DEVELOPMENT OF OFDM IN WDM-RADIO OVER FIBER ACCESS NETWORK

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ABSTRACT

Radio over Fiber (RoF) is one of the latest technologies in optical communication systems that provide effective convergence of optical and wireless access network system. RoF is a technology whereby light is modulated by a radio signal and transmitted over an optical fiber link to facilities wireless access. Wavelength-Division Multiplexing (WDM) is a multiplexing technique for fiber optic system to multiplex a number of optical carrier signals onto a single-mode fiber optic (SMF) by using difference wavelengths of laser light to carrier different signals which promising solutions to the ever increasing demand for bandwidth. Orthogonal Frequency Division Multiplexing (OFDM) technique distributes the data over a large number of carriers that are spaced apart at precise frequencies with overlapping bands. The use of FFT for modulation provides orthogonality to the sub- carriers, which prevents the demodulators from seeing frequencies other than their own. Hence by incorporating OFDM along with the optical fiber, the RoF system with WDM can be used for both short distance as well as long-haul transmission at very high data rate. This improves the system flexibility and provides a very large coverage area without increasing the cost and complexity of the system very much. This project investigates the feasibility of OFDM as a modulation technique to transmit the basebands signal over SMF. RF-to-optical up-conversion and optical-to-RF down-conversion have been modeled and used as optical modulator and optical demodulator respectively. Result from Optisystem model shows the performance of OFDM signal through the WDM RoF access network. The system was utilized to carry data rates 10Gbps, the modulation type for OFDM is 4 QAM 2 bit per symbol for each channel and OFDM demodulator are employed together with coherent detection at receiver part to receive the OFDM signals over a SMF network transmission. The signal power is decreasing while the length of optical fiber was increasing for channel 1 does not apply to other channels.

ABSTRAK

Radio over Fiber (RoF) merupakan satu teknologi terkini dalam sistem komunikasi optik yang tertumpu kepada keberkesanan sistem gentian optik dan sistem rangkaian tanpa wayar. RoF adalah satu teknologi yang menggunakan cahaya untuk memudulatkan isyarat radio dan kemudiannya dihantar melalui rangkaian gentian optik untuk kemudahan capaian tanpa wayar. Wavelength-Division Multiplexing (WDM) adalah teknik pemultipleksan dalam sistem gentian optik untuk memultipleks beberapa isyarat pembawa optik melalui gentian optik mod tuggal (SMF) dengan cahaya laser yang pelbagai panjang gelombang untuk membawa pelbagai isyarat bagi memenuhi permintaan lebar jalur yang semakin meningkat. Orthogonal Frequency Division Multiplexing (OFDM) adalah satu teknik yang menyalurkan data dengan banyak pembawa yang dijarakkan secara bertindihan di antara jalur. Penggunaan FFT pada modulasi memberikan keortogonan untuk setiap pembawa bagi mengelakkan penyahmodulat menerima frekuensi yang bukan dimiliknya. Oleh itu, dengan menggabungkan OFDM dan gentian optik, sistem RoF bersama WDM dapat digunakan untuk penghantaran data yang berkadaran tinggi secara jarak pendek dan jarak jauh. Ini meningkatkan fleksibiliti sistem dan menyediakan kawasan yang sangat luas tanpa meningkatkan kos serta kerumitan sistem. Projek ini mengkaji kebolehlaksanaan OFDM sebagai satu teknik modulasi untuk menghantar isyarat jalur asas melalui SMF. Penukaran bentuk RF ke bentuk optik dan juga sebaliknya telah dimodelkan serta digunakan sebagai pemodulat optik dan penyahmodulat optik. Keputusan dari model Optisystem menunjukkan prestasi isyarat OFDM melalui rangkaian WDM RoF. Sistem tersebut digunakan untuk membawa data berkadaran 10Gbps, dan pemodulatan OFDM 4 QAM 2 bit per simbol bagi setiap saluran serta penyahmodulat OFDM berserta dengan pengesanan koheren di bahagian penerima untuk menerima isyarat OFDM melalui rangkaian gentian optik. Kuasa isyarat telah berkurangan manakala panjang gentian optik telah meningkat untuk saluran 1 dan keadaan ini tidak berlaku untuk saluran yang lain.

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λ	-	Wavelength
ADC	-	Analog to digital converter
ASK	-	Amplitude shift keying
BER	-	Bit Error Rate
BPSK	-	binary phase shift keying
BS	-	Base Station
CATV	-	Cable Television
CBS	-	Central base station
CO	-	Central Office
COFDM	-	Coded OFDM
CO-OFDM	-	Coherent Optical - Orthogonal Frequency Division Multiplexing
CW laser diode	-	Continuous wave laser diode
DAC	-	Digital to analog converter
DFA	-	Doped fiber amplifier
DPSK	-	Differential phase-shift keying
DWDM	-	Dense Wavelength Division Multiplexing
E/O	-	Electrical to optical
EDFA	-	Erbium Doped Fiber Amplifier
FDM	-	Frequency Division Multiplexing

FFT	-	Fast Fourier Transform
FM	-	Frequency modulation
I/Q	-	I - in phase; Q - quadrature (90 degree phase shift)
ICI	-	Inter-carrier Interference
IF	-	Intermediate Frequency
IFFT	-	Inverse Fast Fourier Transform
ISI	-	Inter-symbol Interference
LAN	-	Local Area Network
LiNbO3	-	Lithium noibate
MCM	-	Multicarrier Modulation Method
MSC	-	Mobile Switching Centre
MZM	-	Mach–Zehnder modulator
NRZ	-	Non return-to-zero
O/E	-	Optical to electrical
OFDM	-	Orthogonal Frequency Division Multiplexing
OOK	-	On-off keying
OTDM	-	Optical Time Division Multiplexing
OTR	-	Optical-to-RF down-conversion
PBRS	-	Pseudo-random bit sequence
PM	-	Frequency modulation
PON	-	Passive optical network
PSK	-	Phase-shift keying
QAM	-	Quadrature amplitude modulation
QPSK	-	Quadrature Phase-Shift Keying
RAP	-	Radio access point

RAU	-	Remote access unit
RF	-	Radio Frequency
RoF	-	Radio over Fiber
RS	-	Remote Site
RTO	-	RF-to-optical up-conversion
RZ	-	Return-to-zero
SC	-	Switching Centre
SMF	-	Single-Mode Fiber
WDM	-	Wavelength-Division Multiplexing
WLAN	-	Wireless Local Area Network

CHAPTER 1

INTRODUCTION

1.1 Project Background

Many studies had been conducted in relation to Orthogonal Frequency Division Multiplexing (OFDM), Radio over Fiber (RoF) and Wavelength-Division Multiplexing (WDM) networking to transform something that can improves the efficiency on high speed and low cost accessing networks. All the researchers need to face great challenges on designing a quality access networks that can meet the above criteria for the needs of consumers in terms of speed and efficiency data transmission. Therefore, the understanding of each component in the access network such as OFDM, WDM and RoF are in urgent great demand.

