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Green Radio Communication Networks Applying Radio- over- Fibre Technology for Wireless Access

A thesis submitted for the degree of Doctor of Philosophy (Ph.D.) to:
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by:

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Abstract

Wireless communication increasingly is becoming the first choice link to enter into the global information society. It is an essential part of broadband communication networks, due to its capacity to cover the end-user domain, outdoors or indoors. The use of mobile phones and broadband has already exceeded the one of the fixed telephones and has caused tremendous changes in peoples life, as not only to be recognised in the current political overthrows. The all-around presence of wireless communication links combined with functions that support mobility will make a roaming person-bound communication network possible in the near future. This idea of a personal network, in which a user has his own communication environment available everywhere, necessitates immense numbers of radio access points to maintain the wireless links and support mobility.

The progress towards "all-around wireless" needs budget and easily maintainable radio access points, with simplified signal processing and consolidation of the radio network functions in a central station. The RF energy consumption in mobile base stations is one of the main problems in the wireless communication system, which has led to the worldwide research in so called green communication, which offers an environmentally friendly and cost-effective solution. In order to extend networks and mobility support, the simplification of antenna stations and broadband communication capacity becomes an increasingly urgent demand, also the extension of the wireless signal transmission distance to consolidate the signal processing in a centralised site.

Radio-over-Fibre technology (RoF) was considered and found to be the most promising solution to achieve effective delivery of wireless and baseband signals, also to reduce RF energy consumption. The overall aim of this research project was to simulate the transmission of wireless and baseband RF signals via fibre for a long distance in high quality, consuming a low-power budget. Therefore, this thesis demonstrated a green radio communication network and the advantage of transmitting signals via fibre rather than via air. The contributions of this research work were described in the follows:

Firstly, a comparison of the power consumption in WiMAX via air and fibre is presented. As shown in the simulation results, the power budget for the transmission of 64 QAM WiMAX

IEEE 802.16-2005 via air for a distance of 5km lies at -189.67 dB, whereas for the transmission via RoF for a distance of 140km, the power consumption ranges at 65dB. Through the deployment of a triple symmetrical compensator technique, consisting of SMF, DCF and FBG, the transmission distance of the 54 Mbps WiMAX signal can be increased to 410km without increasing the power budget of 65dB. An amendment of the triple compensator technique to SMF, DCF and CFBG allows a 120Mbps WiMAX signal transmission with a clear RF spectrum of 3.5 GHz and constellation diagram over a fibre length of 792km using a power budget of 192dB. Secondly, the thesis demonstrates a simulation setup for the deployment of more than one wireless system, namely 64 QAM WiMAX IEEE 802.16-2005 and LTE, for a data bit rate of 1Gbps via Wavelength Division Multiplexing (WDM) RoF over a transmission distance of 1800km. The RoF system includes two triple symmetrical compensator techniques - DCF, SMF, and CFBG - to obtain a large bandwidth, power budget of 393.6dB and a high signal quality for the long transmission distance. Finally, the thesis proposed a high data bit rate and energy efficient simulation architecture, applying a passive optical component for a transmission span up to 600km. A Gigabit Optical Passive Network (GPON) based on RoF downlink 2.5 Gbps and uplink 1.25Gbps is employed to carry LTE and WiMAX, also 18 digital channels by utilising Coarse Wavelength Division Multiplexing (CWDM). The setup achieved high data speed, a low-power budget of 151.2dB, and an increased service length of up to 600km.

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In the Name of ALLAH, the Most Beneficent, the Most Merciful
All Thanks to ALLAH for His favours and blessings.

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Dedicated to My Family

My Mother, My Wife

My Son Yacin and My Daughter Betul

Author's Declaration

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Mazin Al Noor

June 2011, London, UK

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List of Abbreviations

A

Low-Noise Amplifier
LNA, 31
Adjustable Modulation and Coding
AMC, 94
Advanced Encryption Standard
AES, 126
Amplitude Modulation
AM, 16
Analogue-to-Digital
A/D, 31
Asynchronous Transfer Mode
ATM, 125

B

Basestation
BS, 2, 3, 4, 5, 30, 31, 32, 41, 42, 101, 130, 131
Bit-Error-Rate
BER, 19, 65, 67, 96
Broadband Passive Optical Network
BPON, 120, 125

C

Central Office
CO, 120, 123, 126
Central Stations
CS, 27
Chirped Fibre Bragg Grating
CFBG,6,26, 37,70,71,78, 97,100 146,152
Coarse Wavelength Division Multiplexing
CWDM, II,6,7,17,31,124,127,128,129 ,133,141,157
Community Access Television
CATV, 16

D

Dense Wavelength Division Multiplexing
DWDM,26,31,34,36,38,67,78,121,129 ,146, 162,167
Differential Group Delay
DGD, 22
Digital-to-Analogue
D/A, 31
Dispersion Compensating Modules
DCM, 23,24

E

Erbium-Doped Fibre Amplifier
EDFA, 127, 145
Error Vector Magnitude
EVM, 67
Ethernet PON
EPON, 120

F

Fast Fourier Transform
FFT, 72
Fibre Bragg Grating
FBG,6, 23, 24, 26,59, 60,61,131

List of Contributed Publication

Conference

I. **M. Al Noor**, K.K. Loo, R. Comley, "WiMAX 54Mbit/s over Radio over Fibre Using DCF, SMF Fibre and FGB for Fibre over 410km", IEEE 7th International Symposium on Wireless Communication Systems (ISWCS 2010), The University of York, UK.

II. **M. Al Noor**, K.K. Loo, R. Comley, "120 Mbps Mobile WiMAX Scalable OFDMA–PHY over Radio Over Fibre For Fibre Length 792 Km", IEEE 6th International Conference on Wireless and Mobile Communications (ICWMC 2010), Valencia, Spain. Selected as one of twenty best papers in the conference.

Journal

I. **M. Al-Noor,** K.K. Loo, R. Comley "Extended Mobile WiMAX Signal Transmission over RoF through Triple Symmetrical Dispersion System SMF, DCF and CFBG" International Journal on Advances in telecommunications (IARIA). Published 15.Aug.2011

II. **M. Al-Noor**, K.K. Loo, D. Singh "WiMAX, LTE & CWDM Signal Transmission via GPON-RoF" Journal of Optical and Fibre Communications Research (Springer).Under review.

III. **M. Al-Noor**, K.K. Loo, D. Singh ""LTE/WiMAX Signal Transmission using WDM-RoF for Long Fibre Distance Network" Multimedia Tools and Applications (Springer).Under review

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Chapter 1

Introduction

1.1 Wireless Access Network

Wireless broadband, fixed and mobile, can be found almost everywhere, and it became a part of our modern life style. The data traffic in telecommunication networks has been growing tremendously over recent years, and experts predict accelerating data volumes from today three Exabyte a year to ninety Exabyte per year by 2015, where an Exabyte is equal to one million terabytes [1]. Wireless mobile services expanded in a range of 15 years (1990-2005) from worldwide 1 million to more than 2 billion subscribers. Delivering the Internet throughout the globe, the IEEE 802.16 committee aimed to engineer a wireless communication system based on new technologies in communications and digital signal processing to obtain a broadband Internet experience for nomadic users over a large area [2]. Long-term Evolution (LTE) is the next crucial step beyond High Speed Packet Access (HSPA) in the development of 3GPP technologies. Supporting and promoting the most fundamental aspects of mobile telephony and broadband, namely unparalleled mobility and coverage, LTE has an increased emphasis on quality and operational efficiency in the explosive growth of data service usage. The commercial launch of LTE single mode has started in Northern Europe at the end of 2009, and LTE dual mode services at the end of 2010 [3]. Both WIMAX and LTE are based on OFDM and provide wireless and fixed access. These technologies bring mobile broadband services to areas where currently fixed broadband access is not practicable due to excessive cost [4].

1.2 Research Motivation

The main challenge of wireless access networks is the vast amount of energy needed to power the base stations. A typical 3G base station needs 12.5 times more input power than it produces output RF power (500W input; 40W output), which adds up to an annual energy consumption of approximately 4.5MWh [5]. With 12,000 base stations building up a 3G mobile network, it consumes more than 50GWh a year. For example, Vodafone needs one million litres of diesel per day to operate its remote base stations worldwide [5]. The number of mobile subscribers is increasing continuously and at the same time the amount of energy consumption. The fact is that sending more data requires more RF energy. At the Mobile World Congress this year, a sale of worldwide 1.4 billion handsets in 2010 was announced, where the Chinese market had 842 million subscribers and presently only 15 per cent on 3G networks [5]. The global shift from 2G to 3G networks, with predicted 775 million handsets supporting 3G in 2011, takes part in the rising quantity of data and so the rising amount of energy needed to transfer the data [6]; 30 to 40 per cent of the total cost of a base station is caused by the power amplifier [6]. The RF cable, carrying the signal between the power amplifier and the antenna introduce some loss that also increases the transmission cost. Furthermore, the cables are expensive, afford strong mechanical support, due to their heaviness, and are regarded as one of the main causes for mechanical problems in base stations. Another challenge for broadband wireless systems is the Mobility Management to find the right balance between capacity and coverage. The wireless network needs to provide the device to reach inactive/active users everywhere in the network, which is described as roaming also, to maintain a persisting session free from interruption while the user is moving (handoff).

1.3 Green Radio Communication

Over a period of ten years, the number of mobile phone subscribers increased from circa 700m to 5bn worldwide by July 2010 [7]. The fastest growth can be recognised in developing countries, like India and China, where wireless Internet has been adopted massively. Of course, this humongous increase of the use of wireless systems is associated with an increase in energy consumption. It is predicted that the majority of Internet access worldwide will be wireless on mobile devices. The future challenge is, to provide wireless Internet globally with significantly reduced energy consumption per bit and a reduction in network operating costs to operate profitably.

Discussions within the Mobile VCE (Virtual Centre of Excellence) group in 2006 / 2007 let the term" Green Radio" firstly appear. In October 2008, a three year Mobile VCE's Green Radio programme was formally launched, jointly funded by Industrial Companies and the

UK's Engineering & Physical Sciences Research Council. The research in this programme is the responsibility of an integrated research team from five different universities in the UK [8] with the ambitious aim, to identify innovative methods to achieve a 100-fold reduction in the total energy consumption used to operate radio access networks. So far, there have been studies in areas like resource allocation, interference suppression, and multi-hop routing, which are able to lead to energy savings. Further key issues for investigation are the cell sizes of a base station, the backhaul method (wireless, fibre and free space optical), and the use of enterprise and femto-cell technologies [9].

1.4 Fibre Optic Access Network

The optical communication technology uses fibre cables to transfer data over long distances as well as for the last mile into the user's home. This technology is capable to overcome the above described problems of wireless networks and participate in the responsible care for the environment and sustainable management of diminishing resources. The demand for and use of optical fibre has grown enormously and optical-fibre applications are widespread, ranging from global networks to desktop computers. The ability transmitting voice, data, or video over very short, respectively, very long distances provides considerable value for communication networks like mobile phone, wireless system and broadband, due to the reduction of energy consumption and cost. Fibre optic technology is understood as the promising technology for future networks and is a system trusted by users. For example, in April 2011, the Australian government has announced its £20bn plan to expand super-fast fibre-optic broadband across the country with FTTH (optical fibre to the home) for 90 per cent of its inhabitants. Additionally, the Australian healthcare service has reported that the investment in an intelligent system of patient records delivered via fibre optic technology could save $23bn over a 10-year time and save 1,300 lives every year [10].

1.4.1 Radio over Fibre (RoF)

This research focuses on RoF wireless access and RoF based on a passive optical network architecture aiming at efficient mobility, bandwidth management, and power behaviour. One of the most prominent applications in the fibre optic system is radio over fibre (RoF). This is a technology, which modulates light into radio frequency and transmits it via optical fibre to facilitate wireless access. Radio signals are carried over fibre utilising distributed antenna systems in fibre-optic cellular and micro-cellular radio networks. Radio signals in each cell are transmitted and received to and from mobile users by applying a separate little box that is connected to the base station via optical fibre. Cells are divided into microcells to enhance the frequency re-use and support a growing number of mobile users. The introduction of microcells has the following advantages: Firstly, the microcell is able to meet increasing bandwidth demands; secondly, reduces the power consumption also the size of the handset devices. The high-power radiating base station antenna is replaced by a divided antenna system connected to the base station via optical fibre [11] . RoF is commonly used for wireless access. RoF networks operate primarily at mm-wave bands, which require an additional attenuation, especially around 193.1THz, due to a limitation of the transmission range by oxygen absorption in outdoor environments. Compared to microwave bands such as 2.4 or 5 GHz, which require various BSs to support a wide service area, mm-wave band needs small cells. Networks operating with a large number of small cells have to cope with the issues of cost-effectiveness and mobility management [11]. RoF offers various benefits, like low attenuation, a large bandwidth, and immunity to radio frequency interference, operational flexibility, reduced power consumption, and a long signal transmission distance [11].

1.4.2 Challenges and Problems in RoF

There are two types of fibre optical cable: Multi mode fibre (MMF), used for a short distance signal transmission and Single mode fibre (SMF), used for long distances. The main challenge of the signal transmission via RoF for a long distance is the power attenuation and chromatic dispersion in SMF at wavelength 1550nm that can limit the signal transmission.

As this thesis considers an approach of green radio communication, the important question of high-energy consumption has to be solved, because most power is used for temperature regulation of the laser element in fibre optic networks. Additionally, the cooling system for the laser module needs itself to be cooled as well.

1.5 Research Objective and Contributions

This research presents a green radio communication system, which is based on RoF to deliver LTE, WiMAX and baseband for a long distance and low-power budget. As the RoF system is considered the future network technology, it has on one hand the capacity to meet the demands for decreasing electromagnetic smoking, wireless traffic, power, noise, cost, and antenna size and, on the other hand, to increase frequency bandwidth, data rate and capacity and eventually improves the spectral efficiency. By the deployment of RoF it is possible to avoid the transmission impairments via the air such as high power attenuation per km, cost of set up a base station (BS), non-line of sight (NLOS) coverage and limitation of signal transmission area. One research focus is the reduction of the power consumption of WiMAX and LTE central and base station by utilising fibre optic technology particularly, RoF, for a transmission range of more than 100km. Furthermore, the research aims for an improvement of the transmission distance in the RoF system and to overcome the problem of energy consumption caused by the laser's temperature control. Addressing the impairment of chromatic dispersion in fibre optic systems, the deployment of different dispersion compensators is introduced in the following chapter.

1.5.1 RoF base SMF, DCF, FBG and CFBG

This thesis studies methods to control the chromatic dispersion in the SMF and power attenuation in the RoF system by utilising symmetrical compensators DCF, FBG, and CFBG. In a first step, the work focuses on WiMAX-LTE signals transmitted over RoF by using SMF, DCF, and CFBG. The thesis addresses the following areas: The theory of light dispersion in the fibre optic cable for SMF, DCF, FBG, and CFBG is presented. The description of the WiMAX –LTE via RoF system is introduced, followed by an explanation of the entire system setup design. Simulation results are presented to investigate the signal transmission over a long distance, with a special emphasis on signal dispersion.

1.5.2 WDM-RoF

In a second part, this research project presents a WDM-RoF network, operating with an increased bandwidth over fibre optic by transmitting multiple signals simultaneously at a different wavelength. Two wireless signals, WiMAX-RF 3.5GHz and LTE-RF 2.6GHz, for a data speed of 1Gbps, were merged into the wavelength division multiplexing (WDM) and transmitted via RoF. The WDM- RoF network raises the capacity also, and more importantly, enhances the number of base stations served by a single central station. The simulation results show the increase of the signal transmission area to 1800km also the improvement of OSNR and the signal attenuation.

1.5.3 GPON/CWDM-RoF

The final and third section of this thesis proposes the deployment of WiMAX-RF 3.5GHz, LTE-RF 2.6GHz wireless systems and 18 wavelengths as baseband signals with a bit rate of 2.5Gbps downlink and 1.25Gbps uplink in GPON-CWDM via RoF technology. The GPON system obtains the ability to deliver extremely high bit rates. The integration of an 18 channel coarse wavelength division multiplexing (CWDM) in the GPON, allows the use of less expensive, un-cooled lasers, operating with reduced energy consumption. The work achieved an extension of the transmission distance to 600km and a low-power budget.

1.6 Thesis Structure

This thesis comprises of six chapters, which are described in the following:

Chapter **1** presents the introduction consisting of the research background, formulation of problems and challenges, explanation of the research objectives and finally, the description of the thesis structure.

Chapter **2** provides the theoretical, respectively, technical basis of the thesis. This includes the propagation of light, optical fibre, Dispersion, Dispersion compensating modules, Radio over fibre communication networks and applications in RoF networks.

Chapter **3** compares the power consumptions of the WiMAX signal transmission via air and via RoF. To improve the transmission via RoF and extend the transmission distance, four different simulation setups for green radio solutions are described and their results, focussing on the power consumption, are discussed.

Chapter **4** examines the WDM-RoF system integrating two wireless systems, LTE and WiMAX, and increasing the fibre span to 1800km through the application of the triple compensators technique.

Chapter **5** focuses on CWDM-GPON for the last mile and describes the simulation design also the results for the transmission of 18 baseband channels, LTE & WiMAX via RoF.

Chapter **6** summarises the thesis and presents ideas for future research.

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Chapter 2

Literature Review - Fundamental Concept of Fibre Optic Technology

Literature Review

2.1 Introduction

This chapter deals with the fibre optic theory, the problems of the transmissions via fibre, the Radio over fibre technology, and the fibre components related to the research project, as described in this thesis.
A look into the history of human communication reveals that the earliest optical communications systems consisted of fire or smoke signals along the Great Wall of China. Countless beacon towers were used to inform about the size of an invading enemy by the number of lanterns or the colour of smoke. Thus, a message could be spread over a distance of more than 7300km, from one end of the Great Wall to the other, in approximately one hour. This can be seen as the first stage of multilevel signalling [12].

Several centuries later, the first generation of fibre optic arose in the 1980s as a means to transport information in communication systems, operating at a wavelength of 0.8nm with 45 Mb/s data rate. One benefit was lower costs for installation and maintenance due to the greater repeater spacing of 10 km, compared to the coax systems. Currently, researchers focus on optical transmission of 100 Gbps per wavelength channel and beyond, by the application of multilevel coding and modulation schemes, polarisation-multiplexing, DSP, and coherent detection [12].

The limited capacity of narrowband wireless access systems is caused by their low carrier frequencies, which only can offer low bandwidth. For instance, GSM works at frequencies around 900 or 1800 MHz and 200 kHz allocated frequency spectrum; UMTS works at frequencies around 2 GHz and 4 MHz allocated bandwidth. The wireless system operates with large cells, which provide high mobility, but for the cost of poor spectrum efficiency and high-power consumption. An option to raise the capacity and economy of wireless communication systems is to utilise fibre optic systems, namely RoF.
RoF employs remote working inside the buildings, where normally the walls are a cause for high signal losses when a system operates with large cells.

2.2 Propagation of Light

The basis of fibre-optic communications is the principle that light in a glass medium is able to convey a high amount of data over a long distance. Information transport, via electrical signals in copper respectively coaxial cables or via radio frequencies over a wireless medium is, compared to fibre-optic cables, not hugely effective. Today, the purity of the glass fibre enables the transmission of digitised light signals for hundreds of kilometres without amplification. The optical fibre can be seen as an ideal transmission medium, due to low interference, minimal transmission loss, and broad bandwidth capacity.

An optical fibre works as follows: Like radio frequency (RF) signals are routed through coaxial cables, the light waves are guided through the core of the optical fibre. The light is reflected within the core to the other end of the fibre. The ability to reflect light is determined by the composition of the cladding relative to the core glass. Usually, the creation of a higher refractive index in the core class than in the surrounding cladding causes the reflection and creates the “waveguide.” A modest modification of the core glasses components increases the refractive index. Another option to create the waveguide is to reduce the refractive index of the cladding by the application of different doping agents [13].

The total internal reflection of the light, the light is reflected with 100% efficiency, reduces the attenuation in optical fibres to useful levels and enables optical fibre communication. Light can pass any transparent material, with a lower speed than in a vacuum.

2.2.1 Refraction of Light Waves

When a light wave travels from one transparent medium into another transparent medium, it changes direction. Firstly, the Muslim mathematician and optics engineer Ibn Sahl accurately described a law of refraction in Bagdad in 984. More than 600 years later, the Dutch astronomer W. Snellius (1580–1626) reinvented the law of refraction.

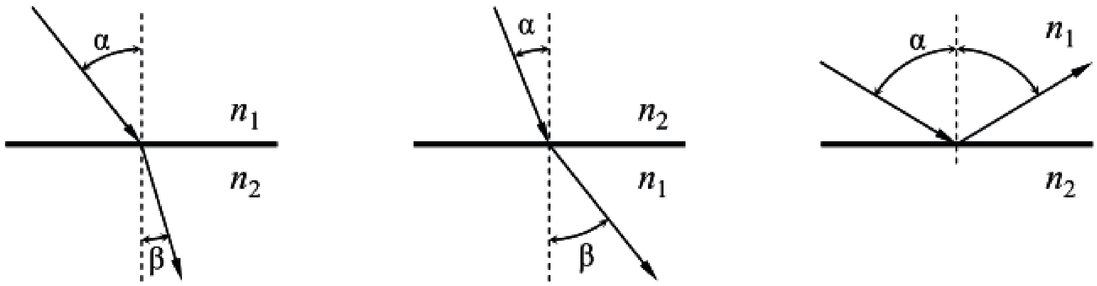

Figure 2-1 a-c: Snell’s law of refraction [14]

Snell’s law describes the refraction of waves when travelling from one transparent medium into another with a different phase speed. This law is applicable for all waves. Figure 2-1-a shows the refraction of light, when passing from an optical thin (n_1) into an optical dense medium (n_2). The light refracts in the direction of the perpendicular; the angle of refraction (β) is smaller than the angle of incidence (α). Figure 2-1-b displays the situation, when light passes from an optical dense medium into an optical thin medium; the angle of refraction is bigger than the angle of incidence. If the angle of incidence increases, as to be seen in Figure 2-1-c, the light beam will be reflected fully and will not enter the second medium[14].

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1} \qquad (2.1)$$

Equation 2.1 describes the refraction at the interface between two different light transmitting materials [14].

$$\alpha = \sin^{-1}\left(\frac{n_2}{n_1}\right) \qquad (2.2)$$

$$n_2 = n_1 \sin(\alpha) \qquad (2.3)$$

Equations 2.2 and 2.3 describe the total reflection of the light beam.
Light travels through a dielectric transparent matter at a velocity, which depends on the dielectric constant of matter and its wavelength. The following equation describes the propagation of a monochromatic plane wave through a dielectric medium in the direction z:

$$E(t,z) = A\,e^{[j(wt-\beta z)]} \tag{2.4}$$

where A is the amplitude of the field, ω = 2π f ,and β is the propagation constant. Phase velocity is v_φ , ωt − βx = constant [15].

$$v_p = \frac{\lambda}{\mathrm{T}\cdot} \tag{2.5}$$

Or, equivalently, in terms of the wave's angular frequency *ω* and wavenumber *k* by

$$v_{p=\frac{w}{k\cdot}} \tag{2.6}$$

The dielectric constant of a medium is a function of frequency; therefore, different optical frequencies propagate at different velocities through the medium. This is an important fact for optical communications, because the optical signal is not purely monochromatic. The optical signal consists of a frequencies band, where each frequency passes the medium at a slightly different velocity and different phase. Therefore, group velocity vg can be expressed as the velocity of the envelope of the frequencies of an optical signal. Also it can be described as the speed of the signal pulse [16].

$$v_g = \frac{L}{\tau_g} = \frac{c}{n_g} = \left(\frac{\partial\beta}{\partial}\right)^{-1} = -\frac{2\pi c}{\lambda^2}\left(\frac{\partial\beta}{\partial\lambda}\right)^{-1} \tag{2.7}$$

Where c = speed of light in a vacuum, m/s, β = phase propagation parameter, rad/m, ω = angular frequency, ω = 2πc/λ, rad/s, vg= group velocity of the signal, m/s n_g= fibre‘s effective group refractive index at w or λ, L = fibre length, km.

2.2.2 Nonlinear Schrödinger Equation (NLS)

The Austrian physicist Erwin Schrödinger was the first person to describe a wave equation. As Einstein, he assumed that light is an electromagnetic ray, that consists of photons, which carry energy (E) and the momentum of the photon (p). Both parts of his equation together indicate the probability of the stay of a photon travelling through a medium. For fibre optic communication, the modified equation is used to take into account dispersion and nonlinear effects of the pulse propagation via the fibre.

The right-hand side of the equation refers to nonlinear effects; the Kerr effect, Raman scattering, and self-steepening. The right side equals 0, when there are no nonlinear effects to consider. The left- hand side refers to fibre attenuation and chromatic dispersion [16][17].

$$\frac{\partial A}{\partial z}+\beta_1\frac{\partial A}{\partial t}+\frac{j\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3}{\partial t^3}+\frac{\alpha}{2}A$$

$$= j\gamma\,|A|^2A-\,j\gamma_R A\frac{\partial\,(|A|^2)}{\partial t}-\ \gamma_S\frac{\partial\,(\,|A|^2A)}{\partial t} \qquad (2.8)$$

γ is: $$\gamma=\frac{2\pi n_2}{\lambda A_{eff}} \qquad (2.9)$$

Where is:

$\beta_1\frac{\partial A}{\partial t}=$ Group velocity

$\frac{j\beta_2}{2}\frac{\partial^2 A}{\partial t^2}=$ Chromatic dispersion effect

$-\frac{\beta_3}{6}\frac{\partial^3}{\partial t^3}= CD\ slop$

$\frac{\alpha}{2}A=$ fibre Attenuation

$j\gamma\,|A|^2A=$ Kerr effect,

$j\gamma_R A\frac{\partial\,(|A|^2)}{\partial t}$= Raman scattering

$\gamma_S\frac{\partial(\,|A|^2A)}{\partial t}=$ self − steepening

A = modulating electric field signal which is a function of distance and time A$(z,t), V/m$.

$|A|^2$ = optical intensity Wm^2.

ϒ= nonlinear coefficient, $(Wm)^{-1}$.

Υ_R= stimulated Raman scattering nonlinear coefficient, $(Wm)^{-1}$.

Υ_s = self-steepening nonlinear coefficient, $(Wm)^{-1}$.

$n_{2=}$ Fibre nonlinear refractive index, which varies for different fibre between 2.0 x10^{-20} and 3.5x 10^{-20} m^2/W.

α =Fibre's attenuation coefficient.

Z is the spatial longitudinal coordinate, β_2 and β_3 represented fibre dispersion.

In Chapter 3, the SMF and DCF parameters, considered to the NLS, are described.

2.3 Optical Fibre

In optical communication systems, Silica-based optical fibres are the medium for long-distance and large-capacity signal transmission. The low-loss characteristics is the most prominent feature of optical fibre; achieving a loss of 0.154 dB/km at λ=1.55μm wavelength. This means that the original signal intensity of light decreases to its half after having travelled 20 km through the optical fibre [18].

There are two general categories of optical fibres: single-mode fibre (SMF) and multimode fibres (MMF). As shown in Figure 2-2, the core diameter of a MMF is six times bigger than the core of a SMF.

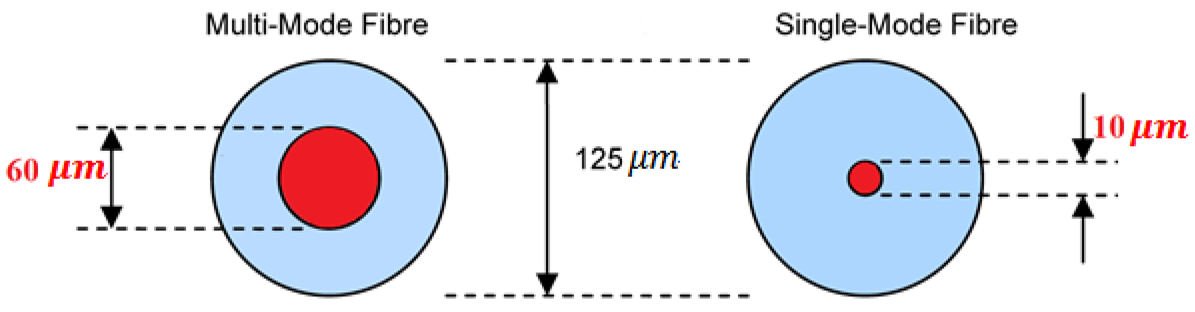

Figure 2-2: MMF and SMF core diameter

2.3.1 Multimode Fibre (MMF)

MMFs have a large core diameter ranging from 50 up to 100 mm. The light waves are spread out into numerous paths, when travelling through the cable's core, typically with a wavelength of 850 or 1300nm. The multi-paths of light cause signal distortion, especially over cable lengths more than 900m, which leads to incomplete and unclear data transmission.

However, MMF offers high bandwidth at high speeds- 100Mbit/s for a distance up to 2km; 1 Gbps for 220-550m, and 10Gbps for 300m - over medium distances and is a low-cost application for short links, e.g., in buildings or on campuses. The deployment of MMF is attractive as it is easier to install than SMF; it is considerably larger, which eases splicing and connector zing. Additionally, it is easier to connect to transceiver modules than SMF, which is more cost-effective. Furthermore, the MMF can be used for the transmission of RF carriers over the modal dispersion limited 3-dB bandwidth [19][20] [21].

2.3.2 Single Mode Fibre (SMF)

SMF is a small core (1-16mm) optical fibre, widely used in transport and access networks for long distances. This fibre obtains beneficial properties, like low attenuation, large wavelength area and high bandwidths over distance. Compared to MMF, they are less suitable for short link FTTH indoor cabling, due to high bending loss and high installation costs. Through the SMF, light rays propagate along a single mode or physical path. The refractive index between the core and the cladding is about 0.6%; for these fibres, the light source is a laser, due to a narrow numerical aperture (NA) [22].

