review

In this phase, investigation on the current research and technology of the linearisation technique in the optical domain are undertaken. The advantages and disadvantages of the overall techniques are investigated thoroughly. The research progress on the feed-forward linearisation technique will be resumed. The laser transmitter has to be studied thoroughly as well as the Volterra Series to model the laser nonlinearity.

1.6.2 Architectural Design

Investigation on the architecture of the optical feed-forward transmitter must be done as well as the operation of the system. Some issues such as the effect of loop imbalance, choosing of the optical-coupling ratio and dispersion penalty are important to be considered on the design since a perfect distortion cancellation is not possible.

1.6.3 Performance Analysis

Furthermore, performance analysis of the proposed design are investigated by modelling the system employing Volterra series approach. While the optimized performance is achieved, the next phase is continued. The architectural design are repeated as long as the expected performance is not achieved.

1.6.4 Modelling and Simulation

In this phase, modelling and simulations using industrial design and simulation suit Optisystem 10.0 from Optiwave System Inc. is carried out. The modelling and simulation are meant to provide the design guidelines and component selections of the feed-forward optical transmitter before the practical measurement. The semiconductor laser is modelled using the laser rate equation. While the optimized performance is achieved, the next phase is continued. The modelling and component selection are repeated as long as the expected performance is not achieved.

1.6.5 Experimental Setup

The optimum configuration from the simulation will be selected and realized through experimental setup. The prototype is developed based on the optimum specification, then the appropriate components are selected. After that, the laboratory testing is carried out.

1.6.6 Measurement and Analysis

In this phase the realized system is measured and performance characterisation is done. This is the crucial part where all the results from both the simulation and system implementation are analyzed thoroughly. It is important to compare both results and an optimum design is determined. If necessary, any problems and limitations on the design are solved and further implications, suggestions and any recommendations are illuminated. Modifications are done on the design until an optimum performance is obtained.

1.7 Thesis Outline

This thesis begins with Chapter 1 where the significance of radio over fiber technology in the future wireless communication systems, overview, benefits and limitation of the radio over fiber technology are described. The overview and performance limitation of semiconductor lasers are also presented. Then, the motivation and goals for the research are presented.

Following the introductory chapter, the previous research works related to this area are presented in Chapter 2. Several linearisation techniques in the optical domain are discussed as well as the state of the art of these techniques. The qualitative and quantitative comparisons between these techniques are also presented. Finally the advantages and disadvantages of these techniques are analyzed.

In Chapter 3, the design and mathematical analysis of the OFT system are presented. Initially, investigation on a performance criteria of the RoF system and the optical transmitter is discussed. Investigation on the semiconductor laser using the Volterra series approach is then presented to be adopted in a mathematical analysis of the previous OFT system. Furthermore, the design methodology is discussed to describe the logical flow of the system design process. The architecural design of the OFT system is presented. The most fitting architecture as well as the system operation are demonstrated. Next, component selection is discussed. Volterra series representation is adopted to model the proposed design. This model is implemented in MATLAB to simulate the system performance. System characterisation is done to determine the optimum parameter. Finally, some design considerations such as the effect of loop imbalance, choosing of the optical-coupling ratio and dispersion penalty are also discussed based on the mathematical analysis.

In Chapter 4, the simulations of the proposed OFT system using the industrial design and simulation suit of 10.0 version Optisystem from Optiwave Design Group are presented. The schematic setups for simulation of the OFT system and nonlinearised system are described. The component parameters used in this simulation are also defined. Furthermore the system characterisation is carried out to predict the system performance. Before that, the amplitude and phase matching are carried out to optimize the system performance. The effect of loop imbalance to the system performance is also investigated. After the optimization, one- tone modulation is applied to predict the gain and harmonic distortion of the system. Moreover, two-tone modulation is applied to predict the IMD reduction.

Chapter 5 discusses the experimental setup of the proposed system to validate the previous results in chapter 3 and 4. The schematic setup for measurement is firstly presented. The components used in this measurement are also described. The measurement procedures and the related results are then presented. Finally the results are analyzed according to the previous results.

Finally in Chapter 6, concluding remarks, achievements and suggestions for future works are discussed. The modelling technique obtained through this research can be applied for the future development of optical feed-forward transmitter design.

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