OFDM is a method of encoding digital data transmission on various carrier frequencies [1] [2]. For instance, in the mobile communication systems, OFDM technique works on splitting a radio spectrum into several sub-channels at the base station. In conjunction, the signal strength at the sub-channel and the channel number assigned to the different devices can be changed as required. Nowadays, OFDM is very popular for Wideband digital communication, both wire and wireless. In a broad context, it is used in applications such as digital television and audio broadcasting, DSL broadband Internet access, wireless networks, and 4G mobile communications.

In addition, the Wavelength-Division Multiplexing (WDM) is a multiplexing technique for fiber optic system to multiplex a number of optical carrier signals onto a single optical fiber by using different wavelengths (i.e. colours) of laser light to carry different signals. This technique allows a multiplication in capacity and it is possible to perform bidirectional communications over one strand of fiber optic.

Radio over Fiber (RoF) refers to a technology whereby light is modulated by a radio signal and transmitted over an optical fiber link to facilitate wireless access. Although radio transmission over fiber serves as multiple purposes in cable television (CATV) networks and satellite base stations, the term RoF is usually applied where there is wireless access.

RoF has made cost-effective, high-data-rate mobile wireless broadband networks, an inherent immunity to electromagnetic interference and reduction on power consumption. Moreover, it provides a huge bandwidth which is convenience for installation and maintenance at ease operational flexibility. [3 - 7]

Apart from that, this system is designed for the compatibility to the wave-multiplexing (WDM) and the wave-division-multiplexing passive optical networks (WDM-PON). It also works well on flexibility to both wired and wireless users at the same time for using the same optical infrastructure which is distributed to its customers. [7 - 10]

The Orthogonal frequency division multiplexing (OFDM) is a promising technology which has a very high spectrum efficiency and robust dispersion tolerance. It is specially designed to improve the system capability and transmission distance over fiber and air links. Recently, several OFDM based access systems have been proposed, such as OFDM modulated WDM-PON, OFDM based metro access and OFDM-ROF wireless system. Nonetheless, the convergence system of OFDM in WDM-Radio Over Fiber access networks has never been analyzed, which can improve the spectral efficiency of the wireless access system, also support the seamless integration between air and optical transmission. Additionally, the re-modulation technology reduces the cost and complexity in base station (BS), while an integrate modulator can be used to generate the RoF and PON signal simultaneously in central station (CS). [6] [8 – 9] [11 – 13]

According to the previously mentioned studies, many researches and works were done in the field of using multicarrier transmission technique especially OFDM for transmitting and receiving data through optical link in Radio over Fiber Networks. Meanwhile this project work is based on modeling and analyzing the performance of the OFDM scheme for Radio over Fiber system to utilized applications based on WLAN IEEE 802.11 b/g standard (2.4 GHz). This project model was simulated using commercial software, Optisystem 10.0.

1.2 Problem Statement

The demand of the broadband services today has driven research on millimeter (mm) - wave frequency band communications for wireless access network in terms of speed, efficiency, spectrum availability and compact size of radio frequency devices. Nevertheless, the mm-wave signal has suffered many losses in the transmission as well as atmospheric attenuation. One of the solution to overcome these problems is the use of low-attenuation, electromagnetic interference- free optical fiber. Apparently, Radio over Fiber (RoF) is considered to be cost effective, practical and relatively flexible system configuration for long-haul transport of millimetric frequency band wireless signals using multicarrier modulation - Orthogonal Frequency-Division Multiplexing (OFDM). In order to maximize the bandwidth usage and prevention on cross-talk in a single fiber optic, the Wavelength-Division Multiplexing (WDM) is positioned to the access networks.

1.3 Project Objectives

The first objective of this project is to investigate OFDM in WDM Radio over Fiber Access network. The second objective is to model and simulate the OFDM scheme for RoF using commercial software, Optisystem 10.0 from Optiwave. The third objective is to analyze the feasibility performance of OFDM in WDM Radio over Fiber Access network in terms of Bit Error Rate (BER) and the effect of fiber length to signal power from OFDM signals at the receiver part.

1.4 Scope of Project

The scopes of this project are:

1. Understanding the basic principle of OFDM modulation technique, WDM and RoF through literature study.
2. Modeling and simulation of OFDM signals through RoF network using commercial software, Optisystem 10.0 from Optiwave.
3. Perform analysis of the design system in terms of Bit Error Rate (BER) and the effect of fiber length to signal power from OFDM signals at the receiver part.

1.5 Methodology

The methodology of this project is described in the following flow chart in Figure 1.1.

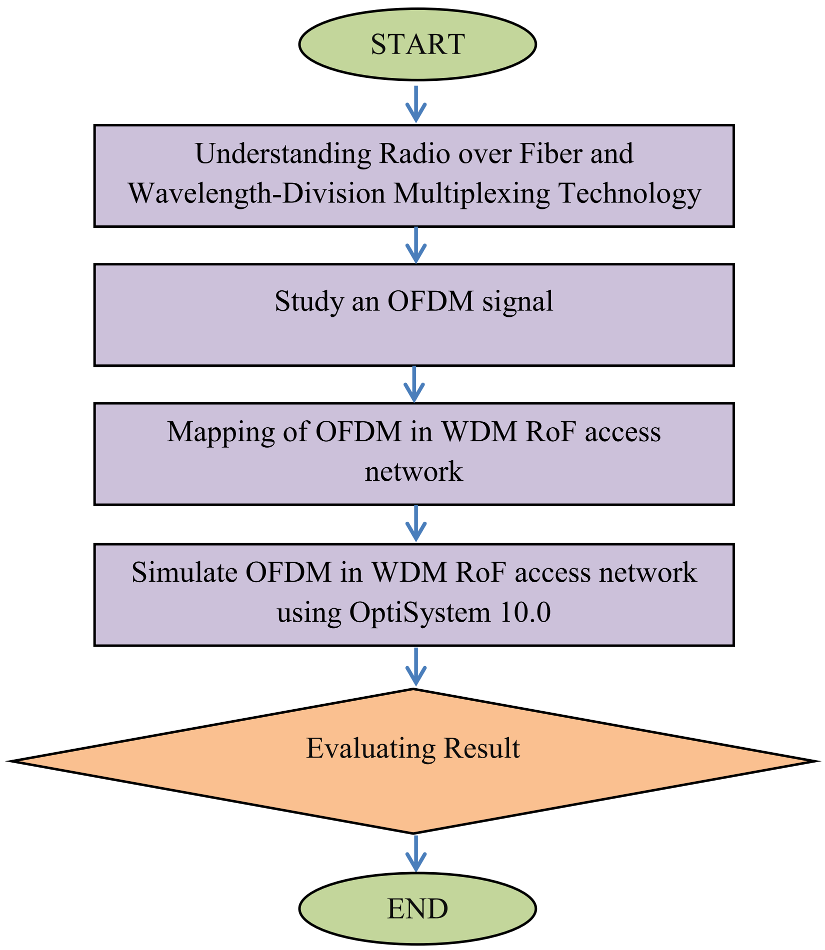


Figure 1.1: Project Flow Chart

The first step is to perform literature study, review and understands the current development of RoF system and OFDM modulation technique. The next step is to identify and understood the modeling design of OFDM modulation technique for RoF system. The main aim of this project is to analyze the basic concept of RoF system, OFDM modulation technique and incorporating OFDM along with WDM RoF access network. Then, the system will be designed and modeled to represent the connection from transmitter to receiver. The chosen simulation software will be identified and applied to the system such as Optisystem 10.0 from Optiwave which is a commercial software.