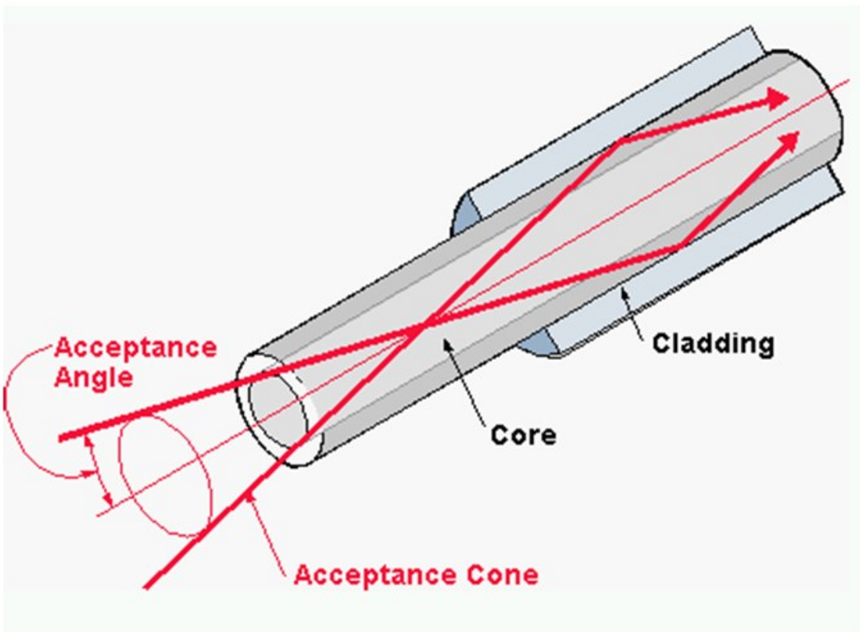

Figure 2-3: Acceptance angle of a fibre [23] .

As illustrate in Figure 2-3, the numerical aperture measures the maximum angle at which the core of the fibre will take in light, described as the acceptance angle of an optical fibre. Regarding the fibre core axis, the measurement of NA is as follows [24]:

$$NA = \sqrt{n_1^2 - n_2^2} \qquad (2.10)$$

Commonly, SMF is applied in amplitude modulation (AM), Quadrature amplitude modulation (QAM), community access television (CATV), and vestigial side band (VSB) transport. Compared to MMF, SMF obtains lower loss and eliminates intermodal dispersion and is, thus, applied in high-speed data rate channels over long distances. Group velocity dispersion (chromatic dispersion) is a significant problem in high-bit rate (>2.5 Gbps) transmission over SMF and will be discussed in Section 2.5.

2.4 Fibre Attenuation

Attenuation means the reduction of light power or signal strength over the length of the fibre cable and is measured in decibels per kilometre (dB/km). In optical communications, the terms fibre attenuation, fibre loss, power attenuation and power loss are used equivalently. Power attenuation within the fibre usually is a result of absorption and scattering. The absorption leads to a loss of the photons, and their energy is transformed into heat. Scattering means, that minor defects in the fibre redirect or scatter some light into rays that are no longer conducted by the fibre [25].

Attenuation of an optical signal changes as a function of wavelength; thus, the attenuation constant or fibre loss is not the same for all frequencies. For an attenuation constant α (λ), the optical power attenuation at a length L is expressed as follows [15][26].

$$P(L) = P(0)10^{-\frac{\alpha(\lambda)L}{10}} \qquad (2.11)$$

P_r represents the minimum power acceptable at receiver; the maximum fibre length is determined by[15]:

$$L_{max} = \left[\frac{10}{\alpha(\lambda)}\right] \log 10 \left[\frac{P(0)}{P_r}\right] \qquad (2.12)$$

The optical power attenuation constant $\alpha(\lambda)$ is non-linear [15]:

$$\alpha = \frac{c_1}{\lambda^4} + C_2 + A(\lambda) \qquad (2.13)$$

where C_1 is constant due to Rayleigh scattering , C_2 is constant due to fibre imperfections and $A(\lambda)$ is a function that describes the fibre impurity absorption as a function of wavelength.

As mentioned in Section 2.3.2, the attenuation for SMF, with a value of 0.35 dB/km at 1300 nm, is exceptionally low compared to copper or coaxial cable. The attenuation at 1550 nm wavelength performs with 0.25dB/km even lower. This gives an optical signal, transmitted through fibre, the ability to travel more than 100 km without regeneration or amplification. The combination of high bandwidth with low attenuation makes the optical fibre an excellent performer over other transmission media. While using fewer regenerators and amplifiers, signals can be transmitted over longer distances, which reduce costs and improve the signal reliability.

2.4.1 Low water peak

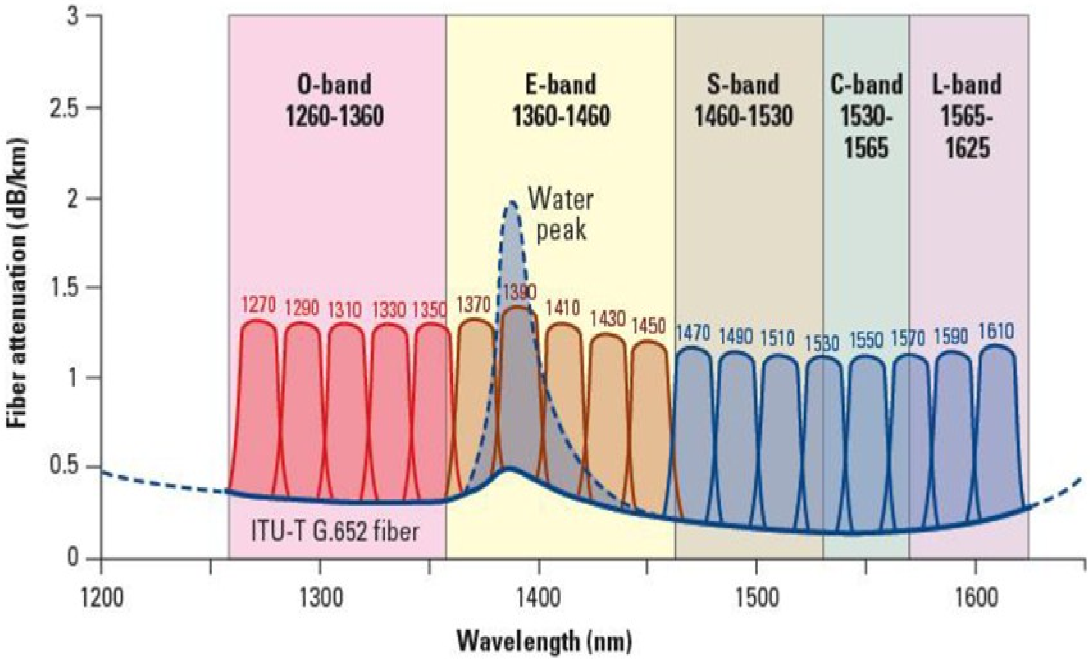

Figure 2-4: Water peak area of CWDM from 1271 nm to 1611 nm [27].

As mentioned in the section above, attenuation is caused primarily by scattering and absorption. The scattering of light, originated by irregularities at a molecular level in the core structure, implicates the usual form of the attenuation graph. Residual materials, such as metals or water ions, within the fibre core and inner cladding absorb photons, which is another reason for attenuation. The hydrogen oxide embedded in the silica (SIO_2) of the fibre cable causes the "water peak" area around 1383 nm on the attenuation curve, as to be seen in Figure 2-4. The broadening effect of the "water peak" region contributes to the attenuation for nearby wavelengths; thus, fibre manufacturers now offer low water peak single-mode fibres, which possess extra bandwidths and flexibility compared to standard SMF. Further factors, such as light leakage due to bends, connectors or splices result in attenuation, as well [16][28].

2.4.2 Rayleigh Scattering

Optical loss in commercial high-quality SMF often originates in the scattering of light along the fibre length, which is called "Rayleigh scattering" [25][26][16]**.** The reason for the scattering is the collisions between the light wave and fibre molecules, which results in light escaping the fibre waveguide or reflecting back to the source. Shorter wavelengths of light are scattered more than longer, due to the characteristic of wavelength sensitivity. This means that the Rayleigh scattering is inversely proportional to the forth power of the wavelength. Therefore, the scattering loss in a fibre can be reduced by increasing the transmission wavelength; long-distance transmission networks operate thus at 1550nm instead of 1310nm. During manufacturing, fibres are cooled very slowly and carefully, to reduce the material imperfections and, therefore, the light loss due to scattering [29].

2.5 Dispersion

Dispersion is defined as the time domain spreading or broadening of the transmission signal light pulses as they travel through the fibre. This can cause interference with adjacent pulses or bits, which leads to Inter-Symbol Interference (ISI) and hence a reduction of the signal-to-noise ratio (SNR). Different types of dispersion can be distinguished:

I. Intermodal or Modal Dispersion.
II. Intra-Modal or Chromatic Dispersion
    a. Material Dispersion
    b. Waveguide Dispersion
III. Polarisation Mode Dispersion.

2.5.1 Intermodal or Modal Dispersion

Intermodal dispersion occurs because each mode of the signal propagates a different distance over the same time period; this means they travel at different velocities along the fibre. The modes of a light pulse, which enter the fibre at one time exit at different times. This condition is the reason for the light pulse to spread. This spreading or broadening of the pulse leads to signal distortion or loss. As the length of the fibre increases, modal dispersion increases. Intermodal dispersion is the predominant dispersion in multimode fibres: this type of dispersion cannot occur in single-mode fibres because they consist of one mode only [15].

2.5.2 Intra-modal or Chromatic Dispersion

This type of dispersion is also a pulse broadening phenomenon. It is defined as the wavelength dependence of the speed of light when traveling through a medium other than a vacuum, such as a glass fibre [21]. Chromatic dispersion leads to pulse broadening with every kilometer the pulses are travelling through the fibre. After some distance, the pulses become broad and overlap with adjacent pulses, which increase the zero level in the transmitted bits stream. Thus, the data cannot be recovered by the receiver and appropriate correction is needed [30][31]. If the pulses spread enough that they begin to interfere with each other, the bit-error rate (BER) of the system starts to rise. As chromatic dispersion is a linear effect, it can be balanced by adding the reciprocal dispersion before any substantial nonlinearity interferes. The material and waveguide dispersion are often referred to as chromatic dispersion, which is defined as:

$$D_{chr} = -\frac{1}{L}\frac{dt_g}{d\lambda} \qquad (2.14)$$

where L is the fibre length and t_g is the time required to propagate a distance L. The subscript g refers to group velocity. When a pulse propagates in a dispersive medium it propagates with the group velocity:

$$v_g = \frac{dw}{d\beta} \qquad (2.15)$$

The phase travels with the phase velocity given by:

$$v_g = \frac{w}{\beta} = \frac{c}{n} \qquad (2.16)$$

The dispersion properties are completely determined by the group velocity.

2.5.2.1 Material Dispersion

Material dispersion is defined as a delay-time dispersion, caused by the fact that the refractive index of the silica varies in agreement with the changing signal frequency respectively wavelength. Material dispersion occurs due to the fact that the refractive index is a function of wavelength n (λ) [32][33][34]:

$$D_{mat} = -\frac{\lambda}{c}\frac{d^2 n_1}{d\lambda^2} \qquad (2.17)$$

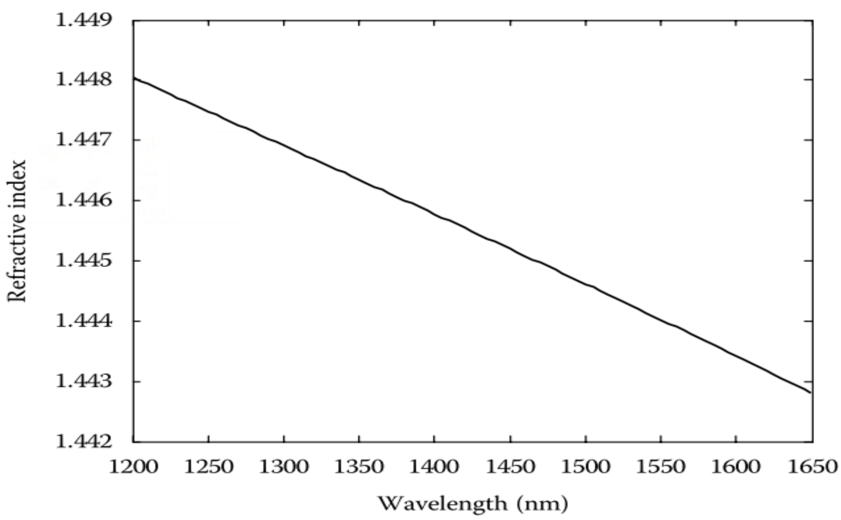

Figure 2-5: Variation in the silica refractive index as a function of optical wavelength.

Figure 2-5 displays that the refractive index of the fibre decreases as the wavelength increases; longer wavelengths propagate faster through the fibre than shorter wavelength. Dispersion of standard SMF is expressed as: D= 16 ps/nm-km; picoseconds of delay, per nanometer of wavelength change, per kilometer of fibre length.

2.5.2.2 Wave-guide Dispersion

Another type of chromatic dispersion is wave-guide dispersion, which is similar to material dispersion so far that both cause signals of different wavelengths and frequencies to separate from the light pulse. However, wave-guide dispersion depends on the chemical composition of the fibre core, its shape and design. Wave-guide dispersion results from the wavelength dependence of the fibre's mode-field diameter (MFD) [25], which is a measure of the beam width of light propagating in a single-mode fibre. Mode-field diameter is a function of source wavelength, fibre core radius, and fibre refractive index profile.

Solely, 80 percent of a light source's power in a standard single-mode fibre is restricted to the core. The other 20 percent propagates via the inner layer of the cladding at a faster velocity, due to the lower refractive index of the cladding than that of the core. Accordingly, signals of varying frequencies and wavelengths are dispersed and the pulse becomes undifferentiated. A rise in the wave-guide dispersion in the fibre can be utilised to adjust material dispersion and shift the wavelength of zero chromatic dispersion to 1550 nm. Wave-guide dispersion is given by [25] [33]**:**

$$D_{wg} = -\frac{\lambda}{c} n_1 . \Delta . \frac{d^2\ b}{d\lambda^2} \qquad (2.18)$$

Where n_1 is the refractive index of the core; Δ is the relative refractive index difference; b is the propagation constant c is light velocity in vacuum and λ is the wavelength.

For fibres fabricated from silica glass, the wave-guide dispersion factor is a negative dimension over the majority of the wavelengths spectrum[25].

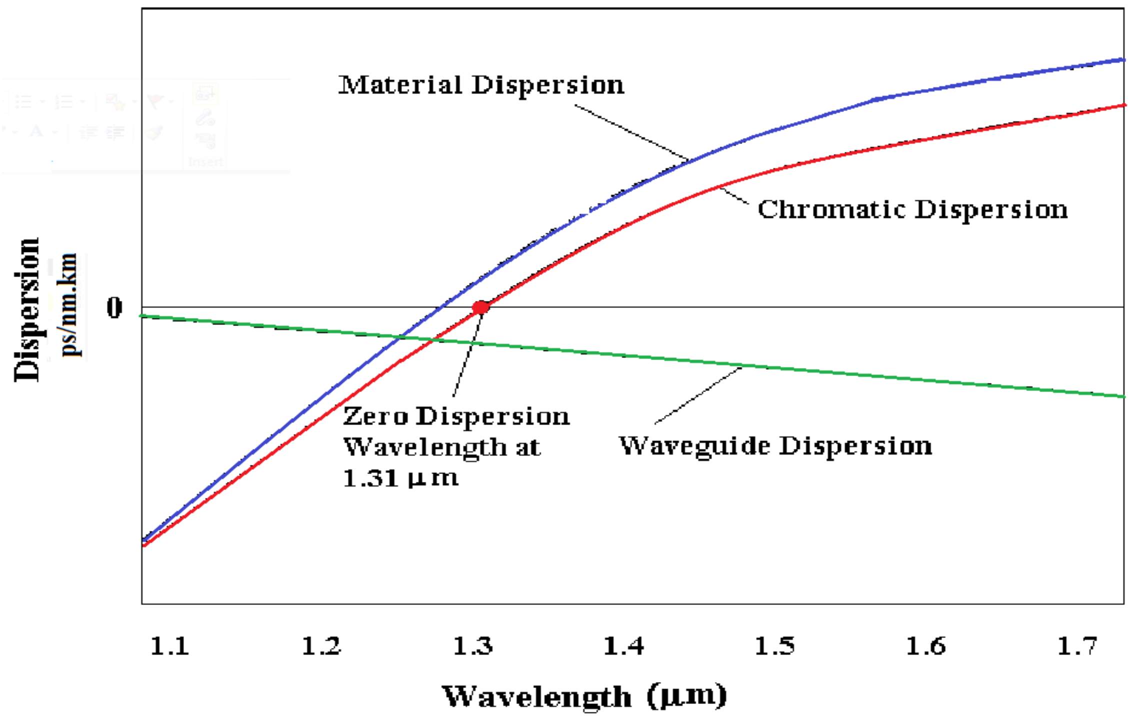

Figure 2-6: Different types of dispersion [32]

As shown in Figure 2-6, the chromatic dispersion is the total sum of material and wave-guide dispersion. Material dispersion determines chromatic dispersion as it exceeds wave-guide dispersion [25]. In SMF, chromatic dispersion ranges at zero for a wavelength of 1.31µm.

2.5.3 Polarisation Mode Dispersion

Polarisation Mode Dispersion (PMD) is caused by imperfections in the fibre and results, like the other described types of dispersion, also in the broadening of the pulse. These imperfections can result from the manufacturing process, temperature changes, weather conditions and the installation process [25][35][36]. Two different polarisations of the light in a waveguide propagate at different speeds, due to the fact that the fibre core is never perfectly circular. This effect, when two orthogonal polarized modes have different group velocities, results in Differential Group Delay (DGD), as displayed in Figure 2-7.

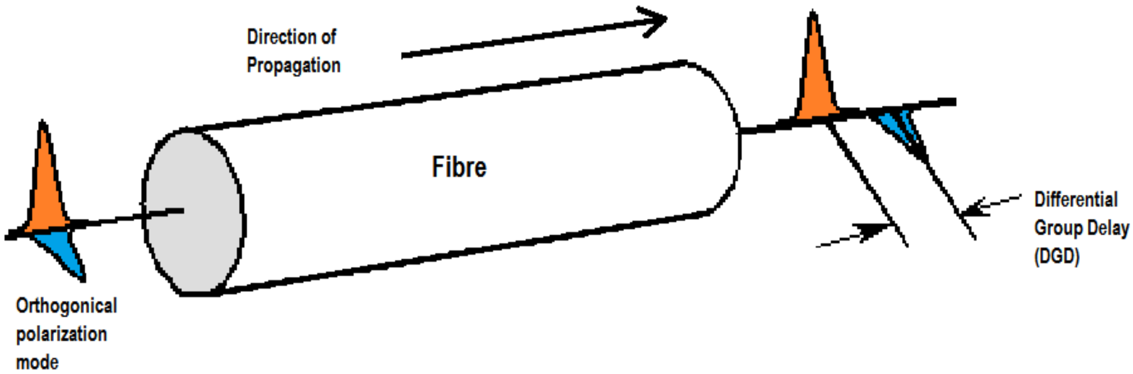

Figure 2-7: Polarisation mode dispersion[16]

2.6 Dispersion Compensating Modules (DCM)

As described in Section 2.5, the main reason for pulse broadening in single mode fibre is chromatic dispersion. In order to compensate chromatic dispersion, recover the initial signal shape and enable signal detection at the receiver, dispersion compensating fibre modules (DCM) are placed in the link. Chromatic dispersion compensation modules, also known as dispersion compensation units (DCU), are fabricated of different spool lengths of dispersion compensating fibre (DCF)[16] [31]. The module can be tuned manually by a network technician prior to or after installation; remotely, using network management software, or dynamically by the module itself. Low bit rate networks can operate without dispersion compensation, even for a transmission over hundreds of kilometres. At high bit rates, as 40 Gbps systems, a transmission distance without dispersion compensation ranges at less than 5 km[37]. Applying DCM, their optical loss must be added to the optical loss budget of the link, and the use of optical amplifiers may be required to compensate. DCMs can be based on different technologies: Dispersion compensating fibre (DCF), Fibre Bragg Grating (FBG), and Chirped FBG (CFBG) are essential fibre components, which are utilised to control the chromatic dispersion, and extend the transmission distance of the signal. In the following sections, these techniques are described.

2.6.1 Dispersion Compensating Fibre (DCF)

The fast development of optical networks accompanied with the increase in transmission distance and data rates demands severe restrictions for chromatic dispersion in optical links. One of the prime appliances to compensate chromatic dispersion for a large bandwidth of wavelengths is to employ dispersion compensating fibres (DCF).

DCF is a highly effective method to overcome the chromatic dispersion in high-speed transmission systems, not only in means of cost effectiveness, but also because of temperature stability, and wide-band dispersion compensating characteristics [38].

DCF is designed to reach a large negative wave-guide dispersion of up to -80 ps/nm, which enables to balance the amount of CD in the fibre. This has the advantage that the dispersion is broadband and adjusts several WDM channels simultaneously without phase distortion. Various DCFs are optimised to balance the dispersion in a single band, e.g., the S-band (1460-1530 nm), C-band (1530-1565 nm), and L-band (1565-1625nm), but are not effective to compensate for dispersion in lower band, i.e. the E-band (1360-1460nm)[39].

A disadvantage of DCF is its typically higher attenuation than SMF, which leads to high insertion loss. A way to overcome this loss would be to increase the signal power. This is acceptable only in a narrow limit, due to the small mode core of the fibre and the long transmission range, which develops nonlinear pulse distortions at high signal intensity.

2.6.2 Fibre Bragg Grating (FBG)

A Fibre Bragg Grating (FBG) is a Bragg reflector placed in a short segment of an optical fibre, which periodically influences the refractive index along the fibre span. Thus, particular wavelengths of light are reflected while all others are transmitted. Accordingly, a FBG can be utilised as an optical filter, which avoids certain wavelength passing the fibre; respectively as a reflector for specific wavelength [40]. Today, FBGs are widely applied in routing, filtering, controlling, and amplification of optical signals, especially in the next generation of high-capacity WDM telecommunication networks [41]. An additional use for fibre Bragg grating is the fibre laser device, where the grating is employed as a resonator reflector. High-power, wavelength-accurate and single-frequency fibre laser transmitters for WDM systems have been designed, due to their advantage of extremely low return loss, very good reflectivity and wavelength stability [42].

In the following equation, the centre wavelength is represented by the well-known Bragg condition**:**

$$\lambda_B = 2.n_{eff}.\Lambda \qquad (2.19)$$

Where λ_B the centre wavelength, n_{eff} is the effective index of the guided mode and Λ is the period of the index modulation [43].

The following equation is related to the forward and backward propagating fields of a Bragg grating with a constant grating period [44] [45].

$$\frac{dU}{dz} = i\delta U(z) + ikV(z) \qquad (2.20)$$

$$\frac{dV}{dz} = -i\delta V(z) - ikU(z) \qquad (2.21)$$

Where U and V represent the forward- and backward-propagating amplitudes of the core mode; δ is the detuning from Bragg wavelength, and k is the coupling coefficient represented by:

$$\delta = \frac{2\pi}{\lambda_0} - \frac{2\pi}{\lambda_B} \qquad (2.22)$$

$$k = \frac{\pi n_g \Gamma}{\lambda_B} \qquad (2.23)$$

The confinement factor Γ (Gamma) refers to the power fraction in the core, represented by:

$$\Gamma = \frac{P_{core}}{P_{total}} \qquad (2.24)$$

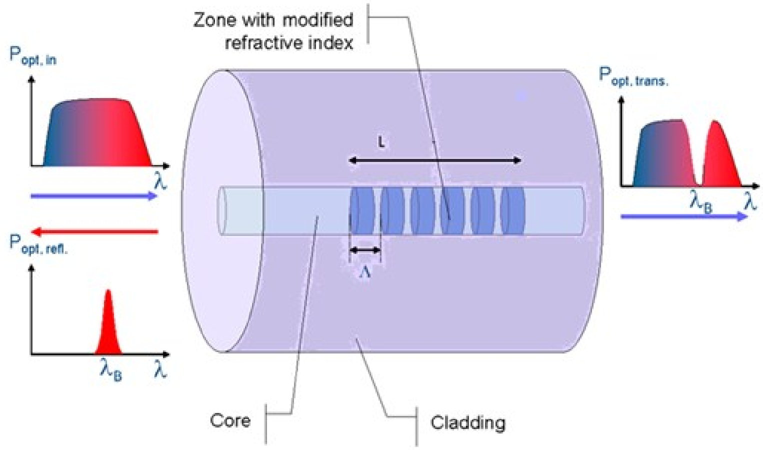

Figure 2-8: Principle of a Fibre Bragg Grating [46]

Figure 2-8 shows the principle of a fibre Bragg grating, where light of a broad spectrum is launched into the fibre and light of a specific wavelength (λ_B), the so-called Bragg wavelength, is reflected. The grating period determines the reflected wavelength. Deployment of the fibre Bragg grating DCM offers the advantage of low insertion loss and high-power handling capabilities without nonlinear signal effects. Fibre Bragg gratings add PMD to the link, which needs to be considered in the PMD budget [16].

A wide range of applications is suitable for the deployment of FBGs: in DWDM or OADM; as EDFA pump laser stabilizer; optical amplifier gain flattening filter; laser diode wavelength filter; tuneable filter; remote monitoring and as sensors.

2.6.3 Chirped Fibre Bragg Gratings (CFBG)

Chirped fibre Bragg gratings have been widely utilised for the compensation of chromatic dispersion, pulse compression and pulse multiplication also for the reduction of power loss. The low insertion loss, nonlinear effects and cost, are the most important benefits of chirped FBGs. A wide range of fibre Bragg gratings are used in optical communication systems, due to their superior performance. The chirp in a grating can take various forms; e.g., the period may appear symmetrical, increasing or decreasing around a pitch in the middle of a grating. Another form is a linear chirp with a linearly varying period over the length of the grating, or a quadratic chirp or one with jumps in the period to correct for linear dispersion[40] [47][48].

The varying wavelengths are reflected by different parts of the grating along the axis and experience a slightly different delay in time accordingly (see Figure 3-18 in Chapter 3). Therefore, the input pulse can be converted by the group delay to balance the chromatic dispersion accumulated along the fibre link. The linear chirp in the grating period is introduced by [44]:

$$\Lambda_N = M^{N-1}\Lambda_1 \qquad (2.25)$$

where Λ_1 represents the starting phase; M stands for the linear change of phase and N is the number of grating periods.

The shortest grating length L_g^{min}, which is required to compensate the accumulated dispersion of an optical fibre link, is calculated as:

$$L_g^{min} = \frac{1}{2}\left(\frac{c}{n_{eff}}\right)\Delta\lambda D_f L_f \qquad (2.26)$$

where c represents the vacuum speed of light; L_f is the whole link length, D_f stands for the dispersion of the fibre, and $\Delta\lambda$ is the compensating bandwidth.

2.7 Radio over Fibre in Communication Networks

Radio over Fibre (RoF) is a developing technology for communication networks, applicable in high-frequency, broadband millimetre-wave access systems. In this system, most of the signal processing, such as coding, multiplexing, RF generation and modulation occur in central stations (CSs). RoF is an analogue optical fibre link used to convey modulated RF signals to enable wireless access. The term RoF is commonly applied for the transmission of radio signals over fibre for wireless access, even though this technique is utilised for various other functions, such as in cable television networks and satellite base stations. The RF signals can be baseband data, modulated IF, or the actual modulated RF signal. They are modulated by analogue or, in most cases, digital modulation techniques, like PSK, QAM, and TCM. Subsequently, the resulting optical signals are launched into the fibre. The RoF architecture serves to transmit the RF signals down- and uplink, i.e., to and from central stations to base stations (BS) [49][50][51][52].

The advantages of radio over fibre are manifold. Since most of the expensive, heavy, and power consuming equipment is now located centrally, remote units are greatly simplified. The centralisation of the wireless access points or radio base stations implies that less radio resources are necessary to provide a given level of service. Radio over fibre has been used extensively in distributed antenna systems around the world, mainly, due to operational cost savings, which provide network operators with significant capital [53]. Further benefits of the RoF systems are:

- Coverage in "dead zone" ; "dead zones" are areas, where wireless signal transmission is not possible because of man-made obstacles, like huge buildings or tunnels, or natural obstacles, like mountains and secluded places. The RoF system is able to cover these zones, as to be seen in Figure 2-9.

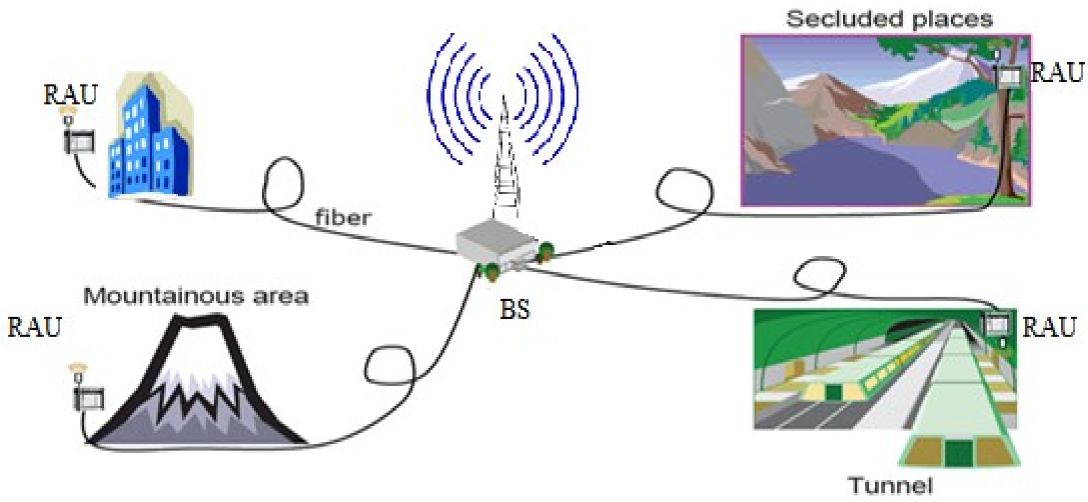

Figure 2-9: Coverage in "dead zone"

- Use of low RF power remote antenna units (RAUs)[54][55]; the benefit is the increased spectrum efficiency; easier frequency/network planning and the low generated interference.
- No electromagnetic interference
- Increased capacity and high-quality signals; the design of fibre optics enables the handling of gigabits speeds, which make them suitable for future network generations.
- Multiple services on a single fibre; services like broadband, mobile and broadcasting are delivered over a single fibre link; broadband multimedia applications for voice and video are supported.

- Line-of-sight (LOS) operation; multipath effects are minimised [55].
- Mobile broadband radio access close to the user in an economically acceptable way;
- Low fibre attenuation; compared to other media especially to wireless, the attenuation, ranging at 0.2dB/km, is much less. The signal travels further, which reduces the need of repeaters.
- Support of intelligent transport systems (ITS); using mobile communication technology to establish road vehicle and inter-vehicle communication networks [54][55].
- Reliability; resistant to bad weather conditions

2.7.1 Direct Modulation

The laser is the prominent feature in fibre optic links as it produces the continuous optical wave that transports the signal. Laser wavelengths are typically 1.3 μm and 1.55 μm, referring to the dispersion, respectively, the absorption minimum of silica fibres; the laser frequency ranges at 200 THz. Two types of modulation can be distinguished: either direct or external.

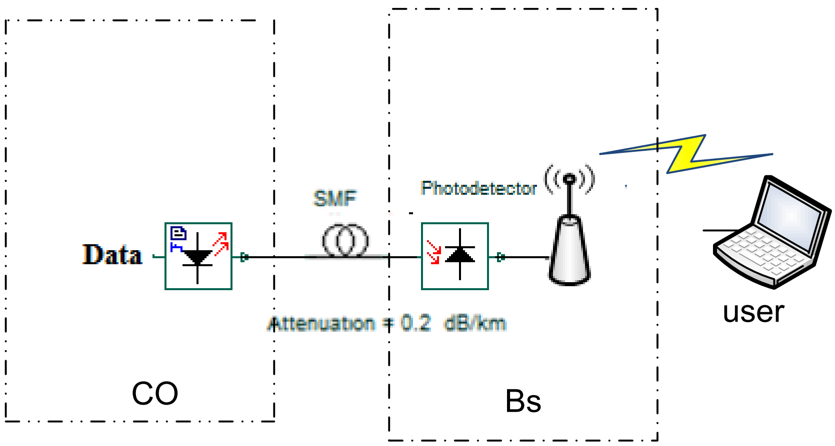

Figure 2-10: Direct modulation

With the direct method, for optically distributing RF signals, the intensity of the light source is modulated directly with the RF signal itself as shown in Figure 2-10. The laser biasing current is changed above and below the threshold value to turn the laser on and off to produce 1 and 0 bits [45]. Subsequently, at the remote antenna site, the photo detector and band-pass amplifier convert the received optical signal to a RF signal to be radiated by the antenna. This relatively simple and low-cost method is called Intensity Modulated Direct Detection (IMDD). Applications of direct analogue laser modulation include cable TV, base station links for mobile communication, and remote antenna [56].

The disadvantage of this technique is the changing of the wavelength with the laser bias current. This chirp of the resulting pulses, where the carrier frequency of the transmitted pulses changes with time, produces a broadening of the optical spectrum relative to the bandwidth. The chirped pulses possess very poor dispersion limits, and if the operating wavelength lies not closely to the zero-dispersion wavelength, serious degradations of the system will appear. For the use of dense WDM in a fibre network, is this degradation not acceptable [45].

2.7.2 External Modulator

The second option, to modulate the intensity of the light, is the external modulation, where the laser operates in continuous wave (CW) mode. As shown in Figure 2-11, an external modulator, such as the Mach-Zehnder Modulator (MZM), is used subsequently. As with direct modulation, the modulating signal is, as well, the actual RF signal to be distributed. The operation of the laser in CW mode avoids the excessive chirp of the pulses. In the case of the utilisation of a low-dispersion fibre in connection with an external modulator, the system is able to achieve linearity. External modulators can operate with bandwidths of up to 40 GHz and bit rates of more than 10 Gbps, which makes them particularly attractive for long-haul optical communication networks. Of course, this modulation system is more expensive than the direct modulation. To support high frequency RF signals, the MZM requires high- drive voltages, which makes use of costly drive amplifiers necessary. Furthermore, inherent static and dynamic non-linearity of the external modulator has to be compensated, which makes the system more complex [57][45].

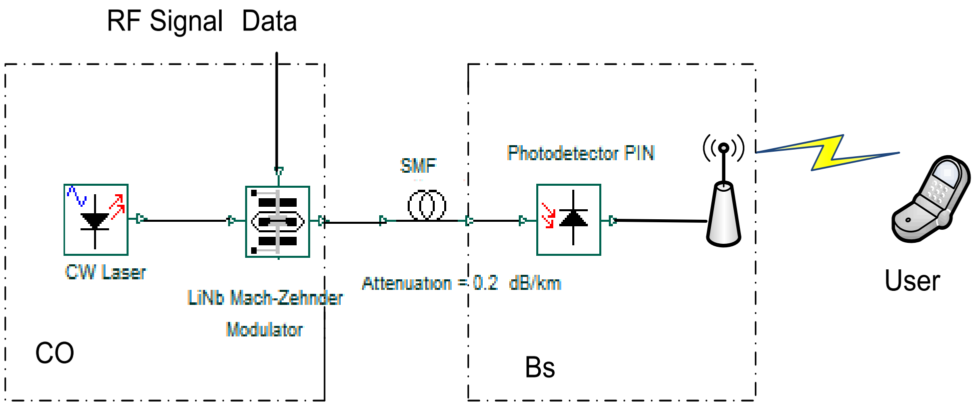

Figure 2-11: External Modulation

2.8 Applications in RoF Networks

In the following section, the techniques of remote RoF, Orthogonal Frequency-Division Multiplexing (OFDM), Wavelength Division Multiplexing (WDM), Dense Wavelength Division Multiplexing (DWDM), and Coarse Wavelength Division Multiplexing (CWDM) are described.

2.8.1 RF over Fibre (remote RoF)

In the usual RF application, the radio signals are deployed through RF copper cables between the base station and the antennas. The deployment of this configuration means for the downlink, from the base station to the mobile antenna, a higher output power of the amplifier to compensate for the RF cable losses. Accordingly, the power consumption and the power amplifier cost increase. Additionally, high-power carrying RF cables are heavy and expensive to build and install also they are susceptible to mechanical malfunction. For the uplink, this configuration yields to degradation of the signal-to-noise ratio, which leads to reduction of the coverage area or an increase of the terminal power consumption. A solution to these problems is the deployment of the signals over remote radio heads and fibre cables, which are significantly smaller, lighter and more cost-effective. The radio head is mainly composed of an antenna, a power amplifier, a low-noise amplifier (LNA), and a duplexer. Further, it consists of up- and down converters and digital-to-analogue (D/A) and analogue-to-digital (A/D) converters. The remote radio head is placed next to the antenna and connected over fibre cable to the base station server. Concerning the downlink, baseband signals are converted electro-optically and sent to the remote radio head via fibre optic cables. There, the optical signals are back-converted to baseband signals and transmitted via the radio head [58]. The great benefits of the remote RF head technology are the large bandwidth and cost-effective coverage in large buildings and remote areas.

2.8.2 Orthogonal Frequency-Division Multiplexing (OFDM)

Orthogonal frequency-division multiplexing is part of multicarrier modulation (MCM) schemes, which employ several subcarriers to transmit parallel low rate data streams. The main benefits of OFDM are its channel dispersion robustness and the easy phase and channel estimation in a time-changing area [59][60]. OFDM has been used in a wide range of communication standards in the RF domain, including digital audio/video broadcasting, wireless local area networks (LANs), digital subscriber line (DSL), and Worldwide Interoperability for Microwave Access (WiMAX)[61]. The subcarriers are themselves modulated by using Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM), where the latter is used in this thesis contribution. Subsequently, they are carried on a high frequency microwave carrier, which is in this research project 2.6 and 3.5GHz. Recent experiments have demonstrated that OFDM can be used to compensate for fibre chromatic dispersion in ultra-long haul communications links. Data rates of 20 Gbps over distances of up to 4160 km can be compensated for chromatic dispersion [62]. However, OFDM also has immanent disadvantages, e.g., high Peak-to-Average Power Ratio (PAPR) and frequency and phase noise sensitivity [60][61][62][63]. An example for the downlink transmission, employing OFDM, is presented in Figure 2-12.

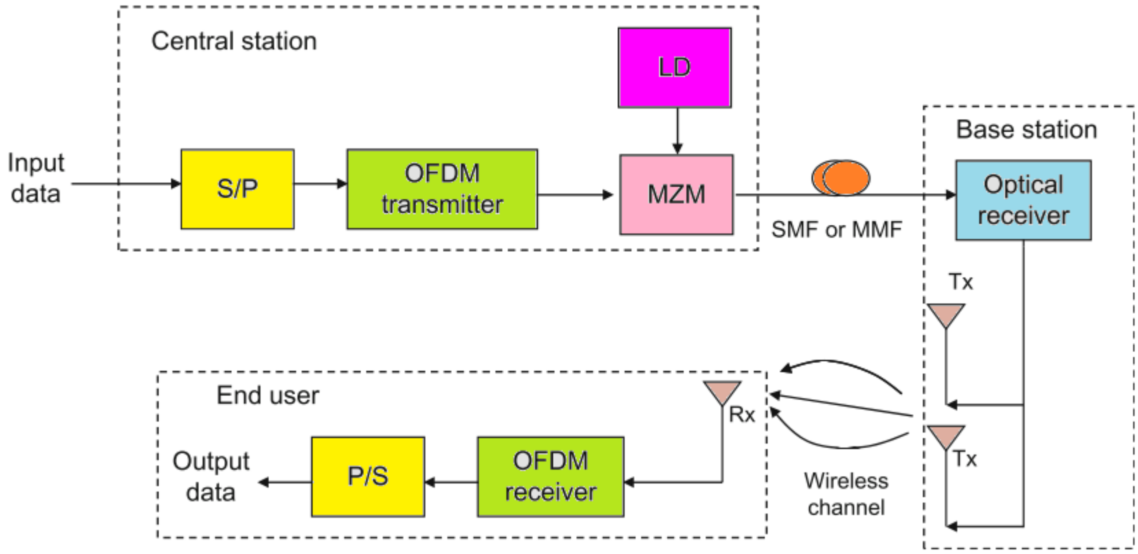

Figure 2-12: Downlink signal transmission, employing OFDM [64]

The data for an individual subscriber is provided in the CS. They are inserted in a number of subcarriers of the OFDM transmitter, which are designated to that user and subsequently, transmitted via optical fibre to a Mach–Zehnder modulator (MZM). The central and base stations are connected via single mode or multi mode fibre, and the optical signal is then converted into an electrical signal by the optical receiver in the BS. From the BS, the signal is transmitted over a wireless channel to the end user's OFDM receiver[64].

2.8.3 Wavelength Division Multiplexing (WDM)

The Wavelength Division Multiplexing describes a milestone in the development of optical communications, enabling a continuous, exponential growth. WDM offers the ability to simplify the network and provides more flexibility. In RoF networks, the introduction of WDM enhances their capacity also increases the number of base stations supported by a single central station. Newly added base stations to the network can be serviced by directing different wavelength channels to them (backhaul) [11][65]. The potential bit rate per WDM channel has increased to 40 Gbps and above, and this application obtains a high tolerance for dispersion [66].

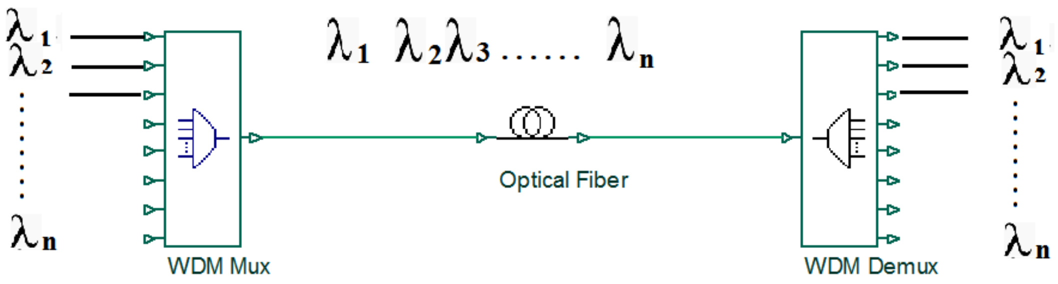

Figure 2-13: Wavelength Division Multiplexing

In optical WDM networks, as illustrated in Figure 2-13, the term "wavelength" is substituted with the term "frequency." Each transmitter sends on a separate wavelength λ_i ,where $1 \leq i \leq N$, to a different receiver [11]. For radio broadcasting, this multiplexing has the advantage of channels transmission at different frequencies without interference. WDM technology is predicted to be part of the new generation of networks. For example, WDM ring networks will use Add-Drop Multiplexers (ADM) and Optical Path Cross-Connect (OPXC) mesh like networks [66].

This thesis demonstrates, in Chapter 4 and 5, the deployment of WDM to transmit LTE and WiMAX-OFDM via a RoF network.

2.8.4 Dense Wavelength Division Multiplexing (DWDM)

Dense wavelength division multiplexing is believed to be the answer for the demand of ever increasing capacity of communication networks. Currently, Internet services are delivered to consumers through cable, which make use of time-division multiplexing (TDM). This technique substantially restricts the available bandwidths for each user. DWDM provides much greater bandwidth by connecting the user's devices directly to the router [67].
DWDM facilitates 32 to 128 channels per fibre also supports various types of fibres with different dispersion characteristics. The increase of the transmission capacity and distance is achieved by the minimised wavelength/channel spacing of optical amplifiers. Wavelength spacing of 0.4–1.6 nm (200–50 GHz) in the 1500–1600 nm wavelength area (C and L bands) is reached. The enlargement of DWDM channels into the S- and L-bands enables to send 320 wavelengths with spacing of 25GHz in the joined C- and L-band with transmission rates per

channel of 10Gbps [56]. The need for multi-tera bits/s of transmission capacities in future large-capacity systems will appreciate the 40 Gbps-based DWDM. The narrow channel spacing requires the utilisation of extremely precise lasers operating with highly stable wavelengths. Additionally, the DWDM de-multiplexer has to be capable to distinguish each wavelength precisely, without crosstalk. Naturally, an expansion of WDM channels produces an increased complexity of the complete optical network [66]; hence the costs rise to operate such a system.

The major drawback of dense wavelength multiplexing is its temperature rise during operation, which leads to a fall in efficiency. An accurate and energy consuming cooling system is needed, which needs itself to be cooled. However, DWDM has increased the capacity of optical links immensely but for the price of high-power consumption. Following estimations, the thermal management of a network applying DWDM consumes up to six times more energy than the optoelectronic circuits, which strains the whole power infrastructure and the environment, as well. Europe is investing in research and development to find sustainable solutions for higher bandwidths, which are cost and environmentally friendly [67].

2.8.5 Coarse Wavelength Division Multiplexing (CWDM)

One of the cost-effective approaches is another variation of WDM, namely, coarse wavelength division multiplexing. This application does not require temperature controlled optical lasers to work accurately. A CWDM grid consists of 18 wavelengths with a typical spacing range of 20–40 nm within the band of 1260 to 1670 nm [66]. The wavelengths deviation tolerance lies within +- 2nm. This tolerance can be reached with the employment of VCSEL light sources, which are not temperature controlled, economical laser diodes. For a single mode fibre, the transmission length target ranges at 50km [68].
Figure 2-14 illustrates the CWDM wavelength division over the entire transmission band (18 channels, 20 nm spacing).With the deployment of low water peak fibres, complying with ITU-T standards, the high attenuation near 1383 nm wavelength can be avoided, as the parameter for attenuation in the figure indicates. The parameter for dispersion alludes to signal broadening, which has a negative effect on the transmission span.

CWDM transceivers are significantly less expensive to purchase and operate than DWDM transceivers; 40 per cent less total system cost is declared. This is attributed mainly to the fact that they can be operated without extensive temperature control circuitry, which avoids the laser deviating from the narrow channel pass band but require a lot of energy. The large CWDM channel pass band of 1600 GHz allows less stringent laser centre wavelength, and spectral width tolerances, which makes this the ideal technology for an increased fibre capacity of up to 18 channels in metro fibre applications [16].

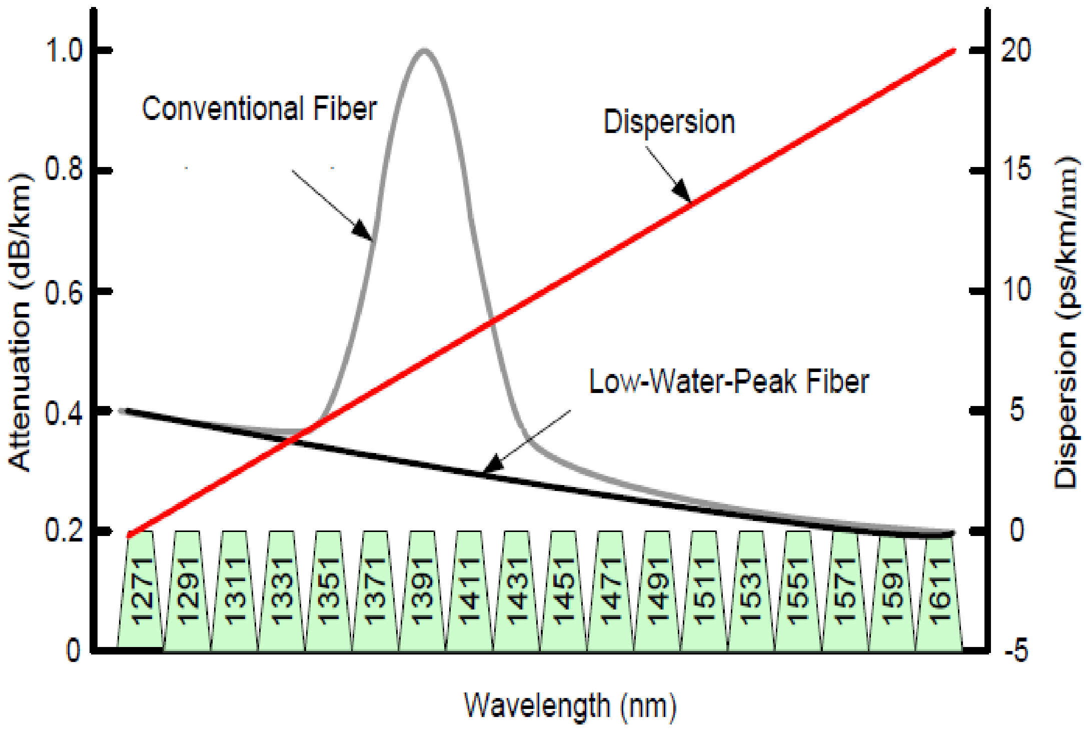

Figure 2-14: 18 channel pass band of CWDM for wavelength from 1271-1611nm [69].

2.9 Chapter Summary

In Chapter 2, the important issues of radio over fibre technology in communication networks were reviewed. Firstly, the propagation of light as a basic of fibre optic communication was introduced. Snell's law was described concerning the refraction of light waves when travelling from one medium into another of different density. The nonlinear Schrodinger equation was presented as a method to design modern light waves systems regarding dispersion and nonlinear effects of the pulse propagation via fibre.

The comparison of multimode and single mode fibres demonstrated the beneficial properties of SMF, such as low attenuation, large wavelength area and high bandwidths capacity over distance. However, there are impairments of optical signal transmission via SMF for more than 100km. Attenuation and especially, chromatic dispersion are responsible for the broadening of the signal over the transmission span and hence a poor signal quality. The dispersion compensating methods, dispersion compensating fibre (DCF), fibre Bragg grating (FBG) and chirped fibre Bragg grating (CFBG) are applied primarily in SMF- based systems to overcome the chromatic dispersion. Even though, DCF is proved to be highly effective overcoming chromatic dispersion, the main drawback is its high attenuation, which leads to signal loss. The FBG is applied in a wide range operating as a router, filter, controller and amplifier of optical signals. As a dispersion compensating method, FBG offers low insertion loss and high-power handling capacities without the difficulty of nonlinear signal effects. The third FBG described in this chapter, CFBG, possesses compensation of chromatic dispersion, pulse compression, and multiplication also reduction of power loss.

The radio over fibre (RoF) technology can be seen as the premier technology for communication networks, due to the advantages of increased capacity high-quality signals and reduced power consumption. The possible operation with gigabit speeds enables RoF being suitable for future network generations. Applying external modulators, e.g., the MZM widens the range of RoF handling bandwidths of up to 40 GHz and bit rates of more than 10 Gbps, which is particularly attractive for long distance optical communication networks. Different applications for RoF networks were presented, which are able to enhance the capacity of the optical system effectively. The application of OFDM has proven to compensate data rates of 20 Gbps over a length of more than 4100km for chromatic dispersion. Wavelength division multiplexing applications, such as DWDM and CWDM, participated enormously in the development of optical communications in means of an exponential, continuous growth. The expansion of DWDM channels allows sending 320 wavelengths with spacing of 25GHz with a transmission rate per channel of 10-Gbps. This is not being reached without the disadvantage of extensive power consumption, consequently high cost and environmental strains. The CWDM application seems to be the ideal technology for an increased fibre capacity of up to 18 channels, due to being more cost efficient and environmentally friendly.

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Chapter 3

64-QAM WiMAX Signals Distributed via RoF Applying Different Compensators

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3.1 Overview

In this chapter, the thesis proposes and demonstrates the improvement of WiMAX power efficiency in green radio communication by utilising a radio over fibre system. Firstly, the simulation is presented for a WiMAX signal transmitted via air for 5Km, and compared to transmission via RoF. In order to compensate for high fibre attenuation and chromatic dispersion, which are the most serious problems creating slops and changes of the frequency spectrum leading to an extremely limited extent of distinct signal transmission, a symmetrical dispersion system was applied. Accordingly, the research project simulated in a second step the transmission of a WiMAX signal via RoF-SMF for a length of 200km, which then was extended by a combination of SMF and DCF to 288km and subsequently by a triple dispersion system, consisting of SMF, DCF, and FBG to 410km. The simulation results show the increase of the signal transmission range and the improvement of the frequency spectrum. Furthermore, the results show a high Signal-to-Noise-Ratio (SNR) also a substantial power reduction of up to 90% in WiMAX-RoF. In a third step, this thesis demonstrates a 120Mbps mobile WiMAX signal transmission via the combination of SMF, DCF and CFBG to overcome the fibre attenuation and chromatic dispersion and thus enhance the data bit rate and the signal transmission length to 792 Km, also simultaneously, the power consumption decreased.

3.2 Introduction

The communication system such as wireless broadband and mobile broadband systems provide a better customer service, by enhancing mobility, accessibility, and simplicity of communication between human beings. Therefore, there has been growing interest in Worldwide Interoperability for Microwave Access (WiMAX) system, WiMAX IEEE 802.16 and 802.16e-2005 mobile. In comparison to Universal Mobile Telecommunication System (UMTS) and Global System for Mobile communications (GSM), WiMAX offers an enlarged significant bandwidth by using the channel bandwidth of 20 MHz and an improved modulation technique (64-QAM) [59].

When equipment is operating with low-level modulation and high-power amplifiers, WiMAX systems are capable to serve larger geographic coverage areas, and they support the different modulation technique constellations, such as BPSK, QPSK, 16-QAM, and 64-QAM. WiMAX physical layer consists of OFDM that offers resistance to multipath. It permits WiMAX to operate in non-line-of-sight environments (NLOS), and particularly is understood for alleviating multipath for wireless broadband. WiMAX provides modulation and forward error correction (FEC) coding schemes adapting to channel conditions; it may be changed per user and per frame [70]. Theoretically, the average cell size of WiMAX ranges up to 50 km and bit rate up to75 Mbps for a channel band of 20 MHz but in reality, the bit rate ranges up to 7 Mbps and the coverage area up to 8 km only. To achieve the defined optimum, the following problems in transmitting the signal have to be solved: path loss, channel interference, fading, Doppler spread, and multipath delay spread [59] .

The electrical distribution of high-frequency microwave signals either through free space or transmission lines causes difficulties and costs. Losses increase with frequency in free space, due to absorption and reflection, and in transmission lines, impedance raises with frequency, which leads to extremely high losses. Therefore, the operator requires expensive regenerating equipment to deliver high frequency radio signals electrically over long distances. The alternative would be to distribute baseband signals and radio frequency (RF) signals via fibre. RF or baseband signals are modulated by an optical carrier, which is produced in the laser diode. At each base station, the optical carrier is down-converted to the appropriate microwave or mm-wave frequency and is transmitted via SMF or MMF. Reverse, from user to the base station, the signals would be up-converted [71] [72].

The radio in millimetre-wave (mm-wave) band is the promising media to convey the ultra-broadband signal in the wireless telecommunication system, and since the recent ten years has been developing to a preferred research topic. By an optics system, the mm-wave signal readily is generated and can be transmitted via a long fibre length. In the RoF system, the generation of the optical mm-wave is one of the key techniques. Several techniques are able to generate the optical mm-wave at around 60 to 120GHz including direct modulation of the laser diode (LD), heterodyne technique with optical phase locking, electrical sub harmonic injection, and external modulation. Of all these techniques, the optical external modulation is an appropriate option to generate the optical mm-wave signal with high spectral purity [18].

RoF systems are analogue fibre optic links, which are used to transmit demodulation signal carrier of radio frequency (RF) directly or indirectly from a central station (CS) to a base station (BS) through remote unit antenna (RAUs) or radio accesses antennae (RAP) to the client[73].

In order to find leading techniques for the WiMAX network deployment, Radio over Fibre has been studied extensively in recent years. Many studies have been focused on the fibre [18][53][49][74], the low attenuation (0.2 dB/km), and high-performance solution for high-speed fibre based on wireless access. The utilisation of millimetre-wave (MMW) frequency for high-speed wireless access in future RoF systems would comply with the demand of high bandwidth also reduce the spectral congestion at low frequency. Surely, the RoF system is the future network technology which has on one hand the capacity to meet the requirements of decreasing electromagnetic smoking, wireless traffic, power, noise, cost, and antenna size and, on the other hand, to increase frequency, bandwidth, data rate and capacity and eventually improves the spectral efficiency.

So far, the investigations focus on the resolution of the dispersion effect and control of the chromatic dispersion. This research project applies the compensator methods to balance the dispersion slope in a fibre, which are demonstrated in the form of DCF and CFBG. DCF has proved to be effective to overcome chromatic dispersion in high-velocity light; with a specific design consisting of a fibre and a negative dispersion slope [75], it compensates the positive dispersion in the SMF. Additionally, an optical amplifier and a chirped CFBG are employed, due to the high-insertion loss of the DCF.

CFBG is a high Bragg reflector placed in a short segment of an optical fibre, used to correct chromatic dispersion.

It can be used as a wavelength-specific reflector or an inline optical fibre. CFBGs are extensively employed for functions such as dispersion compensation, stabilizing laser diodes, and adding/dropping multiplexing in optical fibre systems. The CFBGs comply with environmental requirements by increased stability and durability (free from rust); they can be highly multiplexed (many sensing points in a single fibre cable) and have the advantage of low-power attenuation through transmission over several kilometres [76].

This section of the thesis describes the applied methods aiming to achieve the extension of the WiMAX signal transmission distance through utilising a RoF system; simultaneously, aiming to reduce the power consumption significantly and to achieve adequate OSNR, SNR also high quality signal transmission spectrums. The work focuses on WiMAX signals transmitted via RoF applying the different compensator modules SMF, DCF, FBG and CFBG.

The following section focuses on the power consumption, when a wireless signal is transmitted from a base station to the client over a distance between 1-5 kilometres.

3.3 Methodology

There are different methods carrying out research in the field of optical systems, like experiments and simulations. The building of a design and the testing of it in practical experiments is an expensive and time-consuming method. In the case of this study, it would have been necessary to actually produce the DCF, FBG, CFBG, and other optical components with the specific configuration requirements of i.e. dispersion parameter and chirp lengths. Furthermore, measurement equipment for fibre optic networks is very expensive.

To minimise time and cost requirements also to broaden the investigation, this study focusses on simulation experiments based on OptiSystem software in order to investigate the performance of signal transmission for different comprehensive setups. The software design tool OptiSystem, from the Canadian company Optiwave, is used by telecommunication companies worldwide, like Huawei, Alcatel, Fujitsu, Anritsu etc. A wide range of optical and wireless components and parameters for planning entire optical networks are offered by this simulation tool, which enables the researcher to work highly effectively in a narrow cost and time frame.

3.4 Setups and Simulations of Green Radio Solutions for the Deployment of WiMAX

In general, green radio communication means a reduced power consumption of the communication systems by removing some of the electrical active components and equipment, replacing the passive photonic devices, and centralizing the signal processing. This thesis proposes and demonstrates comprehensive setups to improve the WiMAX power efficiency in green radio communication by utilising a radio over fibre system. The utilisation of the compensator modules SMF, DCF, FBG, and CFBG, in the design of different simulation setups allows the extension of the transmission range from 180km to 792km and improves the power-consumption of the proposed RoF systems.

In this section, a simulation in Matlab-Simulink for WiMAX IEEE 802.16 64QAM is undertaken; the WiMAX signal is transmitted via air with the target to measure and calculate the energy consumption per kilometre between the WiMAX base station and the client's antenna. The simulation result for power consumption is compared to the results of the signal transmission via RoF.

3.4.1 WiMAX-Tx via Air

The following section describes the simulation of 64 QAM -WiMAX IEEE 802.16 Wireless MAN-OFDM PHY model in Matlab-Simulink to indicate the high energy consumption and extremely limited transmission range of a wireless system, where the signal is sent via air. This setup allows the examination and measurement of the power consumption, and SNR for the distance from 1 to 5 KM for a via air transmitted 31 dBm and 3.5 GHz WiMAX signal.
As illustrated in Figure 3-1, the WiMAX transmitter is placed on top of an antenna, usually of 30m height and from there the Tx sends the signal within a radius of 1 to 5km. In the customer's area, the WiMAX receiver is placed, receiving the radiated signal for different services, such as mobile telephony, business access and backhaul, mobile and fixed broadband access.

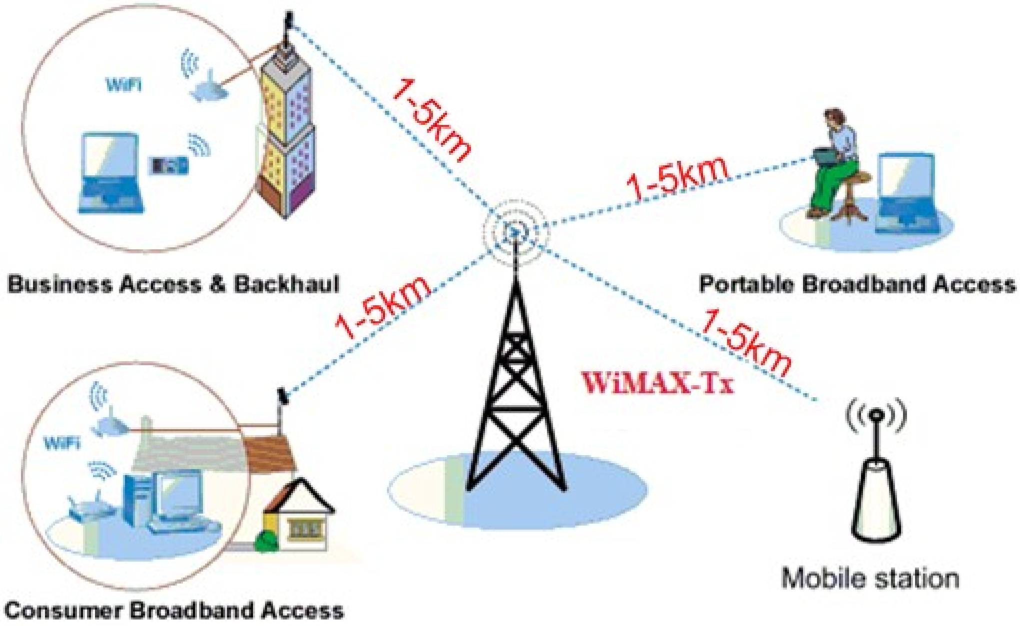

Figure 3-1: WiMAX transmitter's radiation.