The following step is to analyze the result and system performance of the simulation model. While analyzing the results, the proposed system is being optimized to obtain a better performance and best simulation results. This is done by referring to theoretical and numerical analysis of OFDM and WDM to verify the proposed system.

Finally the simulation result produce is to compare with the previous works and theoretical analysis.

1.6 Thesis Outline

This thesis comprises of six chapters and is organize as follows:

Chapter 1 is the introductory part of this project which consists of project background, problem statement, and objective, scope of work, followed by methodology and thesis outline.

Chapter 2 presents the literature review of this project which is explaining some basic theory of Radio over Fiber, the benefits and architecture of RoF. This chapter also explains the optical transmission link and the applications of RoF technology.

Chapter 3 presents the theoretical work of Orthogonal Frequency Division Multiplexing (OFDM). This chapter consists of introduction, general principles and coded OFDM, Coherent Optical OFDM (CO-OFDM and also discusses the advantages and disadvantages of OFDM.

Chapter 4 discusses the methodology of this project in terms of integrating the OFDM in WDM RoF technique, Optisytem 10.0 software is used to model and implement the system. In this chapter the proposed OFDM with 4 QAM modulation systems for WDM radio over fiber access network are presented.

Chapter 5 discusses the simulation result and analysis of the proposed OFDM in WDM RoF system. The performance of the system in term of BER and the power signal at the receiver part are explained in this chapter.

Chapter 6 provides the conclusion for the whole project and also provides the recommendation of future works for developing and modifications of the system presented in this project.

CHAPTER 2

RADIO OVER FIBER

2.1 Introduction

Nowadays, due to the various demands of system users, data capacity for wireless communication has been radically expanded from voices and simple messages to multimedia with evolutionary future services. Radio over Fiber (RoF) systems could be the answer to many urgent needs of the telecommunication networks, as they could provide the necessary bandwidth for the transmission of broadband data to end-users, other benefits are low attenuation loss, and immunity to radio frequency interference [14 - 17]. In a RoF system, most of the signal processing processes (including coding, Multiplexing, and RF generation and modulation) are carried out by the Central Office (CO), which makes the Base Station (BS) cost-effective. Therefore, RoF will become a key technology in the next generation of mobile communication system [19 - 24].

RoF means that a fiber optic link where the optical signal is modulated at radio frequencies (RF) and transmitted via the optical fiber to the receiving end. When reaching the receiving end, the RF signal is demodulated and transmitted to the corresponding wireless user. RF modulation is in most cases digital, in any usual form, for example PSK, QAM, TCM, etc.

This modulation can be done directly with the RF signal or at an intermediate frequency (IF). RoF technique has the potentiality for the backbone of the wireless access network. Such architecture can give several advantages, such as reduced complexity at the antenna site, radio carriers can be allocated dynamically to different antenna sites, Transparency and scalability [28].

RoF technology is now ubiquitous in the telecommunications infrastructure. Fiber optics and WDM technology have increased significantly in the transmission capacity of today's transport networks. Therefore they are playing an important role in supporting the rapidly increasing data traffic.

2.2 Radio over Fiber

RoF technology is a technology by which microwave (electrical) signals are distributed by means of optical components and techniques. A RoF system includes a Central Site (CS) and a Remote Site (RS) connected to an optical fiber link or network. The signal between CS and BS is transmitted in the optical band via RoF network. This architecture makes the design of BSs quite simple. In the simplest case, the BS include mainly from optical-to-electrical (O/E) and electrical-to-optical (E/O) converters, an antenna and some microwave circuitry (two amplifiers and a diplexer). In the event of an application area is in a GSM network, and then CS could be the Mobile Switching Centre (MSC) and RS the base station (BS). As for narrowband communication systems and wireless Local Area Networks (WLANs), the CS would be the head-end while the Radio Access Point (RAP) would act as the RS. RoF systems span a wide range (usually in the GHz region) and depend on the nature of the applications to distribute the frequencies of the radio signals.

Besides transportation and mobility functions, RoF systems are also designed to perform added radio-system functionalities. These functions include data modulation, signal processing, and frequency conversion (up and down) [26] [27]. As shown in Figure 2.1, RoF systems were primarily used to transport microwave signals and to achieve mobility functions in the CS.

The centralization of RF signal processing functions have many benefits such as enables equipment sharing, dynamic allocation of resources, and simplifies system operation and maintenance. These advantages could be translated into major system installation and operational savings, particularly in wide-coverage broadband wireless communication systems, where a high density is necessary. Figure 2.2 shows the concept of RoF system.

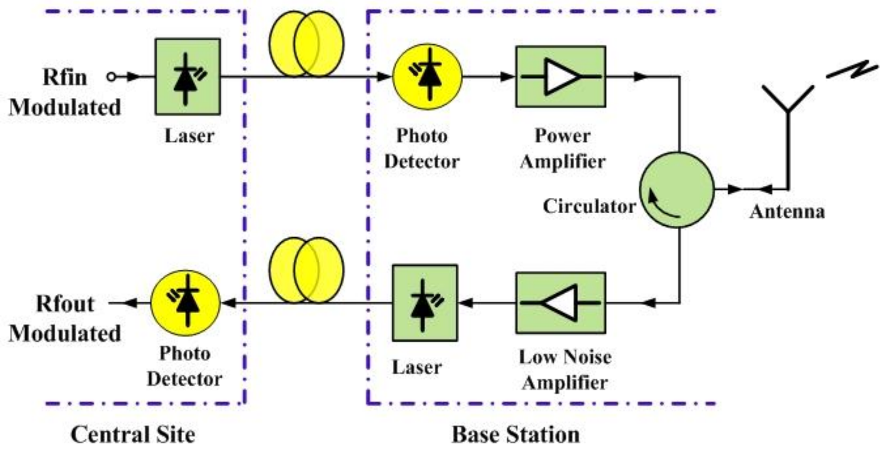


Figure 2.1: A 900MHz Radio over Fiber System [14][30]