Through a fading channel, the WiMAX system will be able to shift to a lower modulation scheme to maintain the quality of connection and link stability. This capacity enables the system to overcome the time-selective fading. Adaptive modulation widens the range of higher modulation schemes being applied. The system can be flexible against actual fading conditions instead of a fixed configuration that is projected for the worst-case conditions. After the signal modulation, the data signal would be distributed by WiMAX Orthogonal OFDM technology, which provides the operator with an efficient mechanism to overcome the challenges of NLOS propagation The WiMAX OFDM signal offers the benefit to be able to operate with the larger delay spread in the NLOS channel. The OFDM signal has eliminated the inter-symbol interference (ISI) problems and the complexity of the adaptive equalization, because of the long OFDM symbol period and by using a cyclic prefix [70].

3.4.1.1 Simulation Results and Discussion

Figure 3-2 illustrates the WiMAX receiver power over distance. The power measures 14.67dB for the length of 100 m via air. For a transmission distance of 900 m, the power ranges at -28dB; for a distance of 2000m at -50dB and for 5km at -175dB. Overall, the power attenuation lies at -189.67 dB for a transmitted WiMAX-RF via air to WiMAX-Rx for 5km length.

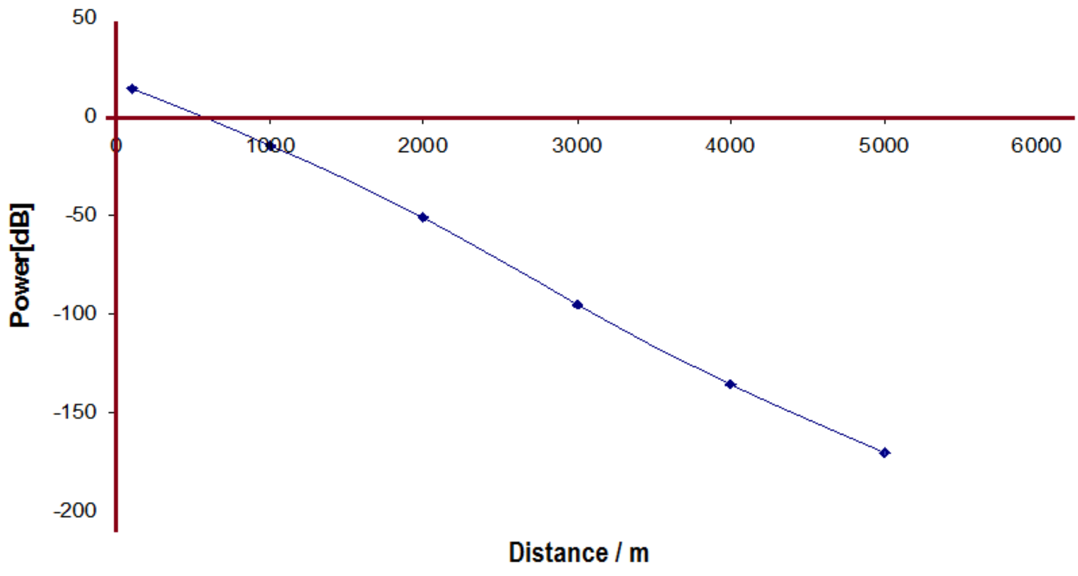

Figure 3-2: Power attenuation in air.

This result proves that the power consumption is too large, and it would not be possible to transmit a signal over air for a long distance.

3.4.2 WiMAX via RoF-SMF

In this setup, the WiMAX signal is converted to an optical signal and transmitted over a fibre optic cable, called Single Mode Fibre (SMF), to extend the WiMAX signal transmission for more than 100km and to prove that the fibre optic medium is ideal for long transmission distance.

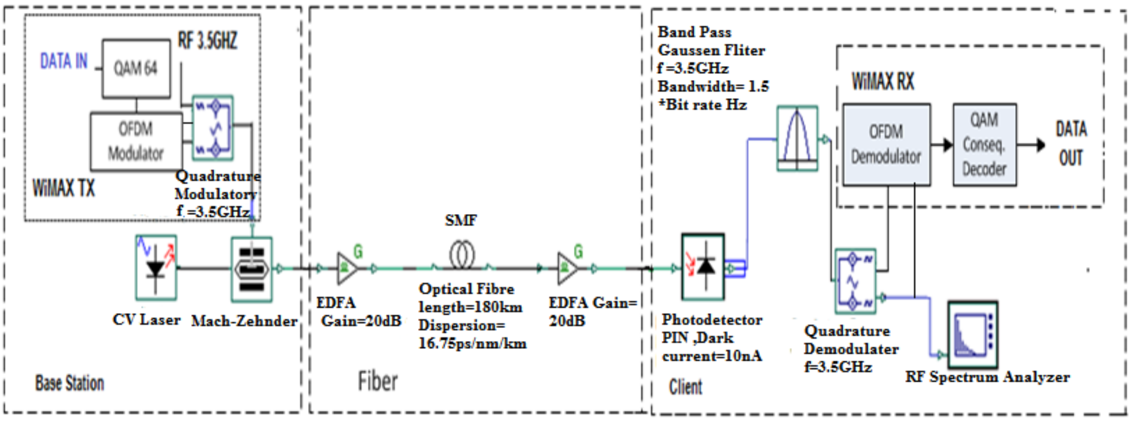

Figure 3-3: Setup schematic of Downlink WiMAX via RoF-SMF length 180km

Figure 3-3 displays the setup configuration for the downlink WiMAX via the RoF-SMF system for the SMF length of 180km; dispersion 16ps/nm/km. The WiMAX transmitter is configured for QAM 64 (6 bit-per-symbol) for a data rate of 54Mb/s and code rate of ¾. Orthogonal frequency division multiplexing (OFDM) is used in the IEEE 802.16-2005 standard for fibre networks. The LiNb Mach-Zehnder Modulator is applied to modulate the WiMAX-Tx with 3.5 GHz RF carrier frequency to the optical carrier with the laser diode signal CW of 193.1THz. The CW laser diode power is swept to 5dBm. The optical signal is transmitted through the SMF with the signal attenuation of 0.2dBm/km, dispersion of 16 ps/nm/km, and the dispersion slop is 0.075 ps/nm2/km . To amplify the optical power signal, an EDFA amplifier is used at the end of the SMF link.

The incoming optical signal is detected by a Photodiode (PD) and converted to the electrical RF signal, then amplified and transmitted over the wireless path for 300m to the BS antenna and to the WiMAX Rx. The PD has the following parameters: 10nA dark current, responsivity 1A/W, thermal noise $100e^{-24}$W/Hz and centre frequency 193.1THz . At the WiMAX –Rx, the electrical band-pass Gaussian filter is used to minimise the electrical signal noise and group delay becomes constant for all frequencies. In a receiver, a band-pass Gaussian filter allows signals within a selected range of frequencies to be heard or decoded, while preventing signals at unwanted frequencies from getting through the centre frequency ; where f_0 is set up to 3.5GHz for a bandwidth of 20MHz.

The RF signal is demodulated by the Quadrature demodulator, which implements an analogue demodulator, using a carrier generator for Q and I Quadrature components; it consists of two low pass filters. The cut off frequency of the low pass filter is configured to 7GHz; the OFDM demodulator is implemented by a complex point 1024 FFT; in OFDM the FFT is used to realize multi-carrier modulation, which reduces the complexity of OFDM systems greatly.

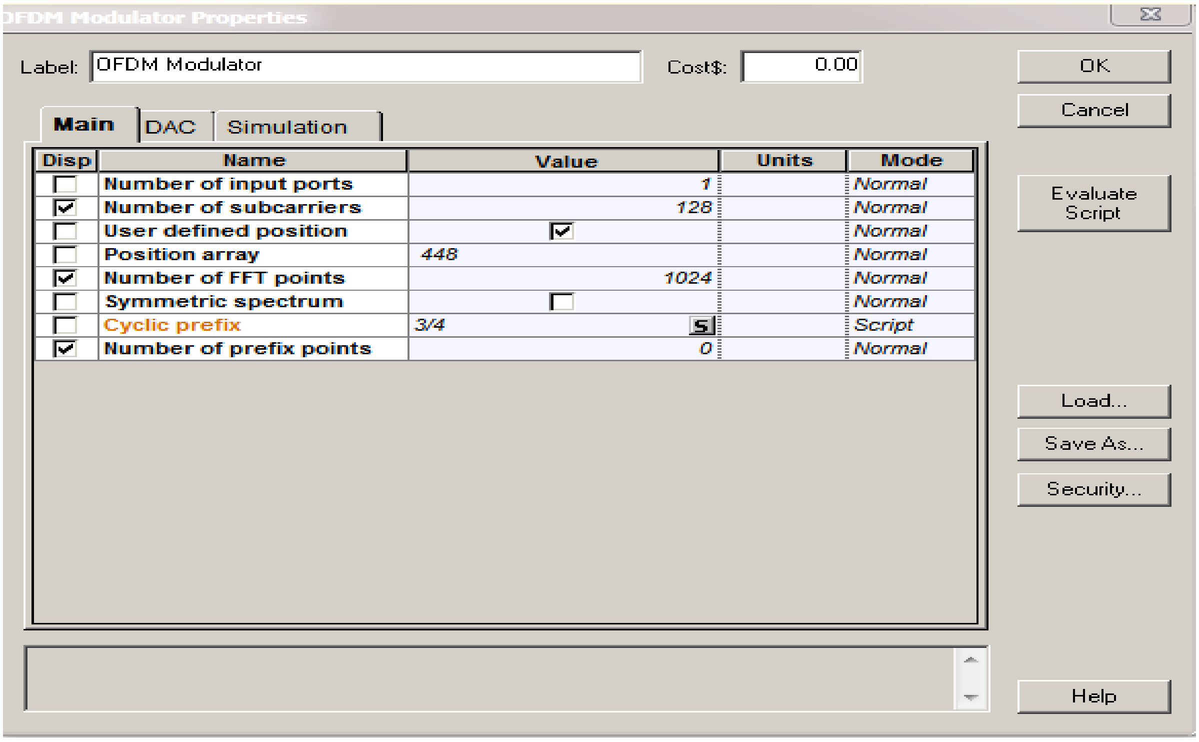

Figure 3-4: OFDM modulator properties of WiMAX-Tx

As shown in Figure 3-4, the transmission parameter of OFDM comprises 128 sub-carriers with a large FFT of 1024, given a general bandwidth of 20MHz, and the OFDM output is modulated with a Quadrature modulator according to (3.1) [77].

$$V_{out}(t) = G[I(t)\cos(2\pi f_c t + \emptyset_c - Q(t)\sin(2\pi f_c t + \emptyset_c)] + b \qquad (3.1)$$

Where I and Q represent the input electrical signals, G stands for Gain, b for bias, $f_c = 3.5GHz$ is the carrier frequency, and $\emptyset_c$ represents the phase of the carrier.

A band-pass Gaussian filter is used to minimize the electrical signal noise and group delay becomes constant for all frequencies. The filter transfer function is described as follows:

$$H(f) = \alpha e^{-ln\sqrt{2}\{2\frac{(f-f_c)^{2N}}{B}\}} \qquad (3.2)$$

Where $H(f)$ represents the filter transfer function, α the insertion loss, and f_c the filter centre frequency, B stands for bandwidth, N for order, and f for frequency.

A Quadrature demodulator recovers the signal from RF to baseband and sends it to the OFDM demodulator; the cyclic prefix is removed before the packet data is sent to an FFT for demodulation.

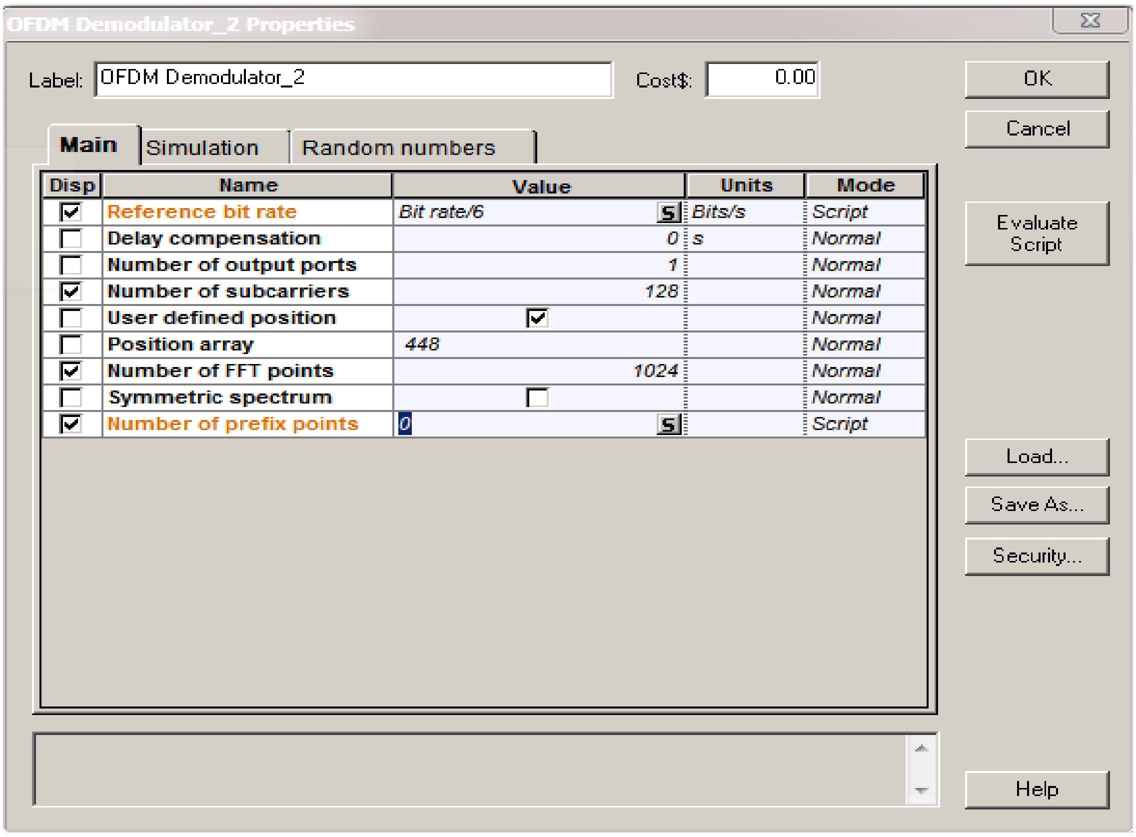

Figure 3-5: OFDM Demodulator properties of WiMAX-RX

Finally, the signal is decoded by a QAM decoder to create a binary signal. As displayed in Figure 3-4, the parameters for the OFDM demodulator are: bit rate divided by 6; subcarrier 128; and FFT 1024.

3.4.2.1 Simulation Results and Discussion

In this section, the simulation results for the 64-QAM WiMAX signal deployment for RF 3.5GHz and 20MHz via RoF for the SMF length from 20km to 180km are described and discussed; the signal is transmitted to the WiMAX-Rx via different fibre lengths.

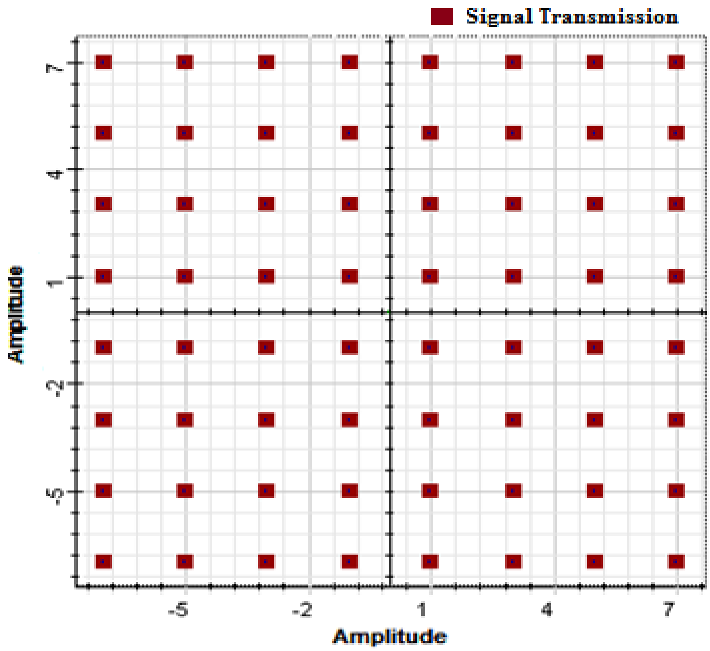

Figure 3-6-a: Constellation for WiMAX signal transmission at WiMAX-Tx.

Figure 3-6-a shows a clear electrical constellation diagram for the signal transmission for 64-QAM digital modulator 6 bit (2^6) at the WiMAX-Tx. A constellation diagram represents a digitally modulated signal, displaying it as a two-dimensional scatter diagram. Constellation diagrams measurements identify the interference and distortion in a signal. The input SNR is measured at 116.96dB.

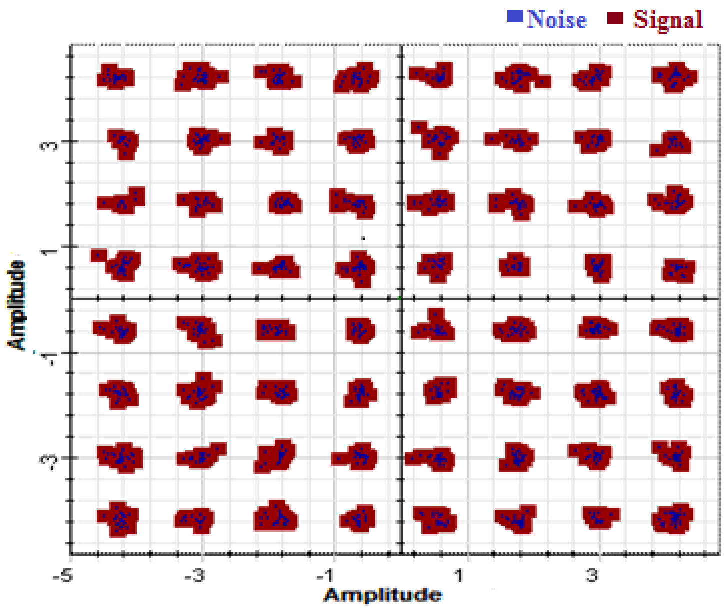

Figure 3-6-b: Constellation for WiMAX signal transmission at WiMAX-Rx for SMF length 20km.

Figure 3-6-b shows the constellation of the 2^6 64-QAM WiMAX-Rx signal at the receiver after 20km fibre length. Compared to Figure 3-6-a, the SNR degraded to 70dB and the signal starts to become unclear, because of noise, power attenuations, chromatic dispersion, and Rayleigh scattering. Power attenuation means the reduction of light power or signal strength over the length of the fibre cable and is measured in decibels per kilometre (dB/km). The SMF power attenuation ranges at 0.2dB/km. The blue points represent the noise of the laser diode (threshold and dynamic), which is independent from the laser diode quality, noise from PD (thermal, shot), and from optic dispersion.

Rayleigh scattering occurs, due to the collisions between the light wave and fibre molecules, which results in light escaping the fibre waveguide or reflecting back to the source. The scattering is wavelength sensitive, whereby shorter wavelengths of light are scattered more than longer, which means, that the Rayleigh scattering is inverse proportional to the forth power of the wavelength. Therefore, the scattering loss in a fibre can be reduced by increasing the transmission wavelength; long-distance transmission networks operate thus at 1550nm instead of 1310nm. Chromatic dispersion leads to pulse broadening with every kilometer the pulses are travelling through the fibre. After some distance, the pulses become broad and overlap with adjacent pulses, which increase the zero level in the transmitted bits stream. Thus, the data cannot be recovered by the receiver and appropriate correction is needed.

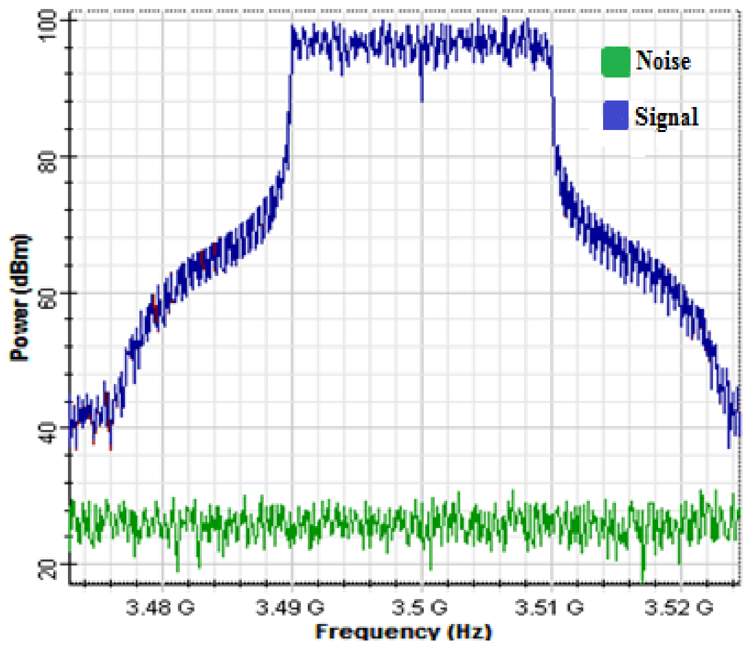

Figure 3-7: RF spectrum for WiMAX over RoF for SMF fibre length 20km

Figure 3-7 illustrates the clear RF spectrum of 64-QAM WiMAX-Rx for 3.5GHz carrier frequency and a bandwidth of 20MHz; the signal is deployed via SMF for fibre lengths of 20km; the PD converts the optical to an electrical signal, which subsequently is transmitted to the receiver. The RF power is measured at 99dBm. The figure shows the carrier frequency is 3.5GHz and bandwidth 20MHz (3.51GHz-3.49GHz), the noise, which is represented in green colour, is at 30dBm; the blue colour represents the signal.

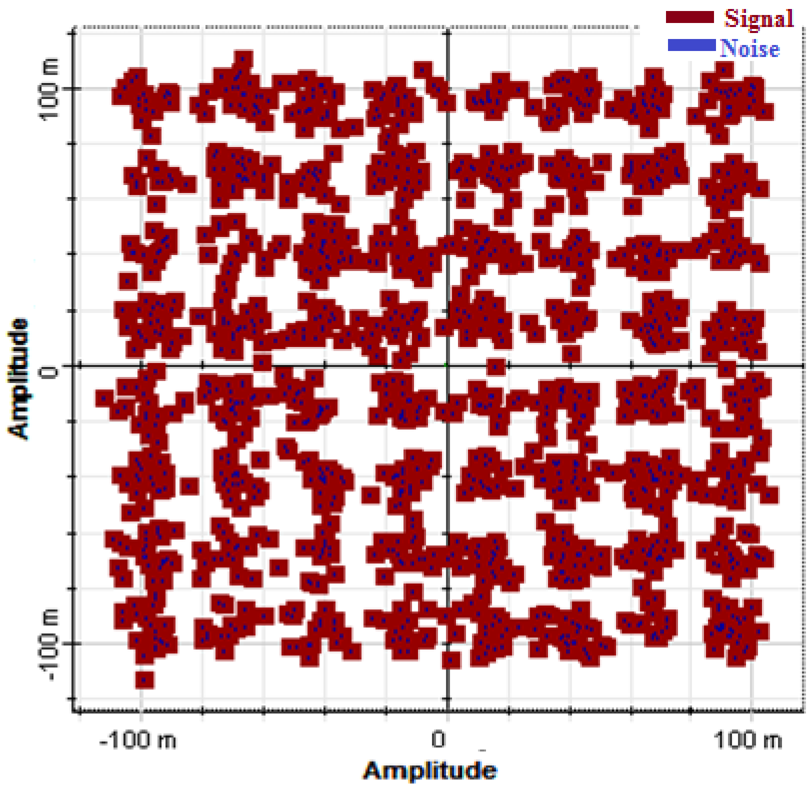

Figure 3-8-a: Constellation at WiMAX-Rx after 100km SMF length.

Figure 3-8-a displays the constellation of 64QAM WiMAX-Rx for 3.5GHz and 20MHz bandwidth after 100km SMF length. It shows, the distortions in the signal at the receiver have increased, because of the signal power attenuation, noise, signal delay (phase shift) and chromatic dispersion effects the noise, which is represented in blue colour and the signal is presented in red colour.

Positive dispersion in SMF causes the broadening of the pulse over the transmission distance of 100km. The pulses overlap with adjacent pulses and the data cannot be recovered by the WiMAX receiver. Therefore, it is essential to control the positive dispersion in SMF by applying compensating fibre components.

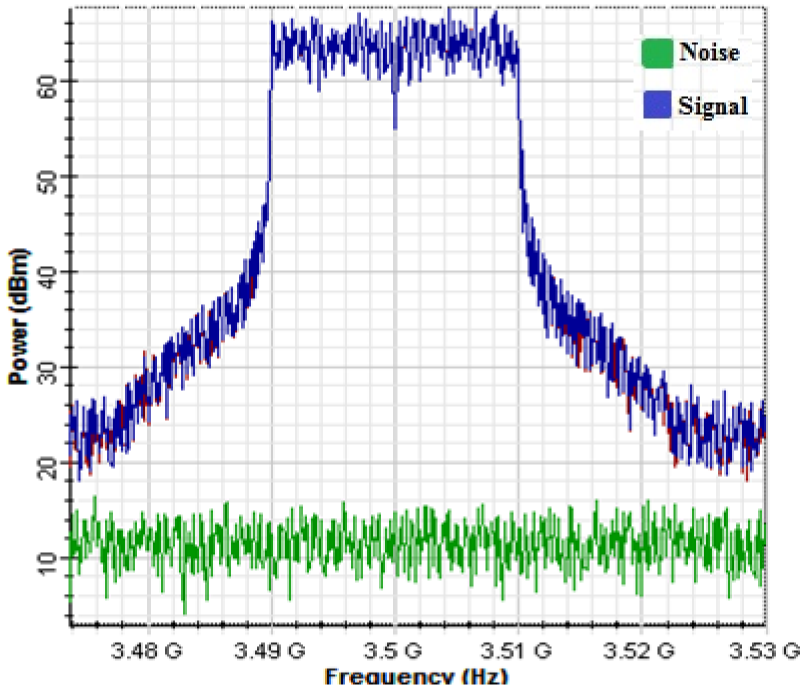

Figure 3-8-b: RF spectrum of WiMAX-Rx after 100km SMF fibre length

Figure 3-8-b illustrates the RF spectrum at the 64QAM WiMAX receiver; the signal is deployed over SMF for a length of 100 km; the power is measured at 65dBm. The result shows that the electrical power is reduced from 99 dBm to 65 dBm when the distance is increased to 180km, due to the attenuation in the fibre; the signal is represented in blue and the noise in green colour.

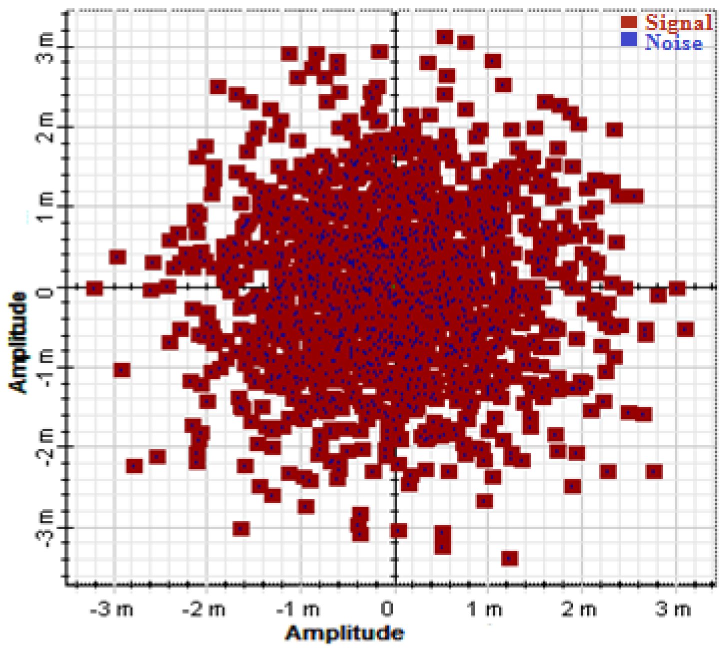

Figure 3-9-a: 140km SMF length, EDFAs power of 35dB.

Figure 3-9-a shows the electrical constellation after 140km, where the signal is corrupted. As mentioned before, the signal began broadening after 100km because of positive dispersion in SMF. The chromatic dispersion in SMF after a long distance can affect the signal quality as well as increase the power attenuation, which is a result of absorption and scattering. The absorption leads to a loss of the photons, and their energy is transformed into heat. Scattering implies, minor defects in the fibre redirect or scatter some light into rays that are no longer conducted by the fibre.

The power amplifier EDFA is increased to 65dB to amplifier the transmission signal in the fibre, and efficiently amplifies light in the 1550 nm wavelength region, where SMF has its loss minimum. An EDFA works like a pump with a wavelength around 980 nm and is combined with the 1550nm fibre optic transmission wavelength. The wavelength 1550nm is amplified through interaction in the erbium area.

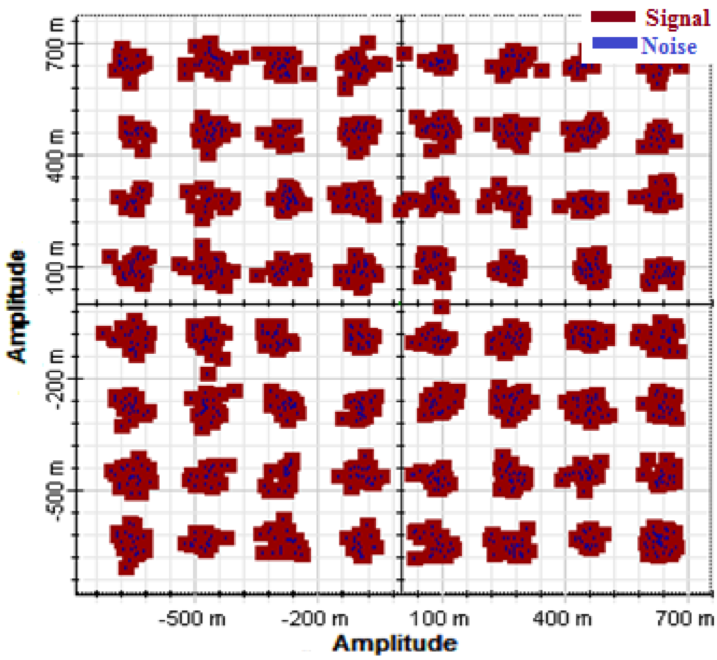

Figure 3-9-b: Constellation at WiMAX-Rx after 140 km fibre length for EDFAs power 65dB

Figure 3-9-b presents the electrical constellation after an increase of the EDFA power to 65dB. Compared to Figure 3-9-a, where the EDFA is at 35dB; the signal at WiMAX-Rx shows a clear improvement with EDFA at 65dB. The SNR is measured at 62dB and OSNR at 99dB; the signal is represented in red colour and the noise in blue.

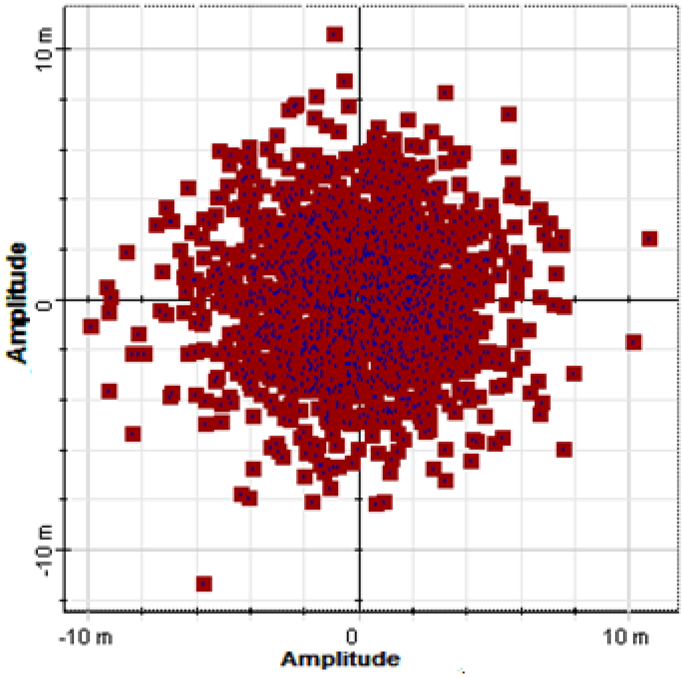

Figure 3-9-c: Constellation after180km SMF length for EDFAs power of 65dB

Subsequently, the signal transmission distance is increased to 180km fibre length, and the EDFAs power is increased to more than 65dB but still the signal corruption has not changed, as shown in Figure 3-9-c. This means the power amplifier cannot affect the signal quality for a fibre span of 180km, because the EDFA only amplifies effectively, when the transmission signal obtains a low power loss.

At a SMF length of 100km, the optical power amplification is increased from 22dB to 35dB, and finally at 150km, the power is scaled up to 65dB to deal with the signal attenuation as well as to improve the optical signal. At a SMF length of 180km, the optical signal is rather weak and despite the EDFAs power is increased, the signal does not improve. To amend the WiMAX transmission signal in the fibre for distances over 180km without the need of increasing the power of the amplifier, a dispersion compensation system is proposed. In the next section, the simulation design is amended to increase the signal transmission distance without increasing the power amplifier by adding an optical component to the SMF fibre.

3.4.3 WiMAX via RoF (SMF-DCF)

Figure 3-10 illustrates the setup configuration for the downlink WiMAX via the RoF-SMF system for the SMF-DCF; SMF dispersion 16ps/nm/km and DCF dispersion at -80ps/nm/km. The WiMAX transmitter is configured for QAM 64 (6 bit-per-symbol) for a data rate of 54Mb/s and code rate of ¾. Orthogonal frequency division multiplexing (OFDM) is used in the IEEE 802.16-2005 standard for fibre networks. The LiNb Mach-Zehnder Modulator is applied to modulate the WiMAX-TX with 3.5 GHz RF carrier frequency to the optical carrier with the laser diode signal CW of 193.1THz. The CW laser diode power is swept to 5dBm.
The optical signal is transmitted through the SMF-DCF. The SMF power attenuation is at 0.2dB /km and DCF is at 0.6dB/km. The SMF dispersion slop is 0.075 ps/nm2/km. The photo detector diode at the end of the fibre converts the optical power Po to an electrical current signal and transmits it to the WiMAX-RX. The photo diode has the following parameters: 10nA dark current, respectively 1A/W, centre frequency 193.1THz. To amplify the optical power signal, an EDFA amplifier is used at the end of the SMF link. Extending the transmission distance in the fibre optic link, a symmetric system of 2xDCF and 2xSMF is applied. The DCF is used as a tuner in RoF systems; the SMF dispersion is 16 ps/nm/km for fibre length 120km and has an accumulated dispersion of 16x120=1920ps/nm. To compensate for the dispersion in SMF a 24km long DCF with dispersion of -80ps/nm.km (24×80=1920 ps/nm) is used. The EDFA power is set to 65dB equally to the EDFA power in the system for WiMAX over SMF.

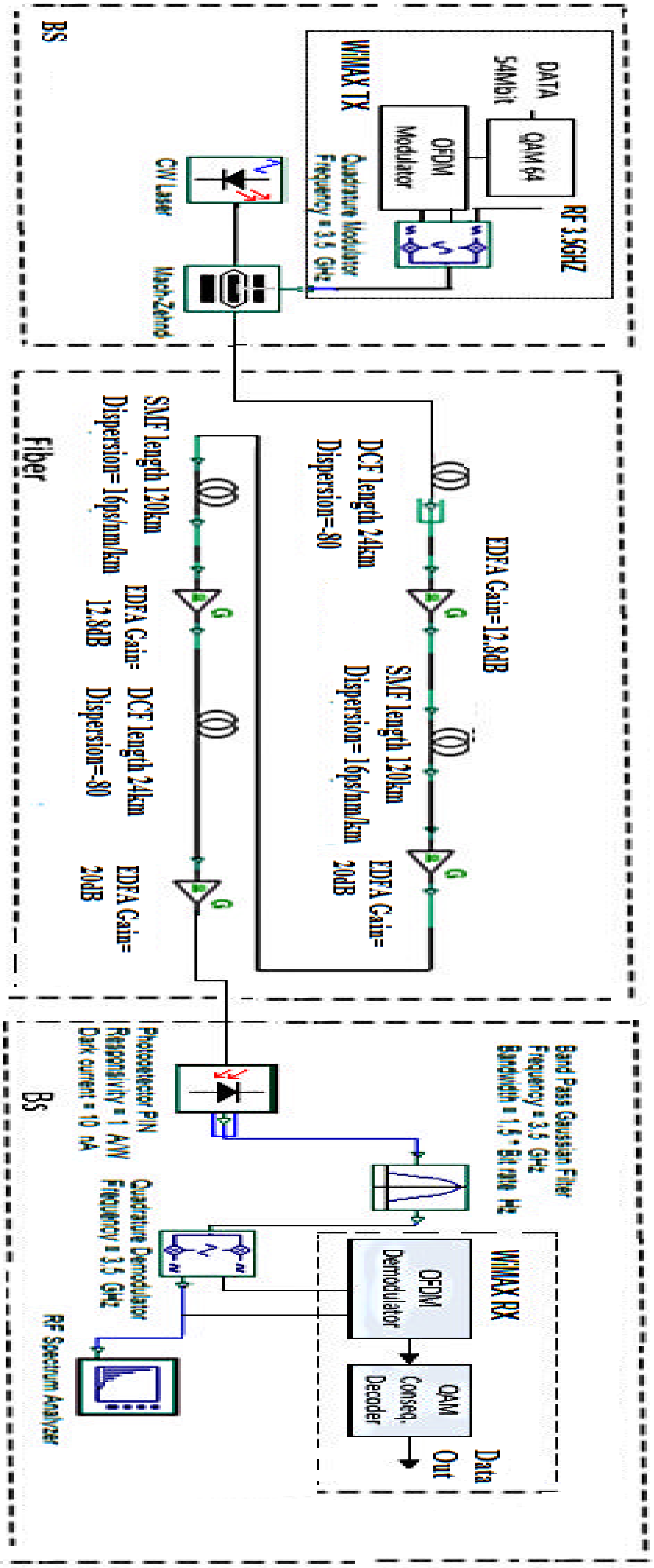

Figure 3-10: Setup schematic of WiMAX via RoF (SMF-DCF) for fibre length 288km.

3.4.3.1 Simulation Results and Discussion

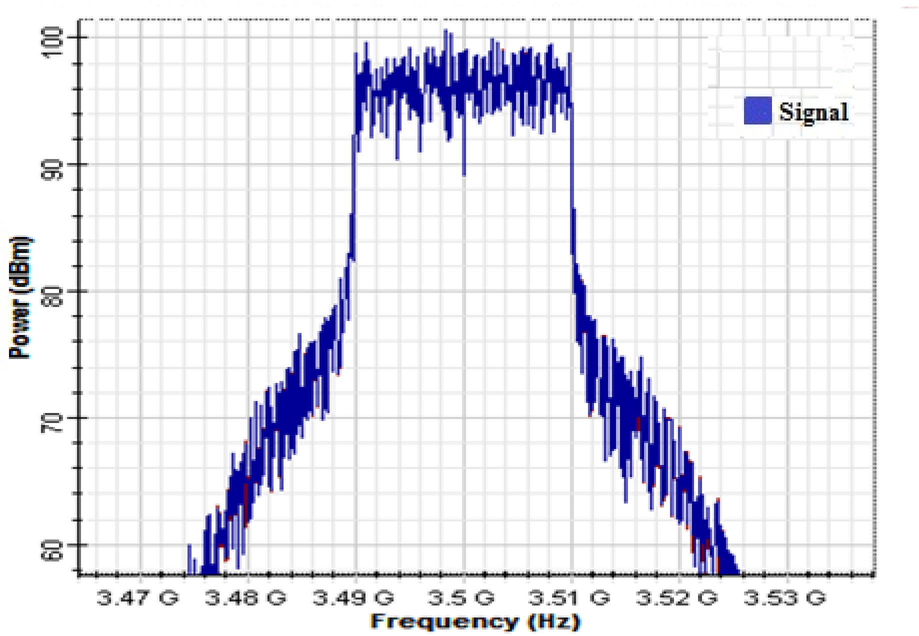

Figure 3-11: RF spectrum of WiMAX-Rx for SMF-DCF length of 288km

Figure 3-11 illustrates the downstream RF spectrum of 64-QAM WiMAX-Rx for 3.5GHz carrier frequency and a bandwidth of 20MHz, the signal is deployed over SMF 2x120km and DCF 2x24km, which makes a total fibre length of 288km; subsequently, the optical signal is converted to an electrical in the PD and then transmitted to the WiMAX receiver. The RF power is measured at 98dBm, the SNR at 30dB and OSNR is at 38dB.

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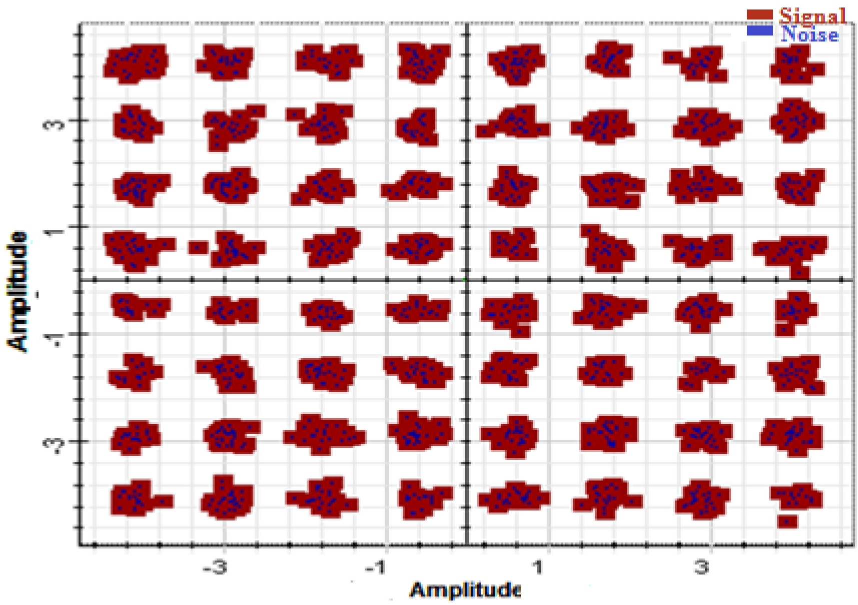

Figure 3-12: Electrical constellation diagram for WiMAX-Rx via RoF (SMF-DCF) for fibre length 288km

Figure 3-12 represents the electrical constellation of 64-QAM WiMAX-Rx after a fibre length of 288km for the combined use of 2x120 SMF and 2x24DCF. The 64-QAM bit clearly shows noise at the WiMAX-Rx; the power amplifier stays unaltered at 65dB, and this is the same amount of energy used in RoF-SMF, to transmit the signal to 180km. By the means of the employment of the DCF, the signal transmission can be extended to 288km.

A further increase of the transmission distance to more than 288km is not feasible with this setup, using SMF and DCF only, due to the high power loss in the DCF (0.6dB/km). In the next section, the simulation design is extended by adding the FBG component to the SMF and DCF to increase the transmission distance to 410km.

3.4.4 WiMAX via RoF (SMF-DCF-FBG)

In this section, the performance of a WiMAX 54Mbit/s signal transmitted with 3.5GHz carrier frequency via a RoF (SMF-DCF-FBG) system for a fibre length of 410km is investigated.

As mentioned in Chapter 2, chromatic dispersion is an extremely influential factor, due to its impact on the bit rate. Chromatic dispersion emerges because the different components of a pulse and different wavelength travel at different speeds along the fibre core. The refractive index of the fibre is a function of the wavelength [45].

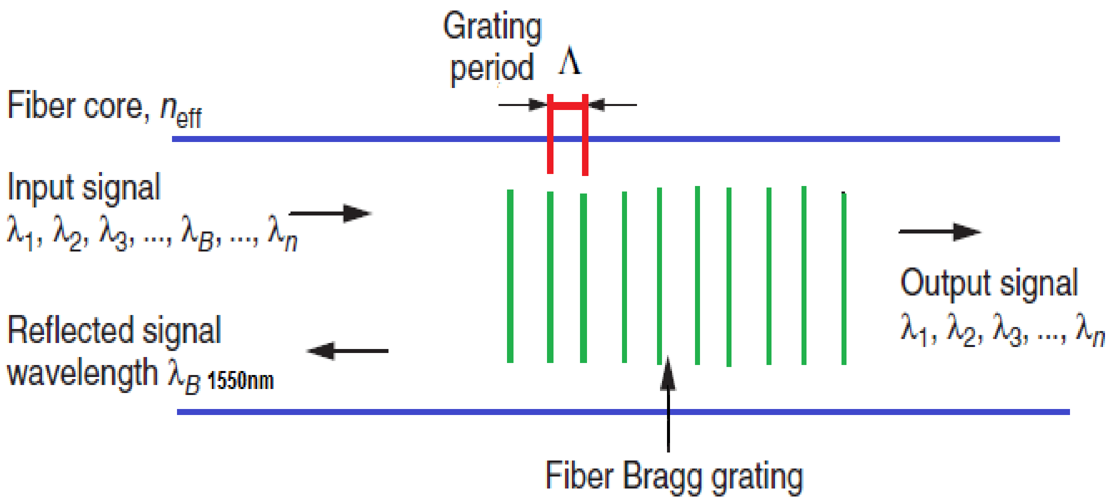

Figure 3-13: Fibre Bragg Grating

An FBG reflects specified wavelengths and let pass all other wavelengths. As shown in Figure 3-11, the wavelength λ_B is the Bragg wavelength, which is reflected in the fibre, and λ_1, λ_2, $\lambda_3 \dots \lambda_n$ are passed wavelengths, depending on whether or not they meet the Bragg condition.

In the described system, λ_B=1550nm (193.1THz) carries the WiMAX transmission signal in the fibre. Bragg's law is expressed in Eq. (3)[40]:

$$\Lambda = \frac{\lambda_B}{(2neff)} \qquad (3.3)$$

Where n_{eff} = 1.46mm effective group refractive index of the fibre core, λ_B stands for the reflected wavelength and Λ represents a grating period.

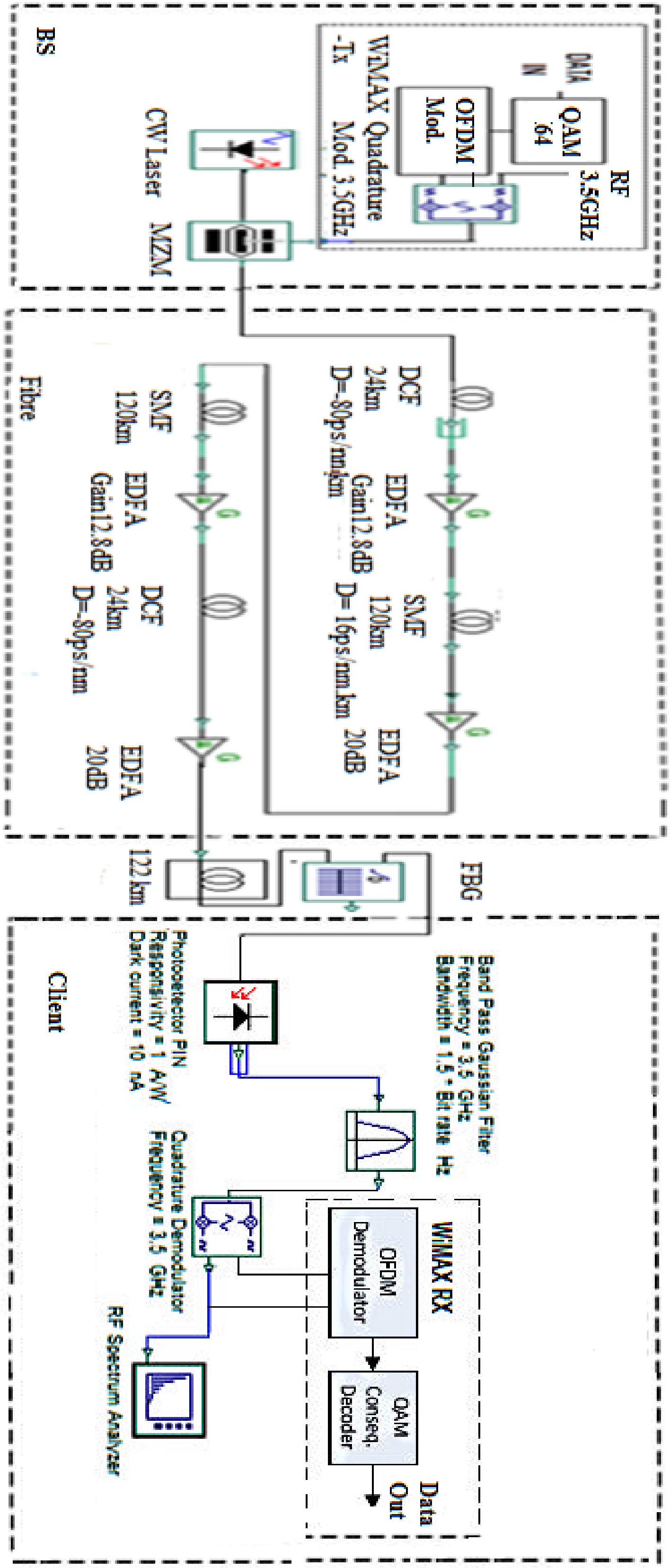

Figure 3-14: Setup schematic of the WiMAX over fibre system using SMF, DCF and FBG filter for fibre length 410km

Figure 3-14 displays the entire simulation setup. In the DCF, the travel path of each signal is controlled by a FBG, which central wavelength is designed to match the signal wavelength. The SMF, DCF and FBG, are used to transmit a 54Mbps WiMAX signal with 3.5GHz carrier frequency and 20MHz bandwidth via the RoF system, The WiMAX transmitter is configured for QAM 64 (6 bit-per-symbol) for a data rate of 54Mb/s and code rate of ¾. Orthogonal frequency division multiplexing (OFDM) is used in the IEEE 802.16-2005 standard for fibre networks. The LiNb Mach-Zehnder Modulator is applied to modulate the WiMAX-Tx with 3.5 GHz RF carrier frequency to the optical carrier with the laser diode signal CW of 193.1THz. The CW laser diode power is swept to 5dBm. The employed SMF and DCF compensate for the accumulated dispersion, and specifically the applied high reflector FBG reduces the signal power loss. The symmetrical dispersion system consists of 2xDCF (24 km) and 2xSMF (120 km) connected to SMF (122 km) and FBG. The SMF dispersion ranges at 16 ps/nm/km for the fibre length of 120km and is combined with the DCF, which is set to the negative dispersion (-80ps/km/nm at 1550nm), and with the FBG, which is configured to negative fibre dispersion (-120ps/nm). Finally, SMF, DCF and FBG are merged into the link, so that the transmission range can be extended to 410km.

3.4.4.1 Simulation Results and Discussion

Simulation results show that the combination of SMF, DCF and FBG has increased the transmission distance in the fibre by more than 100 per cent (from 288 to 410km) using the same optic power amplifier (EDFA) configuration of 65 dB as for the SMF.

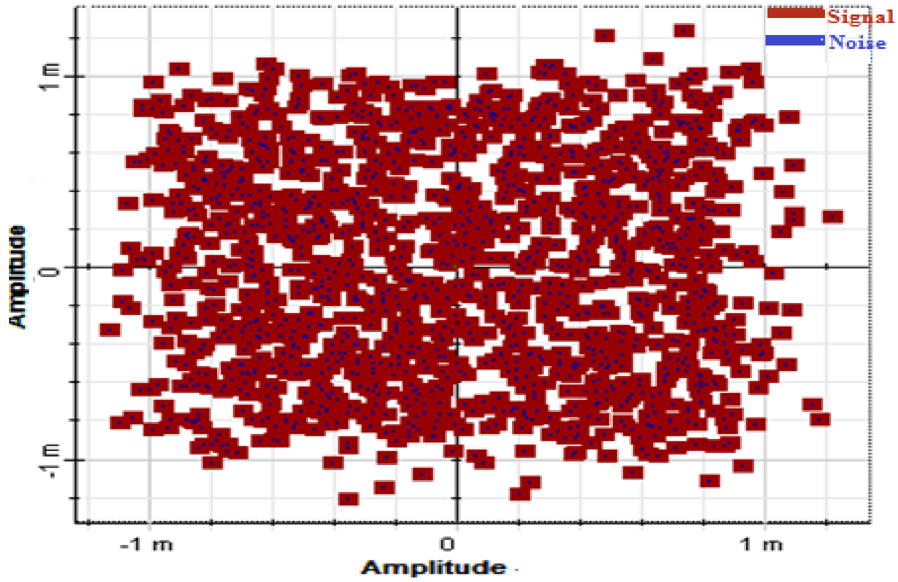

Figure 3-15: Electrical constellation diagram for WiMAX-RX over RoF(SMF-DCF-FBG) for a fibre length of 410km.

Figure 3-15 displays the electrical constellation diagram after a transmission length of 410km. The simulation combined 2x120 SMF and 2x24DCF, SMF122km and FBG; the 64-QAM bit; the signal can travel a maximum of 410km. At the WiMAX-Rx, the power amplifier stays at 65dB. This is the same amount of power that is used for the setups RoF-SMF and SMF-DCF.

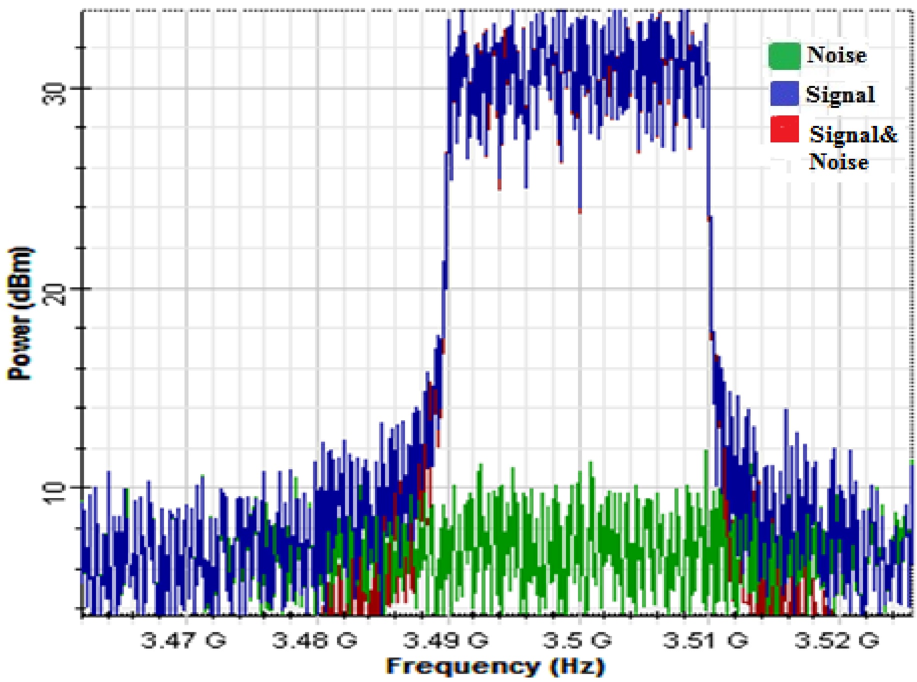

Figure 3-16: RF spectrum for fibre length SMF(3×120km), DCF(2×24) and (1×122)km, and FBG.

Figure 3-16 demonstrates the RF spectrum at the WiMAX receiver; the signal is deployed over SMF-DCF and FBG for the fibre length of 410 km; the power, represented in the red colour, is measured at 33dBm, which is a lot less than the power used in the setup SMF-DCF for a length of 288km. The noise is represented in the green colour area at a level of 10dBm. Figure 3-17 shows the SNR and OSNR for fibre lengths from 20 to 410km. The SNR has increased after 100km, due to the increased power of the optical amplifier EDFA from 30dB to 65dB because the signal attenuation is high after 140km. From 200km to 410km, the SNR has decreased semi-lineally

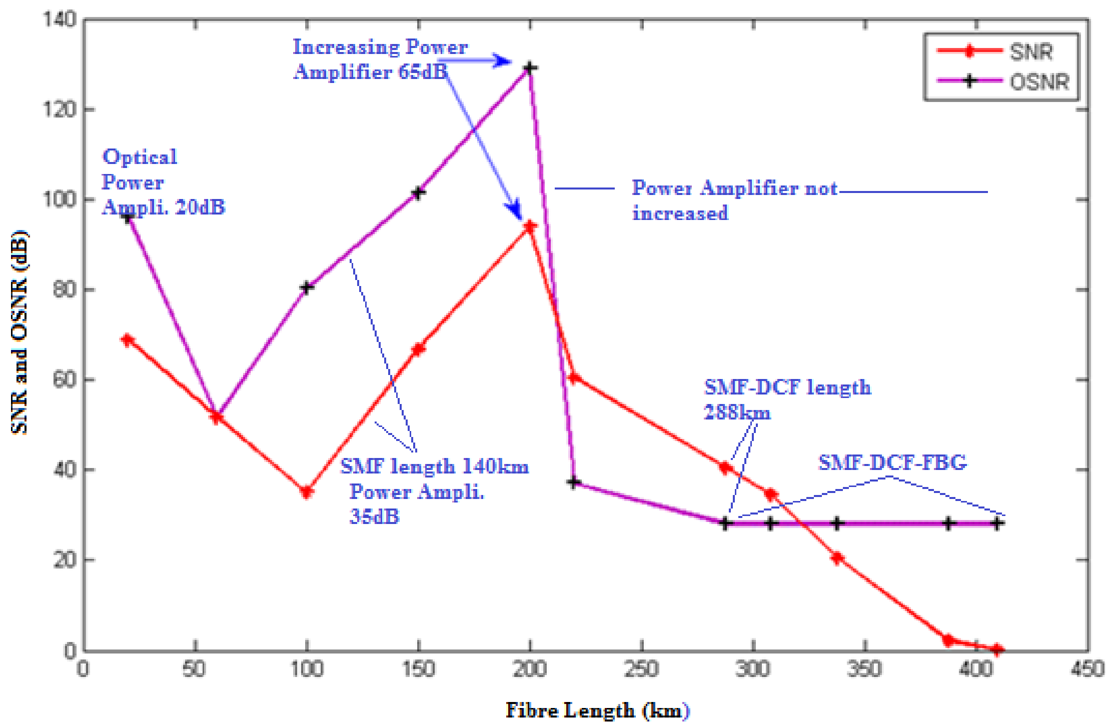

Figure 3-17: OSNR & SNR for WiMAX-Rx via RoF (SMF-DCF- FBG) from 20 to 410km

Figure 3-17 shows the SNR and OSNR for fibre lengths from 20 to 410km. Firstly, the WiMAX signal is transmitted via SMF from 20km to 180km; secondly, the WiMAX signal is transmitted via SMF-DCF from 180km to 288km and finally, via SMF-DCF-FBG from 288km to 410km. After 100km, the signal broadened and has become corrupted by 140km, as shown in Figure 3-9-a. Therefore, the optical amplifier is amended from 20dB to 35dB.

The OSNR has risen after 100km to the level of 130dB and SNR to 95dB. From 140 to 180km the optical amplifier is set to 65dB, but the signal broadens again and becomes corrupted. However the optical amplifier is increased, the signal does not improve, which is displayed in the high rise of OSNR and SNR. Thus, the DCF is used in addition to SMF from 180km to 288km controlling the chromatic dispersion in the SMF; from 288km to 410km the FBG is added to the SMF-DCF to lengthen the span of signal transmission.

As illustrated in the figure, the SNR decreases semi-lineally and OSNR decreases slightly at the fibre span from 210 to 288km and is kept at a constant dB level from 288km to 410km. The reason for the different behaviour of SNR and OSNR is the measurement of OSNR at the end of the optical component, whereas the SNR is measured when the signal has been converted to the electrical signal. Therefore, the bit error rate increases, due to the addition of PD noise to the electrical transmission signal; also the signal quality at the end of the fibre cable depends on the PD quality. The SNR at 230km is 60dB and decreases to 40dB at 288km and at 350km is at 20dB and at 400km is 5dB, whereas the OSNR ranges at 25dB.