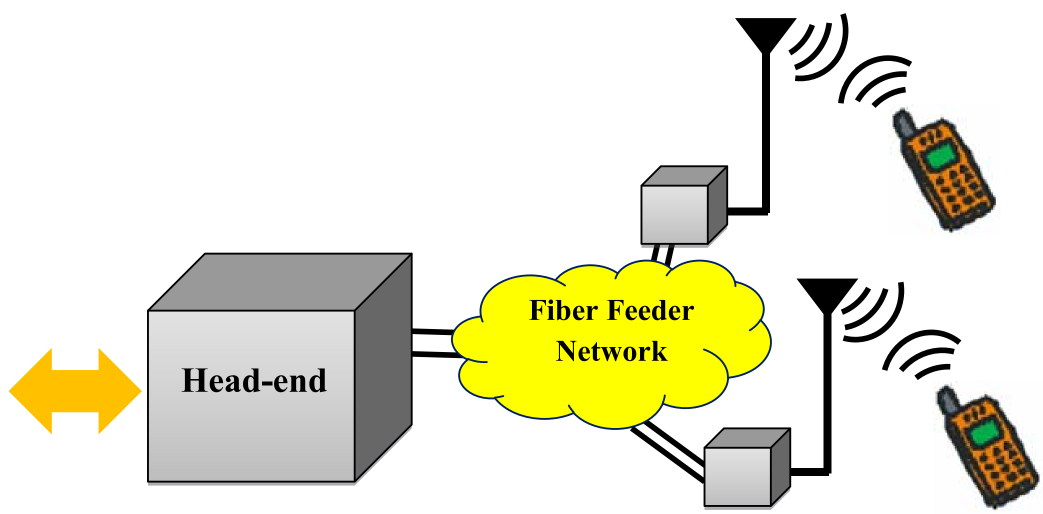


Figure 2.2: The Radio over Fiber System Concept [19]

2.3 Benefits of RoF Technology

Ability to concentrate most of the expensive, high frequency equipment at a centralized location is the main advantage of RoF systems, thereby making it possible to use simpler remote sites. In addition, RoF technology enables the centralizing of mobility functions such as macro-diversity for seamless handover. There are many benefits of having simple remote sites. Some of these advantages will be given and briefly discussed in the following sections.

2.3.1 Low Attenuation Loss

Electrical distribution of high frequency microwave signals either in free space or through transmission lines is problematic and costly. In free space, losses cause absorption and reflection that increase with frequency, whereas in transmission lines, the rise of impedance with frequency leads to very high losses. For this reason, distributing high frequency radio signals electrically over long distances requires expensive regenerating equipment, as for mm-waves, their distribution via the use of transmission lines is not feasible even for short distances.

The alternative solution to this problem is to distribute baseband signals or low intermediate frequencies (IF) from the Switching Centre (SC) to the Base Stations (BS) [14]. The baseband or IF signals are then up converted to the required microwave or mm-wave frequency at each base station, amplified and then radiated. This system configuration is the same with the one used in the distribution of narrowband mobile communication systems. As for optical fiber which offers very low loss, RoF technology can be used to achieve both low-loss distributions of mm-waves, as well as simplification of RAUs at the same time.

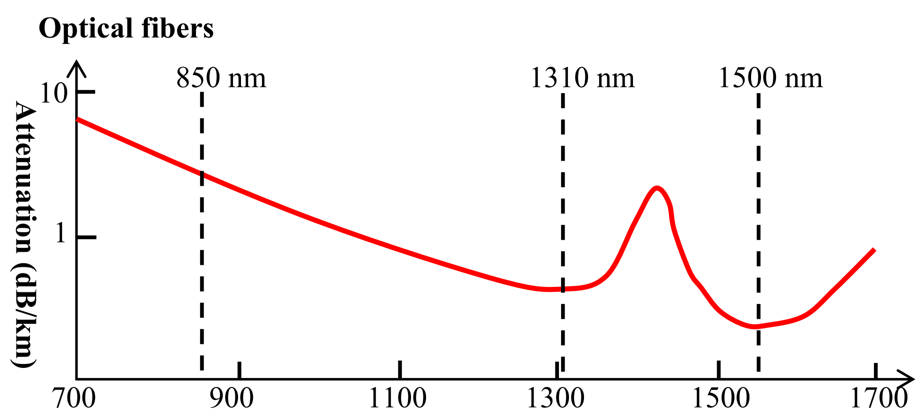


Figure 2.3: Operating regions of optical fiber [2]

Commercially available standard Single Mode Fibers (SMFs) made from glass (silica) have attenuation losses below 0.2 dB/km and 0.5 dB/km in the 1.5 µm and the 1.3 µm windows, respectively as shown in Figure 2.3 [29]. A more recent kind of optical fibers which is Polymer Optical Fibers (POFs) exhibit higher attenuation ranging from 10 – 40 dB/km in the 500 - 1300 nm regions. These losses are much lower than those encountered in free space propagation and copper wire transmission of high frequency microwaves. For this reason, by transmitting microwaves in the optical form, transmission distances are increased several folds and the required transmission powers reduced greatly.

2.3.2 Large Bandwidth

Enormous bandwidth is offer by Optical fibers. There are three main transmission windows, which offer low attenuation, namely the 850 nm, 1310nm and 1550nm wavelengths respectively [29] as shown in Figure 2.3. For a single SMF optical fiber, the combined bandwidth of the three windows is in the excess of 50THz, but commercial systems utilize only a fraction of this capacity (1.6 THz) [30]. Yet, developments to exploit more optical capacity per single fiber are still continuing. The main driving factors towards unlocking more and more bandwidth out of the optical fiber consist of the availability of low dispersion (or dispersion shifted) fiber, the Erbium Doped Fiber Amplifier (EDFA) for the 1550 nm window, and the use of advanced multiplex techniques namely Optical Time Division Multiplexing (OTDM) in combination with Dense Wavelength Division Multiplex (DWDM) techniques.

Besides the high capacity for transmitting microwave signals, the enormous bandwidth offered by optical fibers has other benefits. The high optical bandwidth enables high speed signal processing that may be more difficult or impossible to do in electronic systems. That means some of the demanding microwave functions such as filtering, mixing, up- and down-conversion, can be implemented in the optical domain. For instance, mm-wave filtering can be achieved by first converting the electrical signal to be filtered into an optical signal, then performing the filtering by using optical components such as the Mach Zehnder Interferometer MZI or Bragg gratings), and then converting the filtered signal back into an electrical signal [31]. Moreover, signal processing in the optical domain makes it possible to use cheaper low bandwidth optical components such as laser diodes and modulators. But, it is still capable to handle high bandwidth signals.

The utilization of the enormous bandwidth offered by optical fibers is severely hampered by the limitation in bandwidth of electronic systems, which are the primary sources and end users of transmission data. This problem is referred to as the “electronic bottleneck” [32].

The solution around the electronic bottleneck lies in effective multiplexing Optical Time Division Multiplexing OTDM and DWDM techniques mentioned above are used in digital optical systems. In analogue optical systems, consist of RoF technology is used to increase optical fiber bandwidth utilization.

2.3.3 Immunity to Radio Frequency Interference

Immunity to Electro Magnetic Interference (EMI) is a very attractive property of RoF technology, particularly for microwave transmission. This is because signals are transmitted in the form of light through the fiber. Therefore, fiber cables are preferred even for short connections at mm-waves. EMI immunity is the immunity to eavesdropping, which is an important characteristic of optical fiber communications because it provides privacy and security.