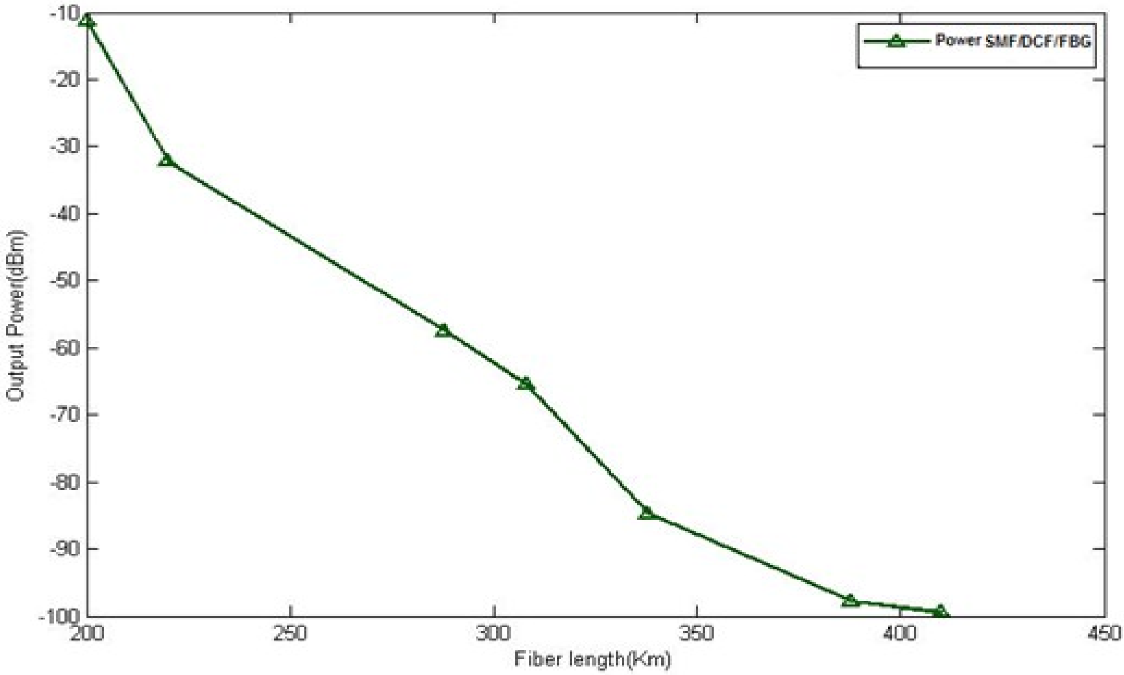

Figure 3-18: Electrical Power for WiMAX via RoF (SMF-DCF-FBG) after photo detector diode.

Fig. 3-18 shows the electrical power in dB for a WiMAX signal transmitted via RoF after the photo detector diode. A fibre length from 180 km to 288km is used for the SMF-DCF. The simulation shows that the signal's electrical power loss is 73.505dBm. For the fibre lengths from 288km to 410km, the application of the triple dispersion system, SMF-DCF-FBG, was able to reduce the power loss by more than 50 per cent to 33.943dB, and increase the WiMAX signal transmission to 410km.

3.4.5 Extended Mobile WiMAX Signal Transmission over RoF via Triple Symmetrical Dispersion System SMF, DCF and CFBG

The main impediments for long distance signal transmission in the RoF system are the chromatic dispersion and signal power attenuation. Additionally, the power consumption in the laser diode and optical amplifiers affect the signal transmission costs; however, it is lower than in a wireless system. Therefore, decreasing the power consumption and chromatic dispersion and increasing the data bit rate in the RoF systems are the demands for the present and future fibre optic network technology. In this section, a mobile WiMAX signal transmission over RoF via a triple symmetrical dispersion system is described, in order to increase the signal transmission range and improve the frequency spectrum. The combination of three different fibres - SMF, DCF and CFBG is used to transmit a 120Mbps mobile WiMAX scalable Orthogonal Frequency Division Multiple Access (OFDMA) signal with 3.5GHz carrier frequency and 20MHz bandwidth over a RoF system. To compensate the dispersion, the SMF and DCF are employed and specifically the high reflector CFBG is applied to reduce signal power loss. The triple symmetrical dispersion system consists of 2xDCF (20 km) and 2xSMF (100 km) connected to SMF (24 km) and CFBG. Simulation results clearly indicate that the limited signal transmission length and data bit rate in the RoF system, caused by fibre attenuation and chromatic dispersion, can be overcome by the combination of SMF, DCF and CFBG. The transmission distance in the fibre is extended to 792 Km; SNR and OSNR are highly satisfactory and simultaneously, the energy consumption is reduced significantly

The chapter is organized as follows: Section 3.3.5.2 focuses on related work; Section 3.3.5.3 describes the theory of light dispersion in the fibre optic cable for SMF, DCF and for CFBG ; Section 3.3.5.4 introduces the description of the WiMAX and RoF system and describes the design of the complete setup. Finally, in Section 3.3.5.5, the simulation results are discussed and the chapter is summarised in Section 3.3.5.6.

3.4.5.1 Related Work

A number of researchers have studied RoF technology as a means to deliver WIMAX signals. Based on the IEEE 802.16d-2004 specification in the 3.5 GHz band, [78] reported about measured spectra and Error Vector Magnitude (EVM) for different single mode fibre spans up to 5 km.

Also, [79] investigated EVM for RoF WiMAX signal transmission. In this approach, fibre lengths between 0km and 5km for both uplink and downlink instances were investigated. The results show, on the downlink, the EVM measured was better than 3.1% between -3dBm and 10dBm. Lowest EVM was measured at 3dBm.

A hybrid radio on dense-wavelength-division-multiplexing (DWDM) transport system for WiMAX applications is proposed in [80]. The researchers were able to improve the bit error rate (BER) over a large, effective area fibre (LEAF) of 100km.

In [81], a WiMAX-RoF transport system is proposed, and achieved satisfactory BER performance over a 120 km SMF length for both, downlink and uplink.

Osadchiy et al[82] proposed a bi-directional WiMAX-over-fibre signal transmission system. The scheme supports signal transmission on a 2.4 GHz carrier at a bit rate of 100 Mb/s downlink and 64 Mb/s uplink for an 80km access fibre link. They also demonstrated a successful transport of 100 Mb/s WiMAX-compliant signals with a 5.8 GHz RF carrier over a 78.8km deployed SMF and a 40km distribution SMF. The results show that the WiMAX signal stayed within 5% RMS EVM after 118.8-km fibre link transmission and air transmission.

All researchers [75-79], mentioned in this section, did not consider to increase the transmission distance to more than 120km. They employed in their setups one type of fibre optic cable, SMF. Moreover, [77] increased the capacity of optical links immensely, but for the cost of high-power consumption. Following estimations, the thermal management (cool systems) of a network applying DWDM consumes up to six times more energy than the optoelectronic circuits, which strains the whole energy infrastructure and the environment, as well [64].

3.4.5.2 Theory and Analyses

As mentioned in Chapter 2.5.2 and 3.3.4, the transmission distance of the signal is limited due to the chromatic dispersion in the SMF. Chromatic dispersion is measured in units of ps/nm.km, where ps stands for to the time spread of the pulse, nm refers to the spectral width of the pulse, and km represents the link length. Standard single mode fibre (SMF) has a typical chromatic dispersion of 16 ps/nm.km at 1550nm [16]. For externally modulated sources, transmission distance limited by chromatic dispersion can also be expressed as follows [45]:

$$L < \frac{2\pi c}{16|D|\lambda^2 B^2} \qquad (3.4)$$

where L is the fibre length; B stands for the bandwidth; λ represents the wavelength, and c the light velocity.

To abolish the limitation of signal transmission in the SMF, techniques like DCF and CFBG have been demonstrated to be useful to compensate the accumulated dispersion in the fibre. It has been shown that strong, long, and highly reflective gratings can be used for dispersion in communication links in transmission with negligible loss aspersion, by proper design of the grating. For high-bit-rate systems, higher- order dispersion effects become important, dissipating the advantage of the grating used in transmission. The rules utilised for the design of the grating to compress pulses in a near ideal technique are a compromise between the reduction of higher-order dispersion and pulse recompression. Bandwidths are limited with this configuration by the strength of the coupling constant and length of a realizable uniform period grating [70].

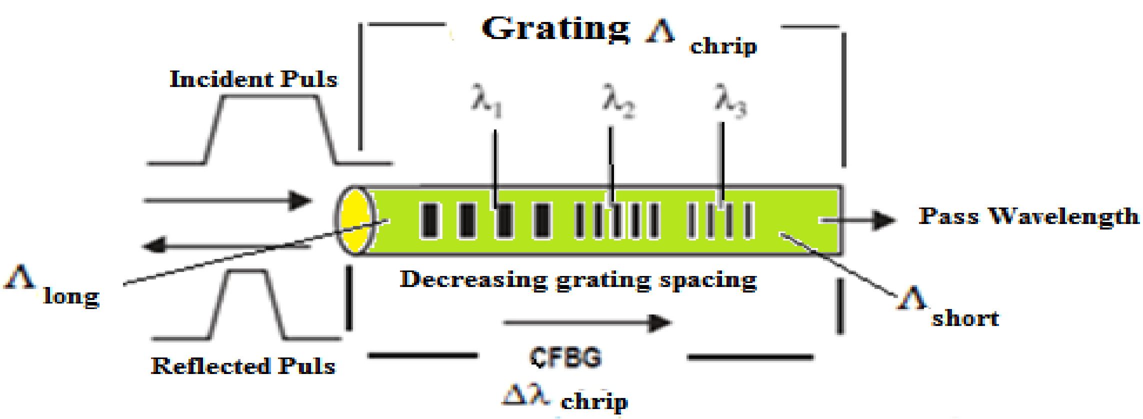

Figure 3-19: The wavelength reflection in CFBG.

As shown in Figure 3-19, the reflected wavelength in CFBG, the so called Bragg wavelength, amends with the grating period λ1. λ2, λ3 because the spacing of the grating varies and is designed for a desired wavelength. The different wavelengths reflected from the grating will be subject to different delays; if the injected light wavelength differs from the grating resonant wavelength, the light is not reflected., the chirp in the period can be related to the chirped bandwidth λ_{chirp} of the fibre grating which is presented in the following equation [83]:

$$\Delta\lambda_{chirp} = 2n_{eff}\left(\Lambda_{long} - \Lambda_{short}\right) = 2n_{eff}\Delta\Lambda_{chirp} \qquad (3.5)$$

The reflection from a chirped grating is a function of wavelength, and therefore, light entering into a positively chirped grating (increasing period from input end) suffers a delay in reflection that is approximately [11].

$$\tau(\lambda) \approx \frac{(\lambda_0-\lambda)}{\Delta\lambda_{chirp}}\frac{2L_g}{v_g} \qquad (3.6)$$

$$\text{for } 2n_{eff}\Lambda_{short} < \lambda < 2n_{eff}\Lambda_{long}$$

where $\lambda_0$is the Bragg wavelength at the center of the chirped bandwidth of the grating, and v_g is the average group velocity of light in the fibre. By introducing a maximum delay of $2L_g/v_g$ between the shortest and the longest reflected wavelengths, the effect of the chirped grating is that it disperses light. This dispersion is of importance since it can be used to compensate for chromatic dispersion in optical fibre transmission systems. The figure of merit is a high-length grating with a bandwidth important feature of a dispersion-compensating device as at 1550 nm, the group delay τ in reflection is ~10 nsec/m. Several parameters affect the performance of the CFBGs for dispersion compensation: the insertion loss due to reflectivity < 100%, dispersion, bandwidth, and polarisation mode-dispersion, deviations from linearity of the group delay also group delay ripple. Ignoring the first and the last two parameters momentarily, we consider the performance of a chirped grating with linear delay characteristics, over a bandwidth of Δλ chirp.

The dispersion coefficient D_g [ps/nm/km] for the linear CFBG is given by the following simple expression [18]:

$$D_g = \frac{2n}{c\,\Delta\,\lambda_{\text{chirp}}} \tag{3.7}$$

where *n* is the average mode index, *c* is the light velocity, $\Delta\lambda$ is the difference in the Bragg wavelengths at the two ends of the grating. Eq. (5) represents that D_g of a chirped grating is ultimately limited by the bandwidth $\Delta\lambda$; the increase in the transmission distance will be possible only, if the signal bandwidth is reduced.

3.4.5.3 WiMAX via RoF (SMF-DCF-CFBG)

An important difference between fixed and mobile WiMAX is the physical layer. Mobile WiMAX uses OFDMA as its physical layer transmission scheme instead of plain Orthogonal Frequency Division Multiplexing (OFDM). OFDMA can also be used as a multiple access mechanism when groups of data subcarriers, called sub channels, are allocated to different users. Mobile WiMAX also introduces more scalability into the actual physical layer parameters.

Cyclic prefix durations and channel bandwidths in multiple OFDMAs, which have different amounts of subcarriers, are utilised to allow the wireless link design to be optimised according to the environment where the system is deployed.

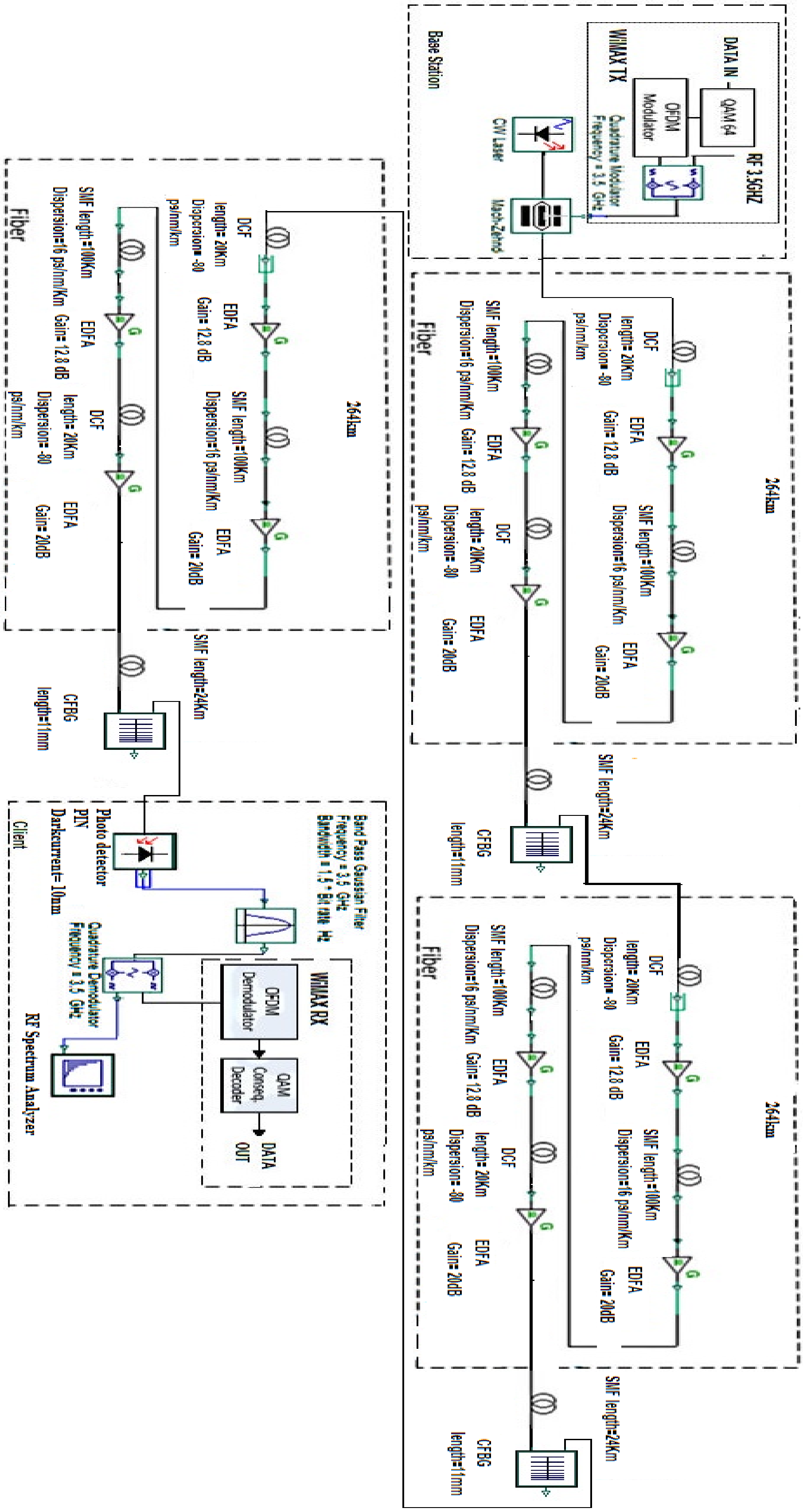

Figure 3-20: Setup schematic of WiMAX downlink via RoF (SMF, DCF and CFBG) for the increased fibre length of 792km.

Figure 3-20 illustrates the schematic of the simulation setup of WiMAX via RoF, applying the dispersion model techniques SMF, DCF and CFBG. In this simulation, the BS deployed the data of mobile WiMAX IEEE 802.16e-2005 to the fibre system as a RF signal; firstly, to the RAU antenna as an electrical signal; subsequently, converted to the fibre optic signal by modulating the RF to the laser beam, which a laser diode has injected into the SMF; this modulation operation arises in the Mach Zehnder Modulator (MZM).

The WiMAX transmission signal is centred at 3.5 GHz; comprising 128 subcarriers and 64QAM (6 bit-per-symbol) modulates each; the bandwidth is 20MHz, and the transmitted bit rate is 120Mbps. The important component in WiMAX is the scalable orthogonal frequency division multiplexing (S-OFDMA). In the basic version of OFDMA, one sub-carrier is assigned to each user. The spectrum of each user is quite narrow, which makes OFDMA more sensitive to narrowband interference. The core of an orthogonal multi-carrier transmission is the Fast Fourier transform (FFT) respectively, inverse Fourier transform (IFFT) operation; synchronization and channel estimation process together with the channel decoding play an important role. To ensure a low cost receiver (low cost local oscillator and RF components) and to enable a high spectral efficiency, robust digital synchronization and channel estimation mechanisms are needed. The throughput of an OFDM system does not only depend on the used modulation constellation and Forward Error Correction (FEC) scheme, but also on the amount of reference and pilot symbols spent to guarantee reliable synchronization and channel estimation [84].

OFDMA utilised in mobile WiMAX is scalable in the ability that by flexibly adjusting FFT sizes and channel bandwidths with fixed symbol duration and subcarrier spacing; it can address wide spectrum needs in different area regulations in a cost competitive approach. The S-OFDMA consists of a flexible and large fast Fourier transform (FFT) size changes from 128 to 2048, and it is used in IEEE802.16e-2005[2].

The WiMAX transmitter's (Tx) source data are encoded, and then modulated by 64-QAM, buffered and manipulated through serial to parallel (S/P) mechanism to build an appropriate vector for IFFT. The signal is transmitted to the fibre as a RF signal; subsequently, converted to an optical signal by the RAU antenna by being indirectly modulated through the MZM. Intensity modulators are important components for high bit rate light wave systems operating at a wavelength of 1552nm.

The MZM structure is composed of an input optical branch, where the incoming light is split into two arms, and two independent optical arms, which are subsequently recombined by the output optical branch.

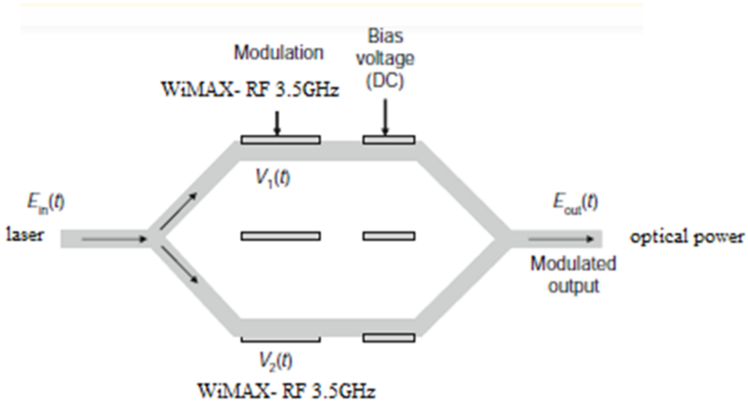

Figure 3-21: Schematic of Mach- Zehnder LiNbO3 modulator (MZM)

As shown in Figure 3-21, the continuous wave (CW) laser diode (LD) emits a light wave into an optical input of the MZM; the WiMAX_RF radiates into two electrical inputs of MZM. The bias voltage of V1, 2_{bias} = Vπ/2 controls the degree of interference at the output optical branch and accordingly the output intensity. The MZM is based on an electro-optic effect that in certain materials, e.g., LiNbO3, the refractive index n changes with respect to the voltage V applied across electrodes. The optical field at the output of the modulator is given by the following equation [16].

$$E_{out}(t) = \frac{1}{2}[exp\left(\frac{\pi}{V_\pi}V_1(t)\right) + exp\left(j\frac{\pi}{V_\pi}V_2(t)\right)]\,E_{in} \qquad (3.8)$$

where V_π is the modulation voltage, which is the differential drive voltage (V_1-V_2=V_π) resulting in differential phase shift of π rad between two waveguides. $E_{in}(t)$ is the optical field applied to the input of the modulator. The MZM modulated electrical signal refers to WiMAX–RF; optical beam refers to the CW laser and is injected in the output as an optical power signal over fibre.

The CW- LD technology is at the standard telecommunications wavelength of 1552.52 nm. The CW- LD output power is too low and would require additional amplification. The CW-LD has an average output power of 3 dBm for laser frequency 193.1 THz with a line width of 10 MHz and relative noise dynamic of 3dB and a noise threshold of -100dB .

Subsequently, the optical signal is transmitted over the RoF system, which is composed of a triple symmetrical dispersion system: each consisting of DCF (20 km), SMF (100 km) SMF (100 km) and DCF (20 km), connected to the SMF (24 km) and to the CFBG, which is added after every 264 km. This setup allows a compensation of the positive dispersion signal in SMF; therefore, the signal transmission is increased to 264km fibre length.

The SMF dispersion parameter is 16 ps/nm/km and the SMF length is set up to 100km; the SMF signal attenuation is 0.2dB/km; therefore, total accumulated dispersion is :

$$16 \times 100 = 1600ps/nm$$

The dispersion slope will be sharper with the increment of the transmitting fibre length. DCF is configured to negative dispersion -80ps/nm/km at 1552nm to compensate the positive signal dispersion in SMF, considered in Eq. (3.9). It is proved to be effective to reverse chromatic dispersion in high-velocity light and it is highly important to increase the signal transmission distance and bit rate by a DCF function to keep the wavelength at a zero dispersion, which is called the "zero-dispersion wavelength" (λ_0).

$$(D_{smf} \times L_{smf}) + (D_{DCF} \times L_{DCF}) = 0 \tag{3.9}$$

where D_{smf} is the dispersion factor in the SMF , L_{smf} is the fibre length of the SMF , D_{DCF} is the dispersion factor in the DCF and the L_{DCF} is the length of the DCF.

$$\left(\frac{16ps}{nm}/km \times 100km\right) + \left(-\frac{80ps}{nm}/km \times 20km\right) = 0 \tag{3.10}$$

Eq. (3.10) shows the result of the accumulated dispersion in combined DCF and SMF. SMF is configured to a fibre length of 100km and DCF to the negative dispersion of -80ps/nm and used over a 20km fibre length to reduce the chromatic dispersion and, as explained before, the DCF is added to keep the transmission signal of zero dispersion for a long distance.

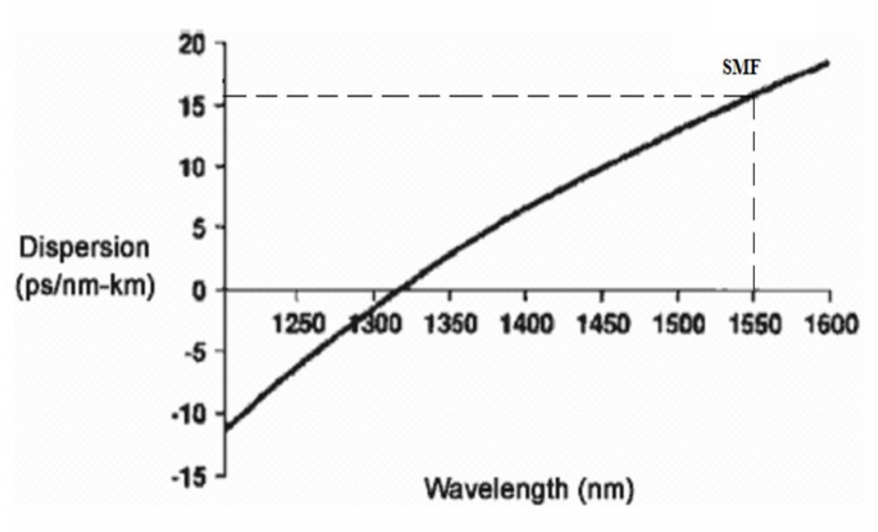

Figure 3-22: Dispersion characteristic of the wavelengths

As shown in Figure 3-22, the dispersion of the light signal in fibre optic is zero by 1330nm and 16 ps/nm/km by 1550 nm wavelength. The advantage of using a wavelength of 1552nm compared to a wavelength of 1330nm lies in low power attenuation. The devices working with the 1330 nm wavelength are able to transmit a high amount of power but the modulation constraints of the laser source can make the design more complicated. The wavelength of 1550nm is the most used in terrestrial communication systems and a wide range of devices are available [42]. The Doppler Effect is lower than at other frequencies and for this carrier it is possible to carry out DPSK (Differential Phase Shift Keying) and QAM modulation schemes.

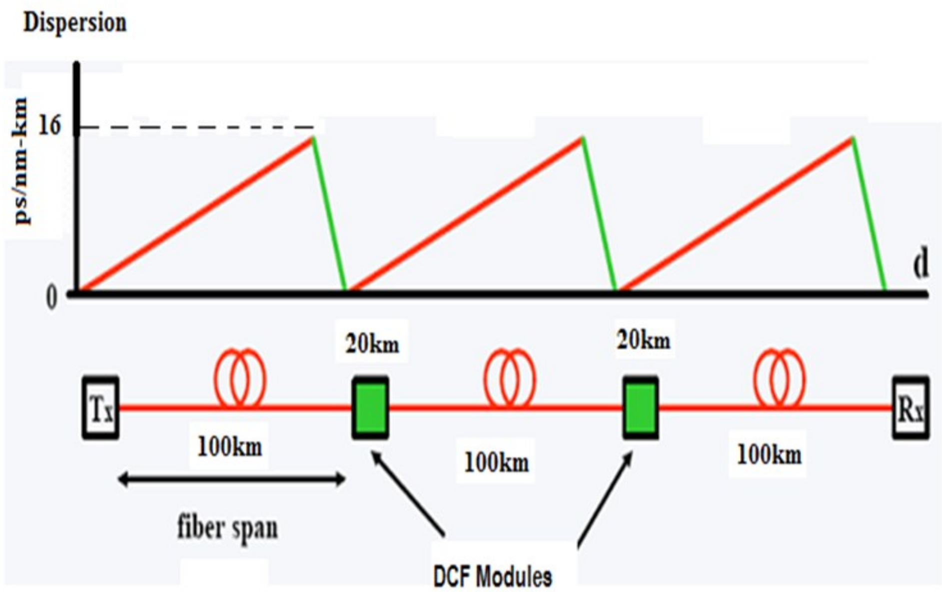

Figure 3-23: DCF compensate for SMF dispersion

Figure 3-23 illustrates that for every 100km SMF fibre length there are 20 km long DCF modules to compensate the accumulation dispersion in the SMF. The signal transmitter Tx injects the WiMAX RF in the fibre after modulation through the laser diode and MZM. In the fibre system the SMF is configured for a fibre length of 100km because of the SMF's dispersion character of 16ps/nm/km at 1552nm, the 20km DCF is added and configured to the negative dispersion of -80nm/ps/km to keep the transmission signal of zero dispersion.

As described in Section 2.6.1, the DCF has a high-power attenuation and cannot be used in this system for a distance longer than 20 km; therefore, the EDFA is employed after 100Km of SMF, being configured to 12.8 dB. The CFBG chirped bandwidth is $\Delta\lambda$=2 nm and n=0.0006. The optical power is converted to the current electrical signal by a photo detector diode (PIN for dark current 10nA and centre frequency 193.1 THz). The electrical band-pass Gaussian filter is used to minimize the electrical signal noise and group delay becomes constant for all frequencies. In a receiver, a band-pass Gaussian filter allows signals within a selected range of frequencies to be heard or decoded, while preventing signals at unwanted frequencies from getting through the centre frequency (f_0). As mentioned before, f_0 is set up to 3.5GHz for a bandwidth of 20MHz.

The applied RAU antenna offers a small antenna size for broadband operation and converts the incoming RF signals to the optical signals and the incoming optical signals to electrical.

The incoming optical signal is detected by a photodiode (PD) and converted to the RF signal, then amplified and transmitted over the wireless path for 300m to the BS antenna and to the WiMAX Rx. At the WiMAX receiver the RF signal is demodulated by the Quadrature demodulator, which implements an analogue demodulator using a carrier generator for Q and I Quadrature components; it consists of two low pass filters. The cut-off frequency of the low pass filter is configured to 7GHz; the OFDM demodulator is implemented by a complex point 1024 FFT; in OFDM the FFT is used to realize multi-carrier modulation, which reduces the complexity of OFDM systems greatly. Generating OFDM symbols with high data rate requires a high-speed FFT processor. Moreover, an FFT processor with low area and low power consumption is needed by the portable feature of OFDM systems. In the QAM sequence decoder, the bit sequence is split into two parallel sub sequences; each can be transmitted in two quadrature carriers when building a QAM modulator. This is achieved by using a serial to parallel converter.

3.4.5.4 Simulation Results and Discussion

The simulation results clearly show that the fibre attenuation and the chromatic dispersion, which are the main cause for a limited signal transmission length and data bit rate in the RoF system , can be controlled by transmitting the WiMAX-OFDMA for 120 Mbps bit rate via the triple symmetrical dispersion modules , the SMF, DCF and CFBG. The results indicate that the use of a accumulated dispersion compensation method, which consist of a triple symmetrical compensator system and, in addition, a CFBG for each system, is the means to control the chromatic dispersion, pulse compression and pulse multiplication also for the reduction of power loss. The low insertion loss, nonlinear effects and cost, are the most important benefits of chirped FBGs; moreover, to keep the transmission signal of zero dispersion and to increase the transmission distance to 792 km.