2.3.4 Easy Installation and Maintenance

In RoF systems, complex and expensive equipment is kept at the Switching Centre (SCs), thereby making remote base stations simpler. For example, most RoF techniques eliminate the need for a local oscillator and related equipment at the Remote Access Unit (RAU). In such cases, the RAU is a combination of photodetector, an RF amplifier, and an antenna. Modulation and switching equipment is kept in the head-end and is shared by several RAUs. This arrangement leads to smaller and lighter RAUs by effectively reducing system installation and maintenance costs. Two of the most important requirements for mm-wave systems are easy installation and low maintenance costs of RAUs, due to the large numbers of the required RAUs. Having expensive RAU would render the system costs prohibitive. The numerous antennas are required to offset the small size of radio cells (micro- and pico-cells), which is a consequence of limited propagation distances of mm-wave microwaves. In applications where RAUs are not easily accessible, the reduction in maintenance requirements leads to a major operational cost savings [28]. The usage of smaller number of RAUs also reduced the environmental impact.

2.3.5 Reduced Power Consumption

Reduced power consumption is an outcome of having simple RAUs with reduced equipment. Most of the complex equipment is kept at the centralized headend. In some applications, the RAUs are operated in passive mode. For instance, some 5 GHz Fiber-Radio systems employing pico-cells can have the RAUs operate in passive mode [28]. Reduced power consumption at the RAU is significant considering that RAUs are sometimes placed in remote locations not fed by the power grid.

2.3.6 Dynamic Resource Allocation

Since the switching, modulation, and other RF functions are performed at a centralized headend, it is possible to allocate capacity dynamically. In a RoF distribution system for Global System for Mobile communications (GSM) traffic, more capacity can be allocated to a certain area during the peak times and then re-allocated to other areas when off-peak. This can be achieved by allocating optical wavelengths through Wavelength Division Multiplexing (WDM) as need arises [34]. Allocating capacity dynamically as need for it arises obviates the requirement for allocating permanent capacity, which would be a waste of resources wavelengths, through WDM [14]. Furthermore, having the centralized headend facilitates the consolidation of other signal processing functions such as mobility functions and macro diversity transmission [14].

2.4 The Applications of Radio over Fiber Technology

There are many applications of RoF technology which consist of satellite communications, mobile radio communications, broadband access radio, Multipoint Video Distribution Services (MVDS), Mobile Broadband System (MBS), vehicle communications and control, and wireless LANs over optical networks. These application areas of RoF technology will be given and are briefly discussed in the following sections.

2.4.1 Cellular Networks

An important application area of the RoF technology is mobile networks as shown in Figure 2.4. The ever-rising number of mobile subscribers coupled with the increasing demand for broadband services have kept sustained pressure on mobile networks to offer increased capacity. For this reason, mobile traffic (GSM - Global System for Mobile Communications) can be relayed cost effectively between the SCs and the BSs by exploiting the benefits of SMF technology. On the other hand, there are other RoF functionalities such as dynamic capacity allocation provides significant operational benefits to cellular networks.

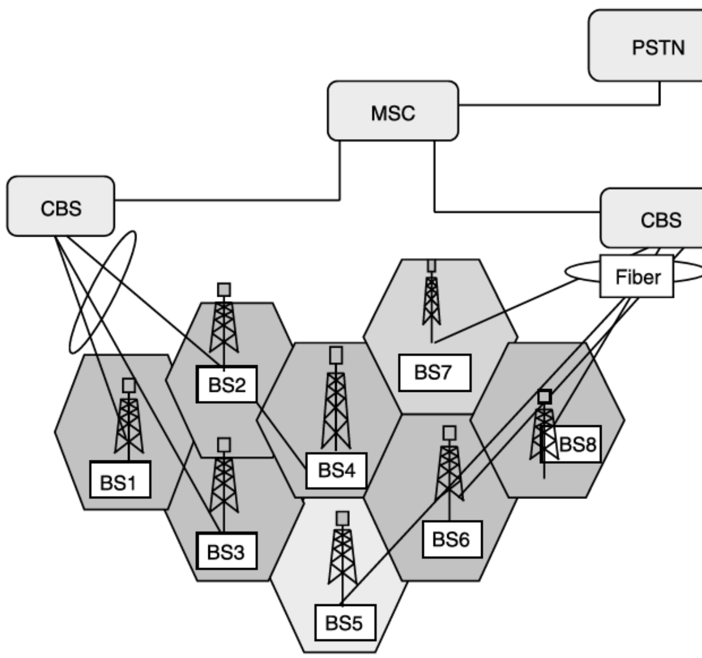


Figure 2.4: Optically fed remote antenna network for microcellular RoF systems [25]

2.4.2 Wireless LANs

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

This will lead once again, to higher carrier frequencies in the bid to meet the demand for capacity. For instance current wireless LANs operate at the 2.4 GHz ISM bands and offer the maximum capacity of 11 Mbps per carrier (IEEE 802.11b).

The next generations of broadband wireless LANs are primed to offer up to 54 Mbps per carrier, and will require higher carrier frequencies in the 5 GHz band (IEEE802.11a/D7.0) [31].

Higher carrier frequencies in turn lead to microcells and picocells, and all the difficulties associated with coverage discussed above arise. A cost effective way around this problem is to deploy ROF technology. A wireless LAN at 60 GHz has been realized [31] by first transmitting from the BS (Central Station), a stable oscillator frequency at an IF together with the data over the fiber. The oscillator frequency is used to up-convert the data to mm-waves at the transponders (Remote Stations). This extremely simplifies the remote transponders and also leads to effective base station design.

2.5 RoF Multiplexing Techniques

RoF multiplexing techniques is the process of multiplexing wavelength of different frequency onto a single fiber. This operation creates a lot of virtual fibers and each capable of carrying different signal. RoF multiplexing uses wavelengths to transmit data parallel by bit or serial by character, which increases the capacity of the fiber by assigning incoming optical signals to specific frequency (wavelengths) within designated frequency band and then multiplexing the resulting signal out on to one fiber.

2.5.1 Wavelength Division Multiplexing in RoF Systems

WDM are passive devices that combine light signals with different wavelengths, coming from different fibers, onto a single fiber. They consist of dense wavelength division multiplexers (DWDM), devices that use optical (analog) multiplexing techniques to increase the carrying capacity of fiber networks beyond levels that can be accomplished via time division multiplexing (TDM).