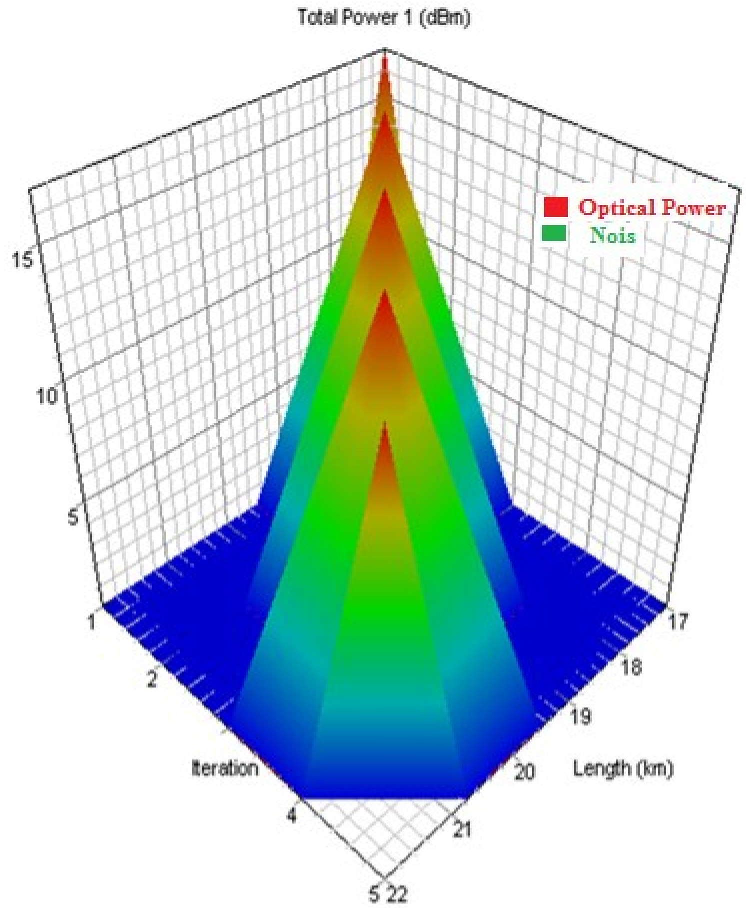

Figure 3-24: Total power in the DCF

Figure 3-24 shows the DCF total signal power, measured in dBm, according to the DCF length from 17km to 22km for a wavelength of 1552nm. At 17km, the signal power ranges at 16.2dBm; at 22km, the signal power ranges at 8dBm, thus the CFBG and EDFA are employed to balance the high signal power loss. The red colour refers to the optical power, the power is focused in the centre of the fibre, and the green colour refers to the noise in the DCF, which is caused by the laser diode.

Apart from the combination in the order of DCF-SMF-SMF-DCF-SMF with a fibre length of 20-100-100-20-24 km, a CFBG with a 55mm long chirp is added at every 264 km to compensate the chromatic dispersion.

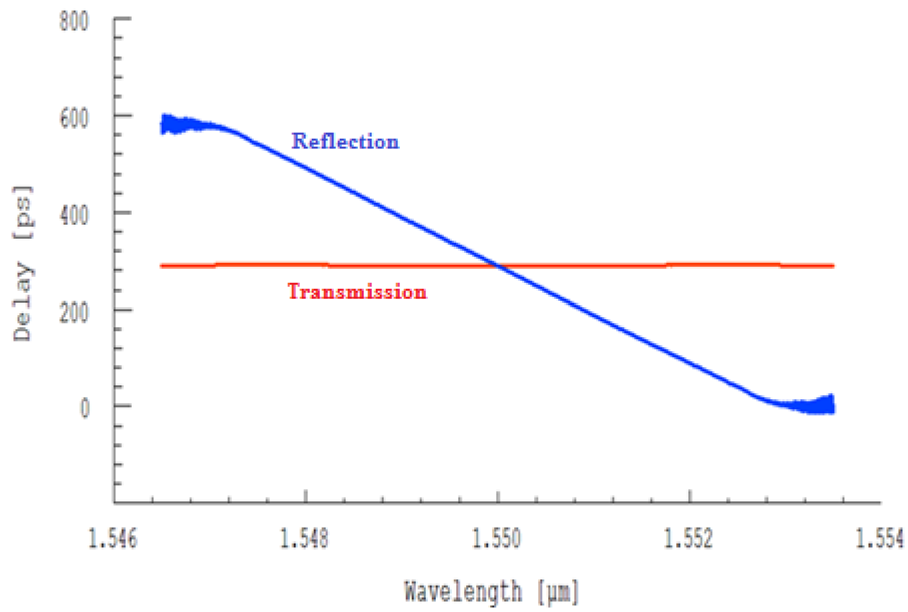

Figure 3-25: Wavelength delay in CFBG

Figure 3-25 shows the delay characteristics of the transmitted and reflected wavelengths for the chirped gratings operating from 10 to 55mm grating length. It is noted that the reflected wavelength of 1548nm to 1552 nm has the delay time of 50ps; respectively the delay in the CFBG is important to balance the wavelength and to control the chromatic dispersion, due to the different frequency velocities in the fibre.

The control of the chromatic dispersion is essential in the fibre optic system network, due to the increase of the signal transmission distance, as well as the data bit rate. The CFBG can be implemented in DWDM and in this research is used as signal tuneable. As mentioned in Chapter 2.6.3, the wave delay in the CFBG plays a significant role, because the light spectrum in SMF and DCF travels with different velocity, which means that it consists of different wavelengths, which reach the end of a fibre optic cable delayed. Therefore, the CFBG is used to control the chromatic dispersion and power attenuation, as well.

TABLE 3-1: OSNR INPUT AND OUTPUT

	Input Signal dB	*Input OSNR (dB)*	*Output Signal (dB)*	*Output OSNR(dB)*
CFBG 10mm	-0.06141464	99.9856	-8.5112	26.63
CFBG 32mm	-0.0141464	99.9856	-11.2111	23.62
CFBG 55mm	-0.06141464	99.9856	-13.4115	19.62621
Wavelength	1552.524nm	1552.524nm	1552.52nm	1552.524nm

Table 3-1 shows the input parameter at transmitter after MZM and the output parameter after 792km. The WiMAX-RF is modulated to the laser for the frequency of 193.1THz for a wavelength of 1552.5244nm. The difference between the input OSNR and output OSNR ranges at ~ -74dB; if the chirped gratings are set up to 10mm, the input signal power ranges at at -0.0614 dBm and the output signal power at -8.5112 dB. The difference between input and output power is -8.4498 dB, when the CFBG chirp grating is set to 10mm for a fibre length of 792km. The result is highly satisfying, because the optical amplifier only used 192 dB for the signal transmission over a fibre length of 792km.

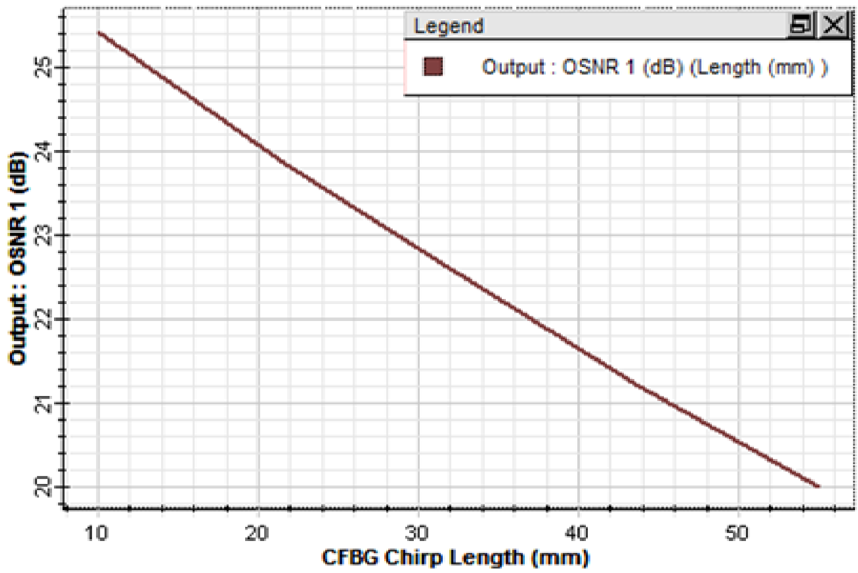

Figure 3-26: OSNR measurement at the CFBG chirped lengths from 10mm to 55mm

As shown in Figure 3-26 , the configuration of the CFBG chirp length has an influence on the OSNR: the shorter the chirp length the higher the OSNR. The higher output OSNR after 792km is 26.63dBm, when the chirp grating is set up to 10mm length, and lower OSNR, when the chirped grating is set up to 55mm. Additionally, the figure shows that the OSNR has decreased linearly, which is an important result because it holds the signal in a stable condition, and the signal quality is affected positively. This means, that the configuration of the CFBG can improve the signal quality in the RoF system and can be used as a band-pass filter and tuneable component, as well.

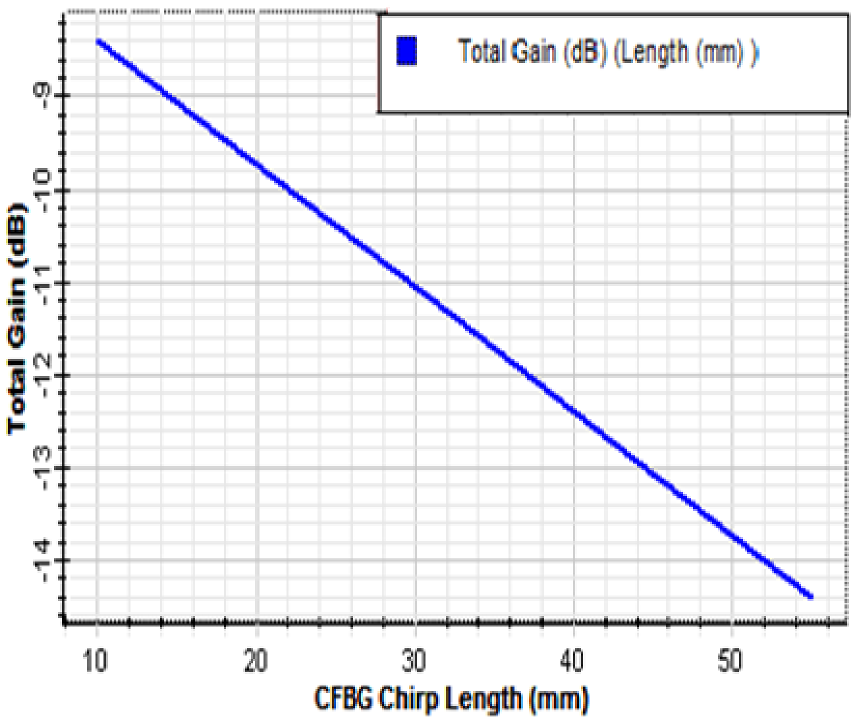

Figure 3-27: Total power measurement at CFBG chirped lengths from 10-55mm

As shown in Figure 3-27, the total gain power measured at CFBG chirp length from 10mm to 55mm at wavelength 1552nm decreases linearly. At a chirp length of 10mm the power is -8.51dB at 32mm; -11.21dB and at 55mm; the power is 13.41 dB.

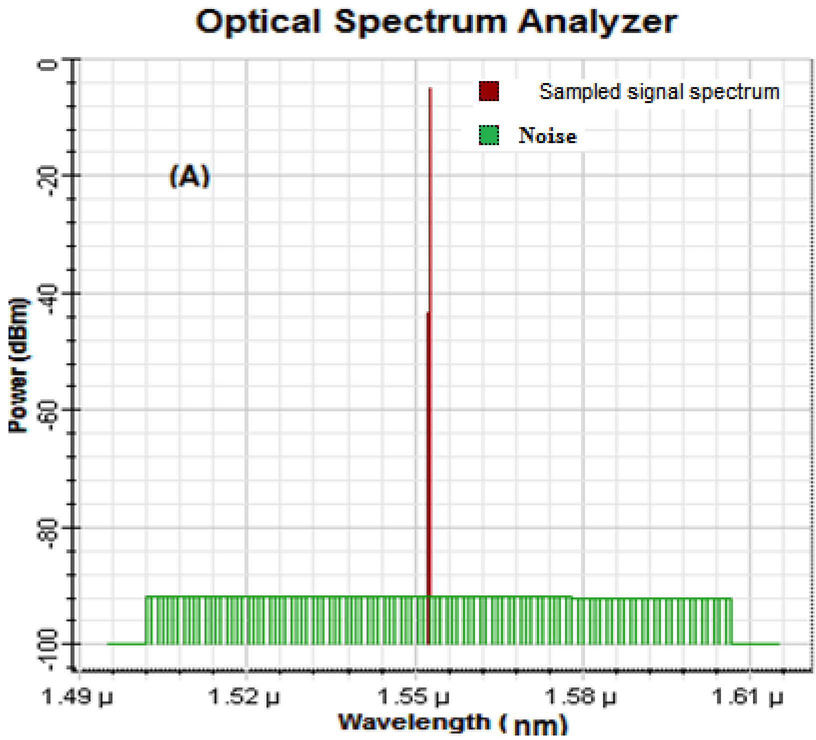

Figure 3-28-a: Optical bandwidth after 264km fibre length

Figure 3-28-a shows the optical bandwidths for a wavelength of 1552nm after the fibre length of 264km. At all fibre lengths, the optical bandwidth measures 300nm. There is a minor change in the optical signal power after the signal has travelled for 528 km: at 264 km, the signal power is -5 dBm, at 792 km the signal power is -14 dBm; however, a limited optical amplifier is used. The green area refers to the noise, which is produced by the laser diode, and the red area refers to the optical bandwidth, which is expressed in terms of wavelength rather than frequency, using the following equation[85]:

$$B_\lambda = \frac{\lambda^2}{c} B_0 \qquad (3.11)$$

where B_o stands for optical bandwidth for a wavelength of 1552nm; c represents the light speed; λ^2 the wavelength square.

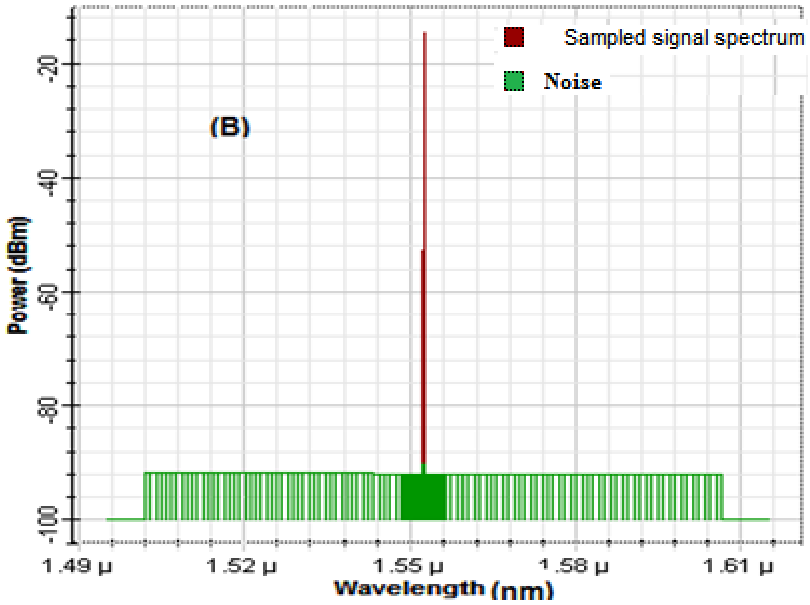

Figure 3-28-b: Optical bandwidth after 792km fibre length

Figure 3-28 –b shows the optical bandwidths for the fibre length of 792km at the wavelength of 1552nm. The intensive green colour at 1552nm (1.55um) refers to the noise intensity in the bandwidth. The red colour refers to the signal power at -25dBm.

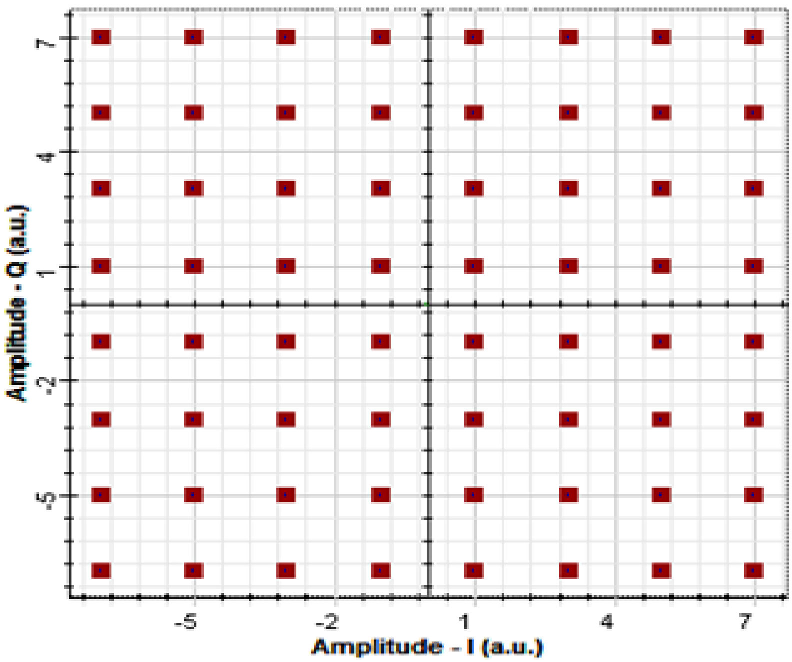

Figure 3-29: Constellation diagram of 120Mbit/s WiMAX QAM-64 transmission downlink for fibre length 792Km

Figure 3-29 shows a constellation diagram, which is a representation of a signal modulated by a digital modulation scheme. It clearly shows the electrical constellation at the WiMAX-Tx, which is a representation of 6 bit-data per symbol of the 64-QAM modulator, for OFDM 1024 and modulator 64- QAM 8 bit by SNR 116.78 dB; the signal is clear and noise free.

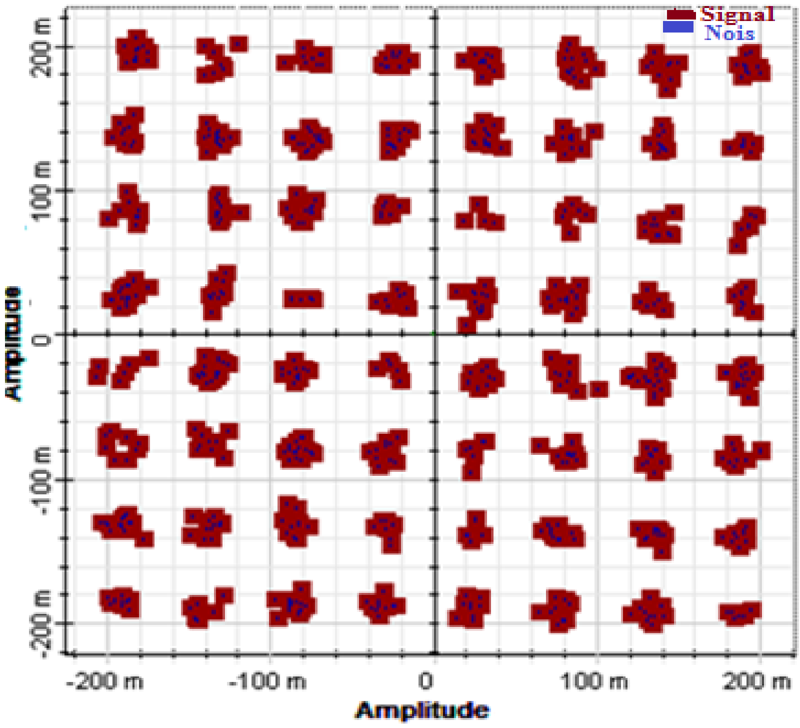

Figure 3-30: Constellation diagram of 120–Mbit/s WiMAX QAM-64 receiver downlink for fibre length 528Km

Figure 3-30 shows the electrical constellation diagram at WiMAX-Rx. The signal at the receiver is transmitted over RoF via the combined SMF and DCF for a length of 528km. The DCF length is set to 4x20km and the SMF length to 4x100km, respectively 2x24km. Compared to Figure 3-28, a change in the 6 bit QAM 64 can be recognized because of noise and power attenuation, which influence the performance of the signal over the transmission distance of 528km .The black colour refers to the noise and the red colour refers to the total signal.

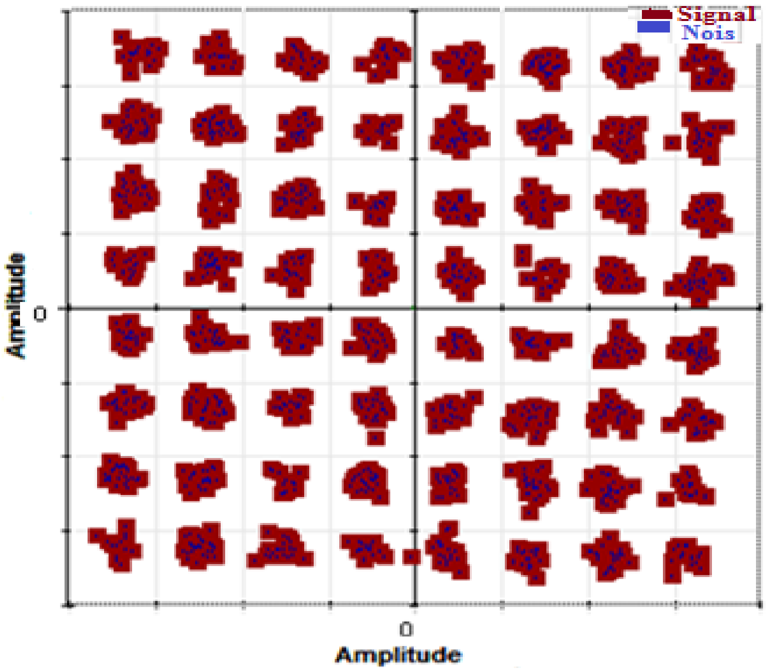

Figure 3-31: Constellation diagram of 120–Mbit/s WiMAX QAM-64 received downlink for fibre length 792Km

Figure 3-31 illustrates the electrical constellation diagram 64QAM for 6 bit at the receiver after the WiMAX signal travelled over a fibre length of 792km and was converted to an electrical signal by the photo detector diode. The signal has a noise, which is shown in blue, due to the laser diode noise; the red colour refers to the total WiMAX signal. The comparison of the Figures 3-29 and 3-30 shows the slight increase of noise, due to the extended transmission distance over the fibre span of 792km; the signal power becomes weak as a result of the laser noise and DCF attenuation. To reduce these effects, an increase of the optical power amplifier is needed. This result shows the maximum signal transmission distance for a limited fixed power amplifier.

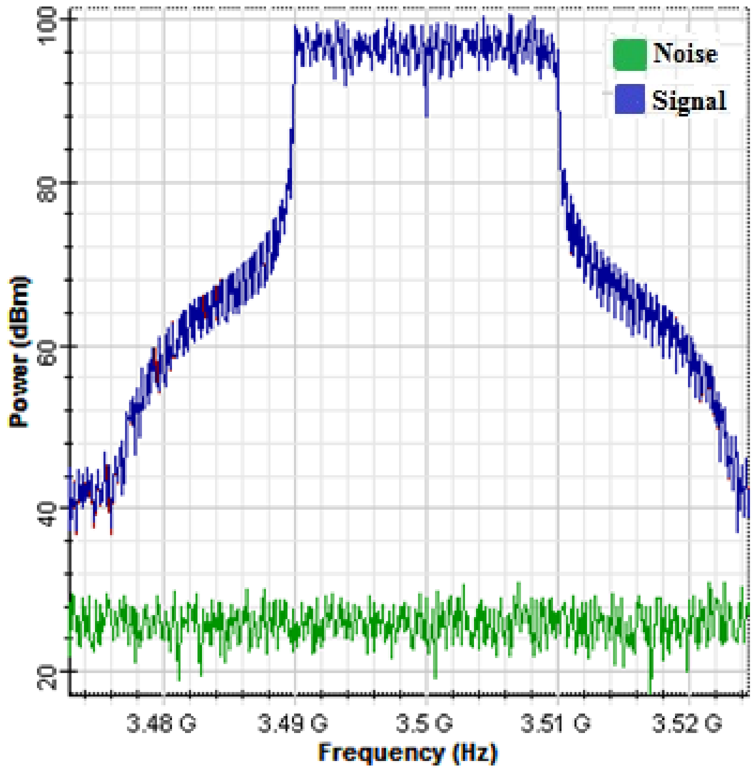

Figure 3-32: 3.5GHz WiMAX-Tx for bandwidth 20MHz and FFT 1024 before transmitting via RoF.

Figure 3-32 shows the RF spectrum of WiMAX 3.5 GHz carrier frequency for bandwidth 20 MHz at the WiMAX transmitter before transmitting over fibre; the bandwidth is in the frequency range of f_0-f_L,f_0,f_0+f_H (3.5-3.49, 3.5, 3.5+3.51) GHz; the spectrum of the signal power, which is displayed in blue, measures 100 dBm; the green colour refers to the noise, which measures 22 dBm.

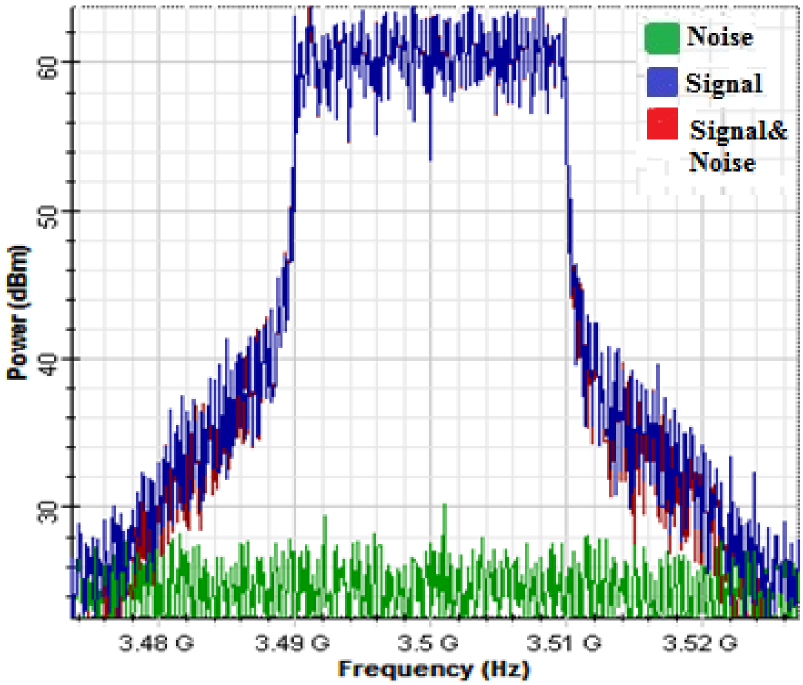

Figure 3-33: WiMAX carrier frequency 3.5GHz for bandwidth 20MHz at WiMAX-Rx after transmission via RoF for fibre length of 792km.

Figure 3-33 shows the 20MHz bandwidth after a fibre length of 792 km for an output power of 60dBm; the noise measures 26 dBm. The spectrum consists of the signal and noise, which is illustrated in blue, and the red area refers to the signal without noise.

The power loss between the transmitter and receiver ranges at 30dBm. The signal is deployed over SMF, DCF and tuned by a CFBG filter for fibre length 792km. At the end of the 792 km fibre length, the OSNR is 26.64 dB. Typically, the larger the OSNR value, the lower the receiver sensitivity.

TABLE 3-2 : TOTAL POWER AND SNR AT TRANSMITTER

	Total Power (dBm)	Signal Power (dBm)	Noise Power (dBm)	SNR (dB)
Min value	-100	-100	-100	0
Max Value	16.785116	16.785116	-100	116.78512
Ratio max/min	116.78512	116.78512	0	116.78512
	(Hz)	(Hz)	(Hz)	(Hz)
Frequency at min	0	0	0	0
Frequency at max	3.5e+009	3.5e+009	3.5e+009	3.5e+009

Table 3-2 shows the parameter at the electrical transmitter at the electrical input of MZM; the maximum value of SNR is 116.78 dB for WiMAX_RF 3.5GHz; the total power measures 16.78 dBm

TABLE 3-3 : TOTAL POWER AND SNR AT RECEIVER

	Total Power (W)	Signal Power (W)	Noise Power (W)	SNR (dB)
Min value	23.26439e-015	0.39134784e-024	23.26439e-015	0
Max Value	0.13552317e-009	0.13547414e-009	49.022992e-015	31.318564
Ratio max/min	5825.3479	346.17323e+012	0.47456081	31.318564
	(Hz)	(Hz)	(Hz)	(Hz)
Frequency at min	50e+006	50e+006	50e+006	50e+006
Frequency at max	3.5e+009	3.5e+009	3.5e+009	3.5e+009

Table 3-3 illustrates the parameter of the electrical signal after having been converted from optical at the photo detector diode; the SNR is 31.32 dB; the difference between input and output is 85.47 dB; considering the WiMAX signal has been transmitted over a fibre length of 792km , this result is highly satisfactory.

As mentioned, the SNR measures 31.32 dB at the receiver; in comparison, the SNR of a WiMAX signal transmission via air is typically 21dB for a code rate of ¾ [20]. The BS-Tx propagation loss via air according to the Egli calculator[26] ranges at 167.57 dB for 5km. Compared to the transmission of the signal via fibre for a length of 792 km, using a laser diode of 5 dBm for fibre attenuation of 180dB per 792km (SMF+DCF) attenuation, the result is highly satisfactory.

3.5 Chapter Summary

In this chapter, methods for transmitting RF signals over fibre using a WiMAX system downlink deployed via different dispersion fibres (SMF/DCF/FBG and CFBG) over a RoF system were proposed.

Firstly, the high power consumption and limited transmission length for WiMAX via air was proved. Secondly, the research project simulated the transmission of a 54Mbps WiMAX signal via RoF-SMF for a distance of 180km, which in the following was extended by a combination of SMF and DCF to 288km, and subsequently, by a triple dispersion system, consisting of SMF, DCF and FBG to 410km.

The simulation results showed the increase of the signal transmission range and the improvement of the frequency spectrum. Furthermore, the results showed a high Signal-to-Noise-Ratio (SNR) also a substantial power reduction of up to 90% in WiMAX-RoF. In a third step, this thesis demonstrated a 120Mbps mobile WiMAX signal transmission via the combination of SMF, DCF and CFBG to overcome the fibre attenuation and chromatic dispersion and thus enhance the data bit rate and the signal transmission length to 792 Km also simultaneously, decrease the power consumption.

The comprehensive system was able to carry a WiMAX S-OFDMA signal of 128 subcarriers with an FFT of 1024 for a 3.5GHz carrier frequency and bandwidth of 20MHz. The bit rate for WiMAX increased to 120Mbps with 64-QAM over a RoF system for a fibre length of 792km. The CFBG chirp lengths from 10mm to 55mm were compared in regard of the OSNR and proved the best OSNR result with the 10mm chirp.