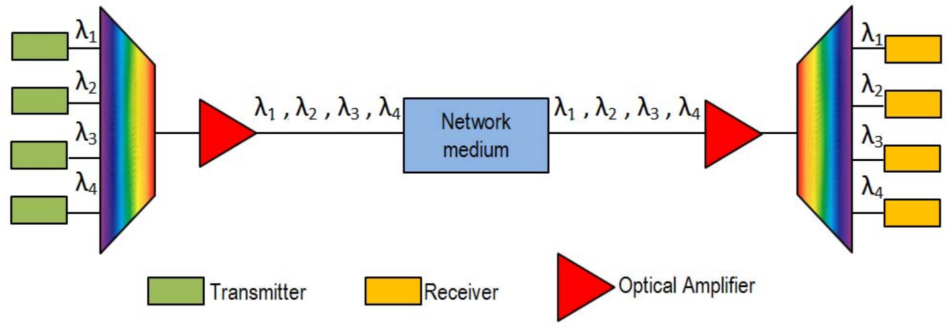


Figure 2.5: A WDM transmission system [49]

The use of WDM for the distribution of RoF signals as illustrated in Figure 2.5, has gained importance recently. WDM enables the effective exploitation of the fiber network's bandwidth. These systems can achieve capacities over 1 Tbps over a single fiber. At the same time, bit rates on a single channel have risen to 10 Gbps and systems operating at 40 Gbps channel rates are becoming commercially available. The channel spacing in WDM can be decreased to 50 GHz or even to 25 GHz and in this way, it is possible to use hundreds of channels. But, if the channel spacing is dropped to 50 GHz instead of 100 GHz, it will become much harder to upgrade the systems to operate at 40 Gbps due to the nonlinear effects.

However, the transmission of RF signals is seen as inefficient in terms of spectrum utilization, since the modulation bandwidth is always a small fraction of the carrier signal frequency. For this reason, ways to improve the spectrum efficiency have been proposed. RoF on WDM systems have been reported. Carriers modulated with mm-waves are dropped from and added to a fiber ring using Optical Add-Drop Multiplexers (OADM). The OADM are placed at base stations and tuned to select the desired optical carriers to drop [28] [35].

2.6 Conclusion

In this chapter a brief description and explanation of the basic theory about Radio over Fiber (RoF) is presented. The basic theories described are about the overview of RoF technologies, the advantages and the architecture of RoF. Besides that, the explanation of optical transmission link and how RoF integrate has been described. The applications of RoF in communication technologies have also been presented.

CHAPTER 3

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

3.1 Introduction

This chapter briefly describes the various theories related to the basic concepts and general principles of Orthogonal Frequency Division Multiplexing (OFDM), multicarrier transmission, Fast Fourier Transform (FFT) and Guard interval and its implementation.

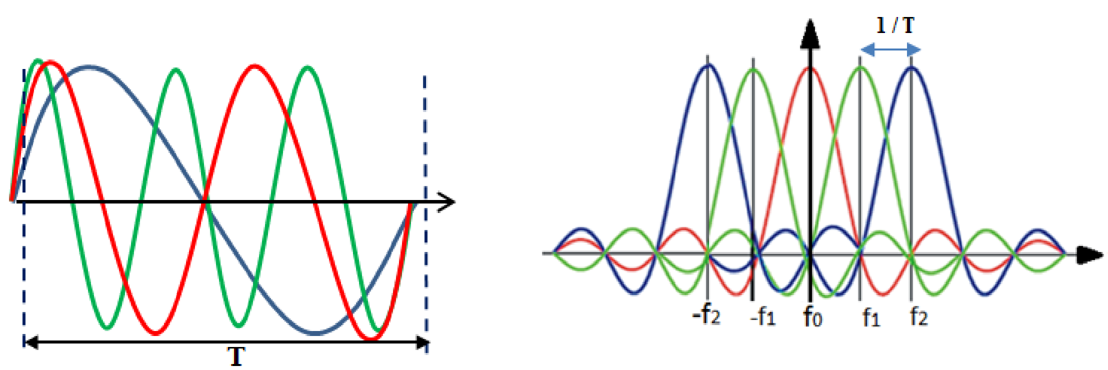
In order to understand the concept of OFDM, it is important to know the coded OFDM and Coherent Optical OFDM (CO-OFDM). In addition, the advantages and disadvantages of OFDM are also discussed in this chapter.

3.2 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is seen as the modulation technique for future broadband wireless communications because it provides increased robustness against frequency selective fading and narrowband interference, and is efficient in dealing with multi-path delay spread [35]. In order to achieve this, OFDM divides the available spectrum into many carriers, each one being modulated by low rate data streams which are utilized in parallel transmission. Therefore, in other words OFDM has enhanced the symbol duration.

One of the advantages of OFDM modulation is that the relative amount of dispersion in time caused by multipath delay spread has been reduced significantly. Furthermore, Inter-Symbol Interference (ISI) is eliminated almost completely by introducing a guard time in every OFDM symbol. Within the guard time, the OFDM symbol is cyclically extended to prevent Inter-Carrier Interference (ICI) [36].

As describe above, OFDM uses variety of subcarriers to transmit low rate data streams in parallel. The subcarriers are themselves modulated by using PSK (Phase Shift Keying) or QAM (Quadrature Amplitude Modulation) and then carried on a high frequency microwave carrier (e.g. 5 GHz for Wireless Broad-band Mobile Communication Systems)[37]. OFDM is similar to FDM (Frequency Division Multiplexing) except for the stringent requirement of orthogonality between the subcarriers. This subcarrier orthogonality can be viewed in either the time domain or in frequency domain. From the time domain perspective, each subcarrier must have an integer number of cycles during each OFDM symbol interval. In other words, the number of cycles between adjacent subcarriers differs by exactly one as shown in Figure 3.1(a). This properly accounts for the orthogonality between subcarriers. From the frequency domain perspective, this corresponds to each subcarriers (which are BPSK, QPSK or QAM modulated) having the maximum value at its own center frequency and all other subcarrier spectra are zero as shown in Figure 3.1(b). Since the OFDM receiver calculates the spectrum values at the maximum points of individual subcarriers, it can recover each subcarrier without ICI interference from other subcarriers.



(a) Three Orthogonal Subcarriers in one **(b)** Spectra of three OFDM subcarriers

Figure 3.1: OFDM Symbol

OFDM processor is intensive because the basic of the OFDM signal is formed using the Inverse Fast Fourier Transform (IFFT), adding a cyclic extension and performing windowing to get steeper spectral roll off. However, there is more to it to build a complete OFDM model. While in the receiver, the subcarriers are demodulated using Fast Fourier Transformation (FFT). Thus, the requirement in OFDM system for the intensive computations accounts for the complexity of OFDM transmitters and receivers. Figure 3.2 and Figure 3.3 show the block diagrams of the basic OFDM transmitter and receiver.

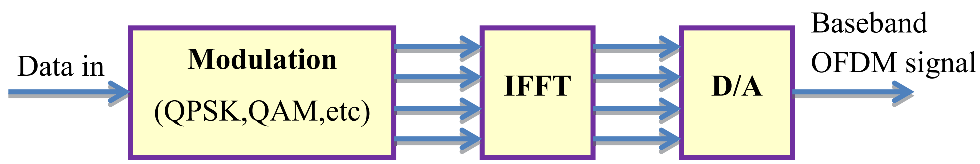


Figure 3.2: Block diagram of the basic OFDM transmitter

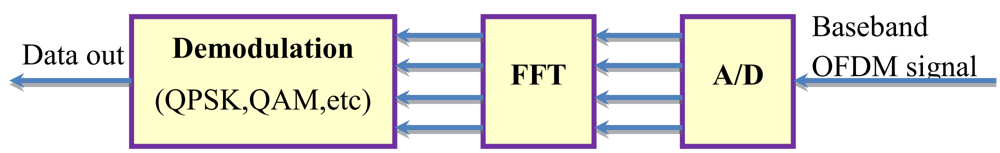


Figure 3.3: Block diagram of the basic OFDM receiver

The difference between the single-carrier modulation systems and the OFDM systems is the OFDM systems are much more sensitive to frequency offset and phase noise. Furthermore, OFDM has a relatively large peak-to-average power ratio (PAPR), which can reduce the power efficiency of the RF amplifier. OFDM is already used in many access network technologies including High-bit-rate, Digital Subscriber Lines (HDSL), Asymmetric Digital Subscriber Lines (ADSL), Very high-speed Digital Subscriber Lines (VDSL), Digital Audio Broadcasting (DAB), and High Definition Television (HDTV) broadcasting.

3.3 General Principles of OFDM

This section describes the basic concepts of OFDM concerned with multicarrier transmission, Fast Fourier Transform, Guard interval and its implementation.

3.3.1 Multicarrier Transmission

Orthogonal Frequency Division Multiplexing (OFDM) system is a multicarrier (parallel) communication system with orthogonal subcarriers. In an OFDM system, the subcarrier spacing, Δf is $\frac{1}{NT}$ where N is the number of the subcarriers and $\frac{1}{T}$ is the overall symbol rate where T represents the duration of an OFDM symbol. With this subcarrier spacing, the sub-channels still can maintain orthogonality even the sub-channels overlap each other. This means that there is no inter-subcarrier interference (ISI) in ideal OFDM systems. The number of subcarriers N is chosen so that the sub-channel bandwidth is less than the channel coherence bandwidth. Under this condition, each sub-channel does not experience significant Inter-symbol Interference (ISI).

The transmitted signal of an OFDM system for one OFDM symbol period as a following form [5]

$$s(t) = Re\{\sum a_n\, h(t) exp(j2\pi f_n t + \phi)\} \tag{3.1}$$

where:

a_n denote the transmitted data symbol for the n-th subcarrier;

$h(t)$ denote the pulse shaping filter response;

f_n denote the n-th subcarrier frequency and $f_n = f_c + n\Delta f$.

The complexity of the modulator and demodulator is increased as the number of OFDM subcarriers increases. However, the OFDM modulator and demodulator can be implemented easily by the inverse discrete Fourier transform (IDFT) and discrete Fourier transform (DFT) respectively. Figure 3.4 shows a block diagram of the OFDM modulator.

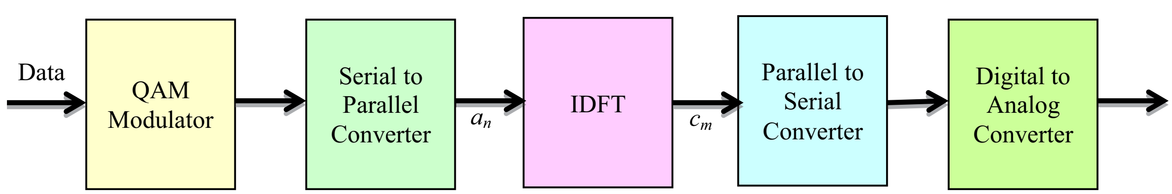


Figure 3.4: A block diagram of an OFDM transmitter

The time domain coefficients c_m can be computed by IDFT as [37]

$$C_m = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} a_n exp\left(-j\frac{2\pi nm}{N}\right) \quad (3.2)$$

where:

a_n denote the input of the IDFT block which is the data symbol for *n*-th subcarrier;

c_m denotes the m-th output of the IDFT block.

After the IDFT operation, the parallel output of IDFT block c_m (which m = 1 until N − 1) is converted to a serial data stream. From equation (3.2), the data symbol in frequency domain can convert into a series of time domain samples. The digital samples are digital to analog converted, then filtered and converted to a carrier frequency, f_c.

At the receiver, the received signal is down converted to baseband and sampled at the symbol rate, $\frac{1}{T}$. Then, N serial samples are converted to parallel data and passed to a DFT which converts the time domain signal into parallel signals in the frequency domain.

The OFDM system transmits many narrowband data signals on closely-spaced carriers to exploits frequency diversity. Therefore, the symbol duration of each subcarrier becomes $N\Delta t$, where Δt is the symbol duration of the input data symbols. Then, assume that each sub-channel experiences flat-fading. If the gain of the *i*-th channel is $|\alpha_i|^2$, then the received signal to noise ratio (SNR) of the *i*-th channel becomes [37]

$$SNR_i = \frac{P_i|\alpha_i|^2}{BN_O} \quad (3.3)$$

where:

Pi denote the signal power at the transmitter;

B denote the bandwidth of each sub-channel;

N_0 denote the noise spectral density.

If the *i*-th sub-channel has low channel gain $|\alpha i|^2$, the sub-channel will have low received SNR_i for constant transmission power. This can cause a higher symbol error rate in the sub-channels with a low channel gain. There are several schemes to compensate for the degradation due to low gain sub-channels. One of the techniques is presetting transmission power with the channel inversion [37]. With the channel inversion presetting, the transmitter allocates more power to the sub-channels with lower channel gain. The transmission power of i-th sub-channel P_i is proportional to the inverse of the channel gain $|\alpha i|^2$.

$$P_i \propto \frac{1}{|\alpha_i|^2} \tag{3.4}$$

The received SNR of each subcarrier is the same and maintain the symbol error rate for each subcarrier with the channel inversion. However, this channel inversion can waste much more power at the sub-channels with low gain. In other word, it is not a power efficient technique in fading channels. This has an adverse effect on Rayleigh fading channel because this fading channel would be required a large amount of power. For example, infinite power is required in the channel inversion to the frequency response. Therefore, channel inversion is not practical used in the multi-carrier communication systems.

For that, OFDM has been used to solve the problem above because OFDM is a multicarrier modulation method (MCM) and the most efficient one. Therefore, OFDM is most frequently used in wireless communications. OFDM is a part of several standards for WLANs (IEEE 802.11a,g), fixed broadband wireless access (IEEE 802.16), digital audio broadcasting (DAB), digital TV (DVB-T), and wireless personal area networks (IEEE 802.15). It is also a promising candidate for future 4G communication systems [38].

In general, there are two types of multicarrier transmission configuration as shown in Figure 3.5 and 3.6. In the Figure 3.5, the parallel data stream excites replicas of the same pulse-shaping filter $g(t)$, and the filtered signals are modulated on the different carriers and summed up before transmission. While the Figure 3.6 show that parallel data stream excites a filter bank of K (or K + 1) different bandpass filters. The filter outputs are then summed up before transmission.

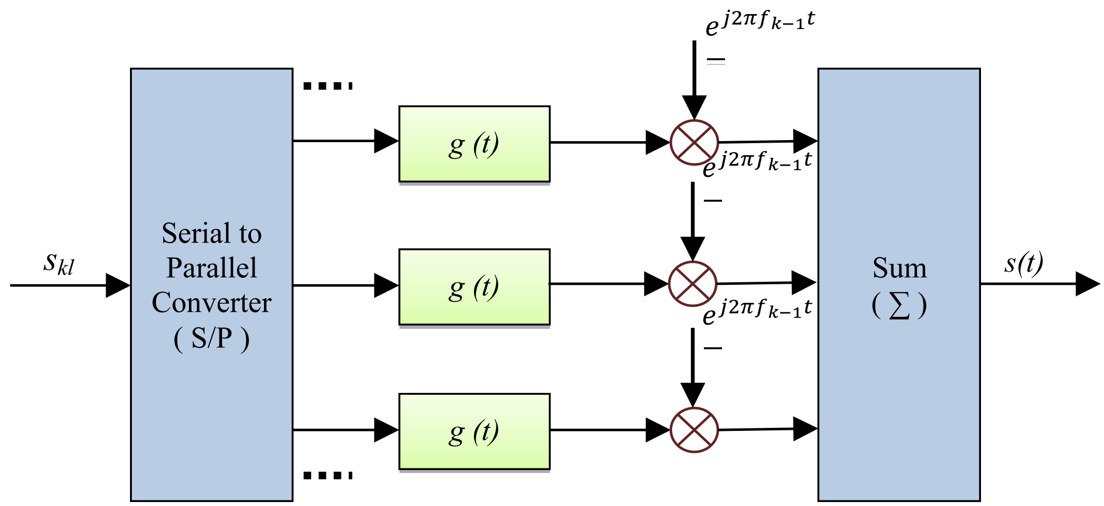


Figure 3.5: Block diagram for multicarrier transmission configuration (Type 1)

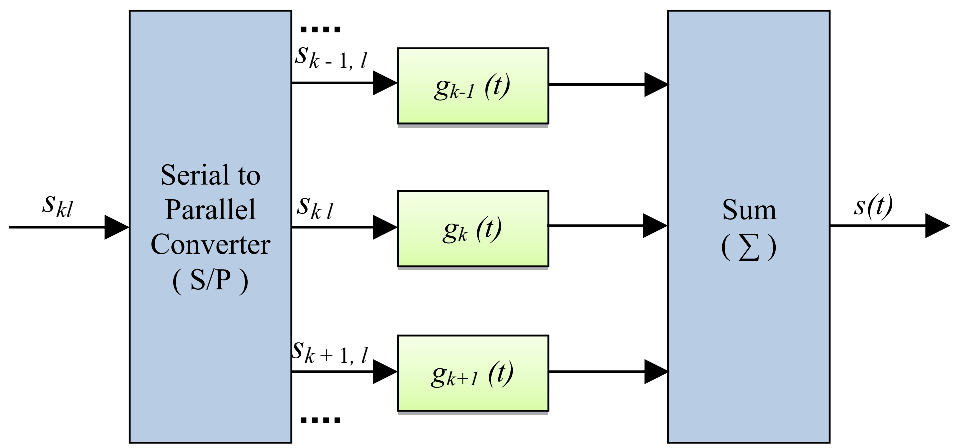


Figure 3.6: Block diagram for multicarrier transmission configuration (Type 2)

3.3.2 Fast Fourier Transform

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

At the receiver, an FFT is used to recover the original data. The FFT allows an efficient implementation of modulation of data onto multiple carriers [39]. Due to the similarity between the forward and inverse transform, the same circuitry, with trivial modifications, can be used for both modulation and demodulation in a transceiver. Figure 3.7 shows the block diagram of IFFT and FFT operation of OFDM transmitter and receiver.

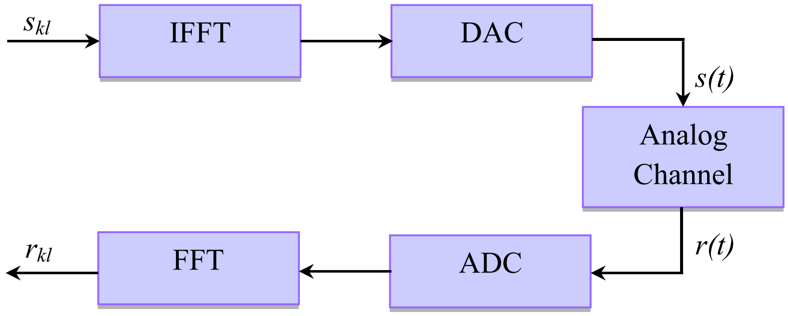


Figure 3.7: Block diagram of IFFT and FFT in the OFDM system

3.3.3 Guard Interval and Its Implementation

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

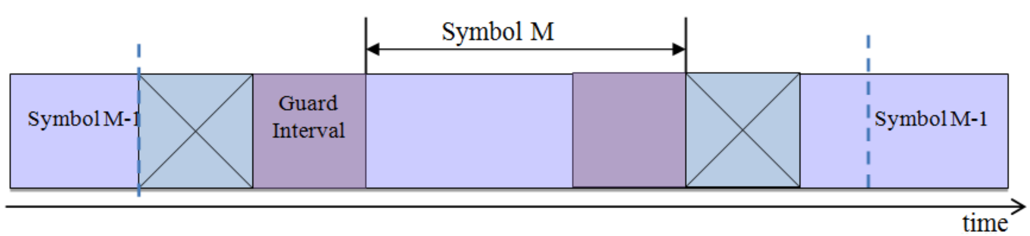


Figure 3.8: Guard Interval

One way to prevent ISI is to create a cyclically extended guard interval, where each OFDM symbol is preceded by a periodic extension of the signal itself.

Figure 3.8 shows the guard interval with symbol. The total symbol duration is T_{total}= T_g + T, where T_g is the guard interval and T is the useful symbol duration. When the guard interval is longer than the channel impulse response , or the multipath delay, the ISI can be eliminated. However, the ICI, or in-band fading, still exists. The ratio of the guard interval to useful symbol duration is application- dependent. Since the insertion of guard interval will reduce data throughput, T_g is usually less than $\frac{T}{4}$.

The cyclic prefix, which is transmitted during the guard interval, consists of the end of the OFDM symbol copied into the guard interval, and the guard interval is transmitted followed by the OFDM symbol. Figure 3.9 shows the cyclic prefix insertion in the guard interval.

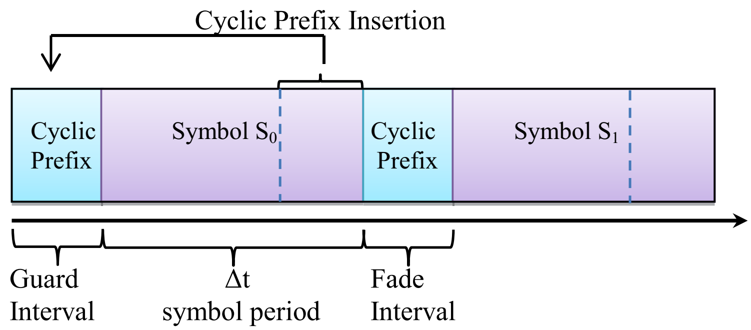


Figure 3.9: Cyclic Prefix Insertion

3.4 Coded OFDM

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

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

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