The results showed, using SMF with a DCF setup for the dispersion of -80 and a CFBG setup for a length of 10 to 55mm, an increase in the WiMAX transmission over fibre distance to 792km was achieved. The proposed setup was able to control the chromatic dispersion affected in the fibre. This means that the power budget of the WiMAX downlink signal improved, compared to the energy consumed in a WiMAX transmission BS antenna of 167.57dB for 5 km; the data bit rate increased to 120Mbps. The bandwidth spectrum stayed relatively constant over the long fibre distance, and the result of SNR and OSNR were highly satisfactory; the power consumption was very low between the input and output of the fibre.

In summary, with the described setup, the aim to increase the transmission distance, improve the frequency spectrum, and reduce the power consumption was achieved.

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Chapter 4

LTE and WiMAX Signal Transmission via WDM-RoF for a Length of 1800km

4.1 Overview

WiMAX and LTE are high-potential technologies in the wireless system, but transmission impairments over the air such as high-power attenuation per km, cost of setting up a base station (Bs), non-line of sight (NLOS) coverage and short area of signal transmission limit their potential. Radio over Fibre has proved to be the best means overcoming these impairments by integrating LTE and WIMAX signal systems into the RoF system. This thesis chapter demonstrates the deployment of LTE 2.6GHz and WiMAX 3.5GHz via RoF for a bandwidth of 20MHz and data bit rate of 1Gbps; OFDMA for FFT 1024 and 128 subcarrier, each one using 64-QAM digital modulation formats, is applied, and both systems are mixed over a wavelength division multiplexing (WDM). The simulation results show, the combination of the different compensating fibres SMF, DCF and CFBG is able to overcome the chromatic dispersion and signal power attenuation in RoF; and to increase the transmission distance in the fibre to 1800km. The SNR, OSNR and data bit rate, are highly satisfactory; the power consumption is remarkably low compared to the wireless system for long distance over an air interface.

4.2 Introduction

WiMAX as a digital wireless data communication system was planned to ease broadband access, and is likely to replace the aged broadband access through landlines and DSL. By transmitting high speed, mobile broadband services from 54Mbps to 1Gbps for a distance of up to 50km under LOS conditions, it is able to reach even remote areas. WiMAX uses radio frequency (RF) of a mobile and fixed spectrum to transfer data, and thus provides two kinds of wireless broadband access services. The system consists of a tower and a receiver, either a fixed receiver or an advanced hardware equipment with antennae [70]. The system is capable to serve larger areas and supports the different modulation technique constellations, such as BPSK, QPSK, 16-QAM and 64-QAM. WiMAX physical layer consists of OFDM or OFDMA, which offers immunity to multipath, and permits WiMAX to operate in NLOS with a typical cell radius of up to 5 miles/8 km. Relieving multipath for wireless broadband makes OFDMA a highly applied modulation scheme. WiMAX provides modulation and forward error correction (FEC) coding schemes adapting to channel conditions.

The advantages of WiMAX are being easily and quickly to assemble in large numbers of base stations compared to the wiring, which requires a lot of components and handwork [59]. Additionally, the multi-user connectivity, which means that one WiMAX tower supports one hundred clients, and every client is independent of each other. The scalable OFDMA (S-OFDMA), introduced in the WiMAX IEEE 802.16e amendment, supports the bandwidths from 1.25 to 20 MHz. Scalability of spectrum resources for wireless broadband and mobile is a decisive factor to guarantee worldwide usability and flexibility of the system. Scalability assures an increasingly globalized economy to benefit by providing Internet access even in rural areas, and advance mobile broadband access capacities in suburban and metro regions [59].

Disadvantages of WiMAX are the specialised equipment requirements, due to the need of hardware with dedicated antennae to employ the full functionality of WiMAX. Compared to other techniques of broadband connectivity, like satellite Internet and fibre optic cables, the limited data rate makes WiMAX laggard. The system is forced to use lower bit rates and thus a decreased data transfer rate, due to bit rate errors happening at large distances. Another drawback is the shared bandwidth among users, which slows down the performance further. As WiMAX uses radio waves, interference caused by other equipment can affect the connectivity, also severe weather conditions, because fixed WiMAX requires line-of-sight radio links[59] [70] [86].

Long-term Evolution (LTE) is the next crucial step beyond High Speed Packet Access (HSPA) in the development of 3GPP technologies. Supporting and promoting the most fundamental aspects of mobile telephony and broadband, namely unparalleled mobility and coverage, LTE has an increased emphasis on quality and operational efficiency in the explosive growth of data service usage [87].

The LTE program concentrates on the design of a new radio system and air interface design. In addition to be fully packet-based, the following characteristics are framed for the novel network:

- State changes in reduced time – in HSPA networks, the time it takes a mobile device to connect to the system and start communication on a high-speed carrier is relatively long. This negative impact on usability makes the user recognize the hold-up when resorting a service on the Internet after a time of inaction. Thus, it was decided that the new network design should achieve full connectivity after being inactive in less than 100 ms. An additional shortcoming of current cellular networks are the much higher transmission delays, compared to fixed-line networks. Hence, this leads to disadvantages for applications such as telecommunication and real-time gaming. Currently, the one-way delay at the user's computer at the edge of a DSL network connecting to the Internet is some 15ms, whereas HSPA networks have a delay of approximately 50ms [88][89][90]. The aim for LTE is that the air interface delay should be of 5 ms reaching end-to-end delays equalling fixed-line networks.

- Scalable bandwidth – today, HSPA networks are limited to a bandwidth of 5MHz, and a higher throughput can only be sensibly achieved by increasing the bandwidth of the carrier. However, a carrier of 5MHz is too large for some applications and, therefore, the air interface should be scalable in the other direction, as well [4]. A difference between LTE, GSM and UMTS, is that, in LTE, an IP address will be allotted to mobile devices as soon as they apply to the network. LTE uses the transmission scheme OFDMA, which transmits a data stream by simultaneously using several narrow-band subcarriers, 512 or 1024, or more, depending on the available bandwidth of the channel (e.g. 5, 10, 20MHz).

- Physical parameters - 15 kHz subcarrier spacing; 66.667ms OFDM symbol duration; Standard cyclic prefix 4.7ms or for demanding environments 16.67ms. The selected subcarrier spacing and symbol period countervail adverse effects on the signal such as the frequency shift (Doppler Effect), due to the mobility of the customers. The chosen parameters allow speeds of beyond 350 km/h and range from 1.25 MHz to 20MHz [4].

A comparison between LTE and WiMAX shows that both technologies offer wireless alternatively to fixed access, and will even expand broadband services with the mobility to areas where today no fixed broadband access is feasible because of excessive cost[86]. Furthermore, both apply technology trends such as utilisation in narrow frequency reuse, flexible bandwidth scalability up to 20 MHz, 512 up to 2048 FFT and OFDMA with fast adjustable modulation and coding (AMC) [2][59]. Scalable orthogonal frequency division multiplexing (S-OFDMA) is a vital component in WiMAX and LTE. The basic version of OFDMA is more sensitive to narrowband interference, as one sub-carrier is assigned to each user and the spectrum of each user is quite narrow. To guarantee a low-cost receiver (low cost local oscillator and RF components) and to facilitate a large spectral efficiency, stable digital synchronization and channel estimation mechanisms are necessary [91].

Currently, the technology of LTE is one of the promising candidates to be classified officially as a 4G technology by the telecommunications industry. The cost is the main drawback of LTE because new network infrastructure has to be setup, and the network has to be upgraded. It would be necessary for data transmission to use supplementary antennas at network base stations, due to the application of Multiple Input Multiple Output (MIMO). In consequence, to the network upgrades, users would need to buy new cell phones to enable them to make use of new network infrastructure [92].

RoF is an ideal transmission medium as it avoids the disadvantages in both WiMAX and LTE, providing the potential to increase the bandwidth and data rate also improving the spectral efficiency and raising the broadband speed between users and between users and base stations (BS).

This chapter of the thesis focuses on WiMAX and LTE signals transmitted over RoF applying SMF, DCF and CFBG. The compensator methods are employed to equalise the dispersion slope in a fibre and have been demonstrated in the form of DCF and CFBG. A further, essential aim is to reduce the power consumption. Additionally, satisfactory OSNR, SNR, and high quality signal transmission spectrums should be obtained. Section 4.3 presents related research projects; Section 4.4 gives a brief summary of the theoretical aspects of chromatic dispersion, and the compensation modules SMF, DCF and CFBG. In Section 4.5, the system description of WiMAX and LTE over the RoF system is introduced, and the design of the complete set-up is described. The simulation results are discussed in Section 4.6 and finally, conclusions are drawn in Section 4.7.

4.3 Related Work

The WiMAX performance in Radio over fibre networks is a topic in several research works in recent years [76] ,[90][94] [96-104].

In[93], the simulation of an applied FBG to a WDM-RoF network is described. A SMF is used transmitting six OFDM-QPSK signals, without channel equalization, with 100 and 400 Mbit/s per customer over a distance of 10km. The system is found to be limited by band-edge FBG induced dispersion and inter modulation distortion.

An experimental study is undertaken by Yee et al in [79], investigating the down- and uplink transmission quality of the WiMAX signal via RoF between the base station and the RAU. The WiMAX signal has the parameters of 2.6 GHz 15Mbps 64-QAM OFDMA, compliant to IEEE802.16e standard. The experiment utilises the SMF lengths between 0 and 5km for both, uplink and downlink, instances. The EVM, measured for the downlink ranges between -3dBm and 10dBm; the lowest EVM is measured at 3dBm (3.1%).

The research work proposed in this chapter aims to simulate the deployment of two different mobile broadband signals, WiMAX-3.5GHz and LTE 2.6GHz, over the long distance of 1800km with a data bit rate of 1Mbps. The results show the signal quality, OSNR at 26dB and SNR at 24.12dB, as satisfactory.

4.4 Theory and Analyses

In modern telecommunication systems, the development of optical fibre has created a revolution not only because of the enormous amount of data that can be transmitted but also of the high-speed delivery, wide bandwidth, and resistance against electromagnetic influence. An optical transceiver is an electronic device that works as a converter for an electrical and optical signal. It transforms the electrical signal to an optical signal and vice versa. The transceiver consists of the light source (transmitter) and the receiver. The transmitter is composed of a solid-state laser and an associated circuit that produces coherent light, which can be modulated by the electrical signal and injected into a single- mode fibre. Similar to an electronic oscillator, the laser generates coherent light. To perform the lasing process, a clear cavity is created in a semiconductor crystal [16]

The spectral widths of laser sources used in telecommunication networks are much smaller than those of incandescent lights or sunlight. The different wavelengths travel at marginally different velocities, due to the fibre's chromatic dispersion. Hence, the pulses broaden after travelling an adequately long distance, as described in Chapter 2 and 3. By the time, the pulses sufficiently spread, they begin to interfere with each other and, therefore, the bit-error rate (BER) of the telecommunication system starts to rise. This increase in the BER is the foremost reason for the effort to minimize dispersion. Compared to the multimode fibre, the SMF is able to eliminate perfectly different types of dispersion, but chromatic dispersion still need to be compensated. There is chromatic dispersion in the base material that results from the wavelength dependence of the fibre's refractive index, and waveguide dispersion occurs, which results from the wavelength dependence of the fibre's MFD. As described in Chapter 2, the phenomenon of Rayleigh scattering is high at a wavelength of 1310 nm. Thus, the transmission wavelength of 1550 nm, where attenuation is the lowest, is preferred [103].

The Dispersion Compensating Fibre has a dispersion characteristic that is converse to that of the transmission fibre, in particular designed for different transmission fibre types. DCF contains a higher concentration of germanium and a smaller core area than SMF, the core, and cladding are designed in a way that the waveguide dispersion is negative with respect to the material dispersion; accordingly, the total chromatic dispersion is set to zero. Figure 4.1 shows the dispersions in ps/nm.km in different fibre cable for the wavelengths in nm. At wavelength 1310nm the dispersion for SMF is zero, increases with rising wavelength to positive dispersion and is 16ps/nm.km at 1550nm. The dispersion for DCF is negative for all wavelengths.

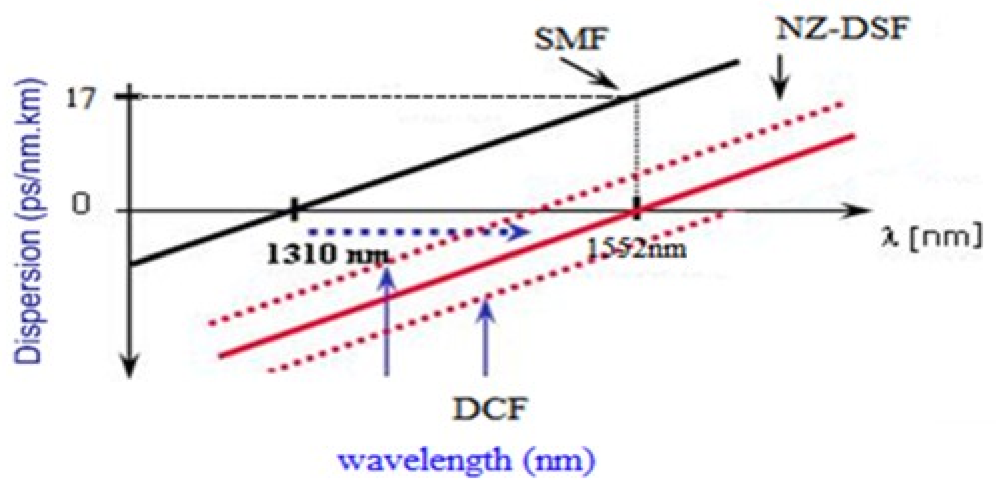

Figure 4-1: Positive and negative dispersion for SMF and DCF for wavelength [16].

Accordingly, the simulation design of the research project deployed the combination of DCF and SMF to keep the signal dispersion in SMF at zero. To achieve the compensation of dispersion an open loop of DCF is inserted into the transmission path, and the total dispersion in the DCF open loop needs to be equal and opposite of the accumulated dispersion in the SMF. In other words, in case of low positive dispersion in the SMF, a large negative dispersion in the DCF will appear.

Applying this technique, the total dispersion is nonzero at all points along the fibre length while the totally accumulated dispersion is zero after some distance. The length of the DCF should be minimised, due to the higher attenuation in this special fibre than in the transmission fibre. The attenuation is around 0.6dB/km at 1550nm compared to 0.2dB/km for SMF, leading to higher attenuation and Rayleigh backscattering coefficients. Towards 1400 nm wavelength, the attenuation of DCF enlarges rapidly [28]; therefore, the chirped fibre Bragg grating is used. The high Bragg reflector is designed specifically for SMF dispersion compensation and obtains a grating period, which changes linearly with position. This linear change in the grating period reflects different wavelengths at different points along the fibre length and hence reflections occur over a spectral band of wavelength [24]. Higher-order dispersion effects become significant for high-bit-rate systems, spending the benefit of the grating used in transmission. Compressing pulses in an almost ideal way needs a design of the grating, which is a compromise between the reduction of higher-order dispersion and pulse re-compression.

WDM is a popular technology that assists significant increases in the data rate being carried over a single fibre by using multiple wavelengths, each carrying a separate channel. Therefore, the capacity of telecommunication networks can be expanded without the need to install more fibre cables. WDM achieves this by dividing the optical spectrum into smaller channels, which can be used simultaneously for transmitting and receiving data at peak electronic rates. The potential bit rate lies in the range of 40 Gbps per WDM channel, due to modern high-speed electronics[70][104][66]. As described in Chapter 2.8.3, WDM applied in RoF systems enlarges their capacity and rises the number of base stations supported by a single central station. Eight to sixteen WDM channels are included in a band (size of aggregation), which should be determined considering entire network cost and equipment modularity.

4.5 System Description and Simulation

The LTE supports scalable multiple transmission bandwidths including 1.4, 3, 5, 10, 15, and 20 MHz. The target peak data rate for WiMAX and LTE via RoF is for both systems 1Gbps; whereas 100 Mbps for both in the wireless system and 54Mbps solely for WiMAX. On the physical layer, modulation schemes range from QPSK over 16QAM to 64QAM and can be amended rapidly for various subcarriers, regarding the different reception conditions of subscribers. The physical layer is a crucial difference between fixed and mobile WiMAX. The system in this research project is set up with Mobile WiMAX because it uses Orthogonal Frequency Division Multiple Access (OFDMA) as its physical layer transmission scheme, which introduces increased scalability into the actual physical layer parameters. When groups of data subcarriers (sub channels) are allotted to individual users, OFDMA can also be used as a multiple access mechanism. Cyclic prefix durations and channel bandwidths in Multiple OFDMA, which has different amounts of subcarriers, are utilised to allow the wireless link design to be optimised according to the environment where the system is deployed.

TABLE 4-1: LTE AND WIMAX PARAMETERS

	Parameter	LTE	WiMAX
	RF	**2.6GHz**	**3.5GHZ**
Common	**System Band**	**20MHZ**	
	FFT Size	**1024**	
	Modulation Format	**64QAM**	
	Channel Coding	**RC=3/4**	
	Frame Period	**1*ms***	**2*ms***
	Cyclic Prefix	**4.7ms short** **16.7us long**	**1/16**
	Subcarrier Spacing	**15KHz**	**10.94KHz**
	OFDMA Symbol Duration	**66.666μs** **(1/15KHz)**	**91.40μs**

In Table 4.1, the essential simulation assumptions and parameters are listed, which are applied to the LTE and WiMAX performance. Focus is set on scenarios in the 2.6 GHz and 3.5GHz carrier frequency with 20 MHz bandwidth; comprising of 128 subcarriers 64QAM (6 bit-per-symbol) modulated each; bit rate 1Gbps.

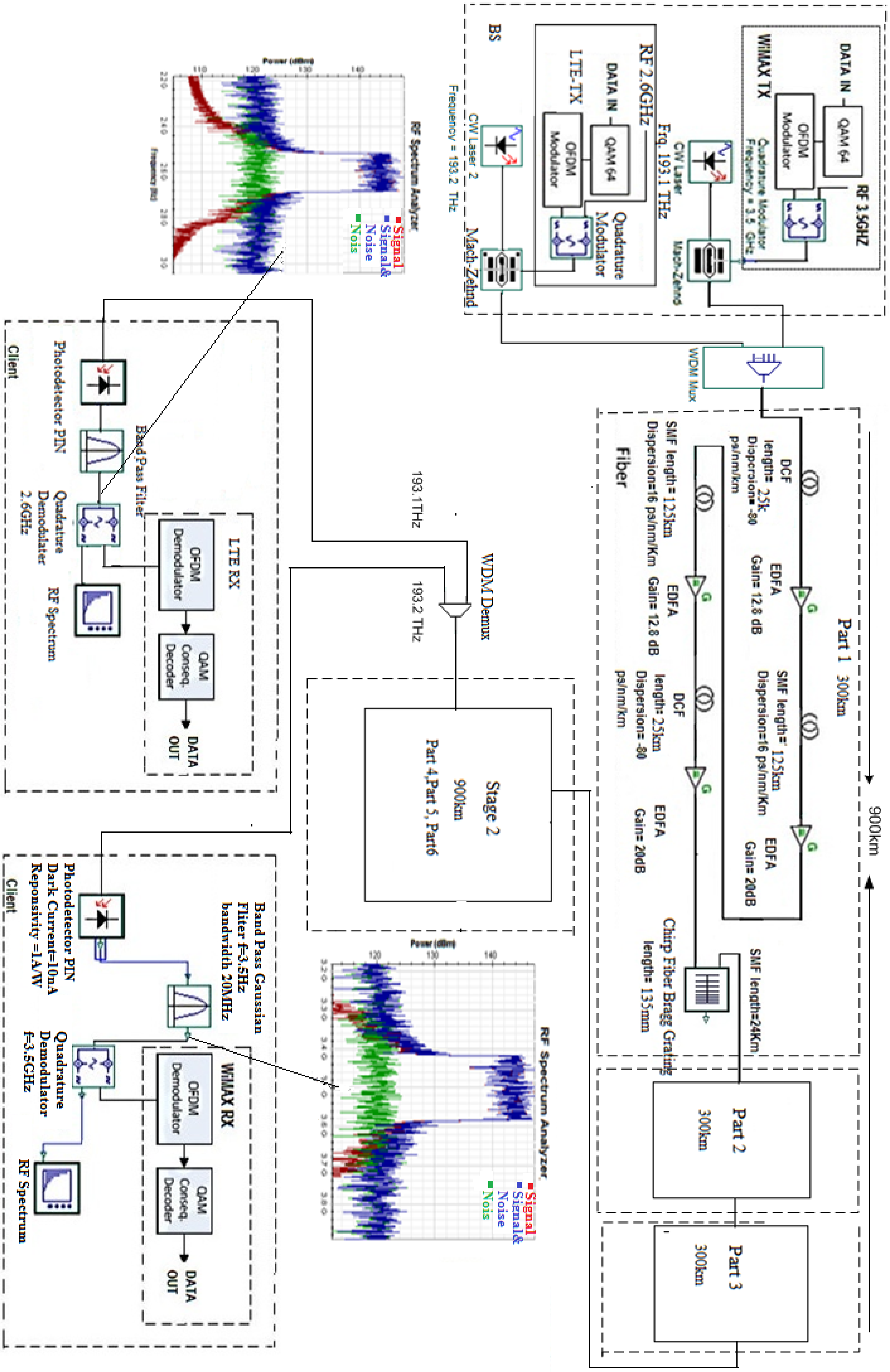

Figure 4-2: Setup schematic of WiMAX downlink via RoF (SMF, DCF and CFBG) for 1800km.

Figure 4-2 illustrates the schematic of the simulation setup for WiMAX and LTE via RoF including the dispersion model techniques SMF, DCF and CFBG. In this simulation, the base station (Bs) deploys the data of mobile WiMAX IEEE 802.16e-2005 and LTE to the optical fibre network as a RF signal 3.5GHz and 2.6GHz. Firstly, the signals are sent to the radio access unit (RAU) antenna as electrical signals; subsequently, in the MZM they are converted to the fibre optic signals by modulating the RF signal to the laser beam, which a laser diode has injected into the SMF.

The CW_{WiMAX} laser diode operates at the standard telecommunications wavelength of 1552.5nm (193.1) and the CW_{LTE} LD at 1551.7nm (193.2THz). The wavelength difference between the optical carrier signal of WiMAX and LTE is 0.8nm. The CW LD has an average output power of 3 dBm for the laser frequency of 193.1 THz. The line width ranges at 10 MHz; the relative noise dynamic at 3dB, and the noise threshold at -100dB. The laser diode emits a light wave into an optical input of the MZM; WiMAX_RF radiates into two electrical inputs of MZM_1 and LTE radiates into two inputs of MZM_2; the output of MZM_1 and MZM_2 is an optical signal. Both optical signals are launched into the WDM_MUX and filtered by a Gaussian optical filter. The output optical signals, having two different wavelengths, are merged into one signal and injected into the fibre. The compensation component DCF and CFBG are added to the SMF, enabling the extension of the signal transmission distance to 1800km. The DCF and CFBG control the chromatic dispersion in the SMF keeping the optical beam in zero dispersion. Additionally, the CFBG works as tuneable for wavelengths and reduces the power attenuation in SMF and DCF, as well as the light scattering.

Subsequently, the optical signal is transmitted via the RoF system, which consists of two stages. Each stage is composed of a triple symmetrical dispersion system, consisting of DCF (25 km), SMF (125 km), SMF (125 km), and DCF (25 km). DCF is configured to negative dispersion -80ps/nm/km at 1552nm to compensate the positive signal dispersion in SMF, which is connected to the CFBG being added after every 300 km. The signal transmission which is combined of two wavelengths (1551.7 and 1552.5nm) carrying the WiMAX and LTE signals. The WDM-DEMUX separates the two wavelengths at the end of the fibre span of 1800km. Each wavelength is detected by a separate PD and converted to the electrical signal; the band-pass filter recovers the RF signal 3.5GHz and 2.6GHz. Afterwards, the signals are transmitted over the wireless path for 300m to the BS antenna and to the WiMAX and LTE-receiver. There, the RF signal is demodulated by the Quadrature demodulator, which implements an analogue demodulator using a carrier generator for Q and I Quadrature components. The OFDM demodulator is utilised by a complex point 1024 FFT realising multi-carrier modulation reducing the complexity of OFDM systems immensely. In the QAM sequence decoder, the bit sequence is split into two parallel sub sequences; each can be transmitted in two quadrature carriers when building a QAM modulator. This is gained by applying a serial to parallel converter.

This setup achieves compensation for the positive dispersion in SMF and hence, the signal transmission can be increased to 1800km fibre length.

In the following figures from 4-3 to 4-9, the simulation configurations of the optical components are displayed.

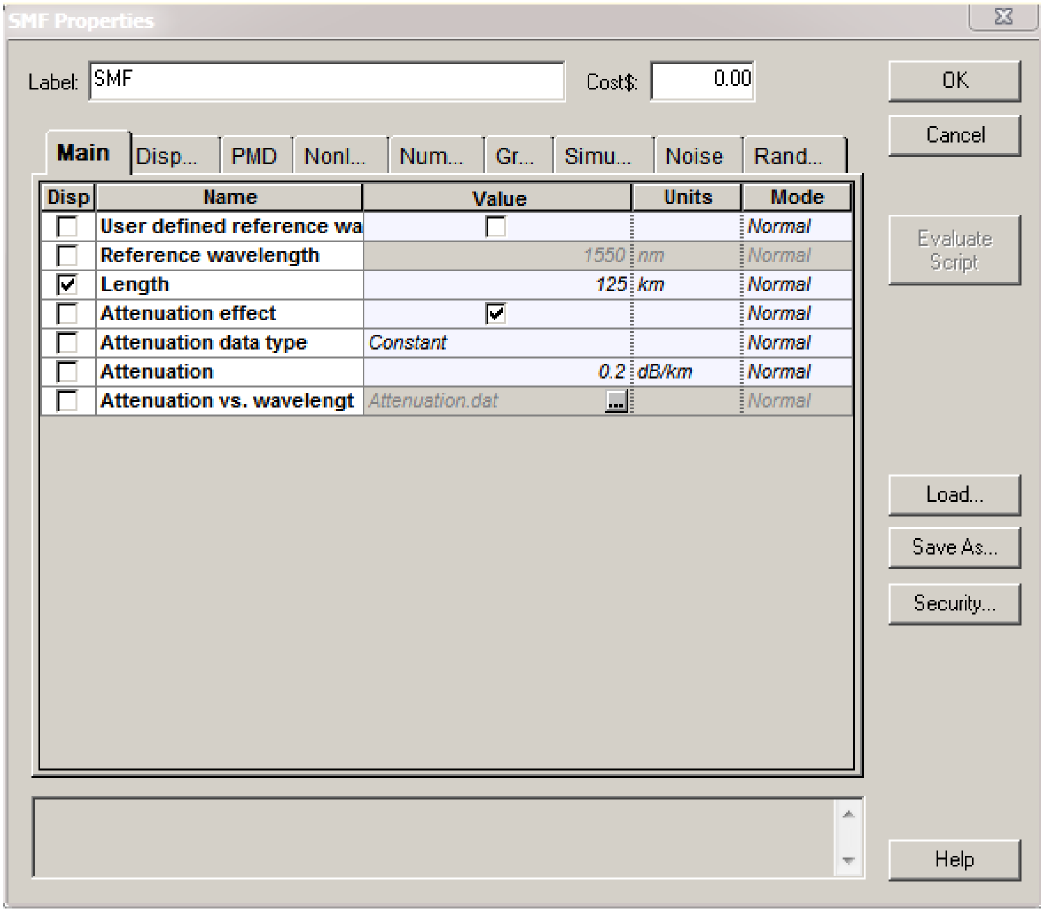

Figure 4-3: Optisystem software parameters configuration for SMF

The configuration of the SMF parameters in the simulation program of the Optisystem 9 software are displayed in Figure 4-3, 4-4 and 4-5. Figure 4-3 shows 125km SMF length; the reference wavelength is 1550nm and signal attenuation 0.2dB/km.

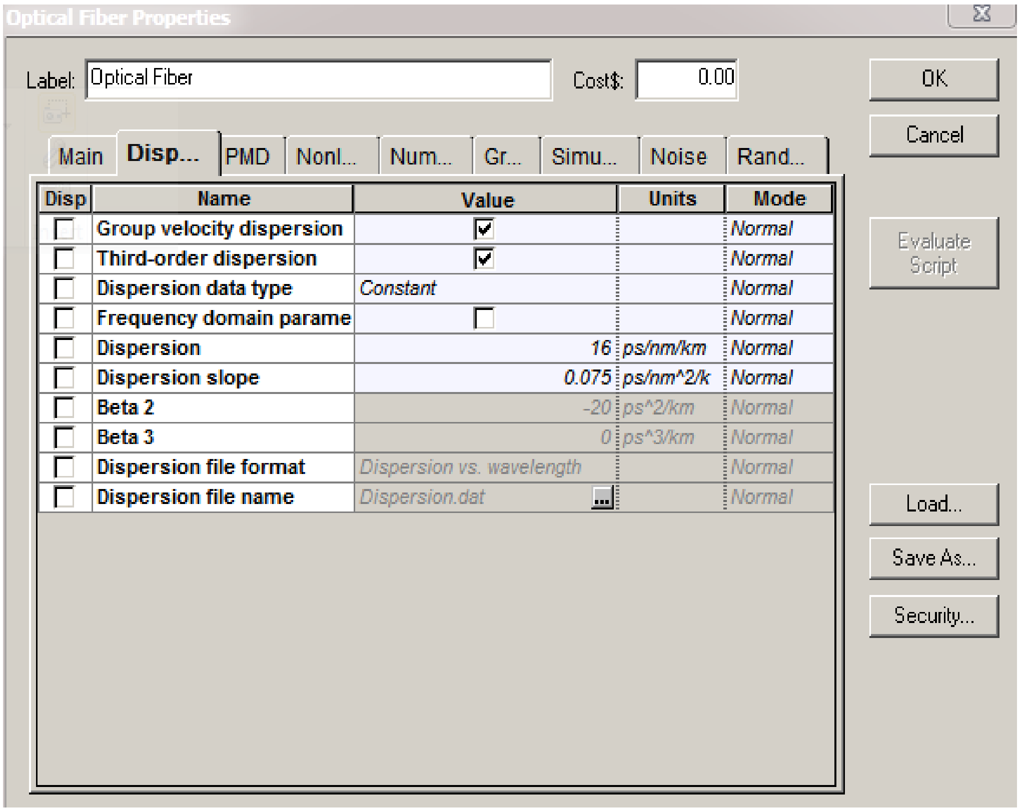

Figure 4-4: Optisystem software dispersion parameters configuration for SMF

Figure 4-4 displays the SMF configuration parameters, which are setup to the unit of 16 ps/nm.km and 0.075 ps/nm2.km for the unit of the dispersion slope; β_2, which stands for the value of group velocity dispersion (GVD) in the frequency domain, ranges at -20 ps2/km. According to the given parameters, the totally accumulated dispersion is 16×125=2000 ps/nm.

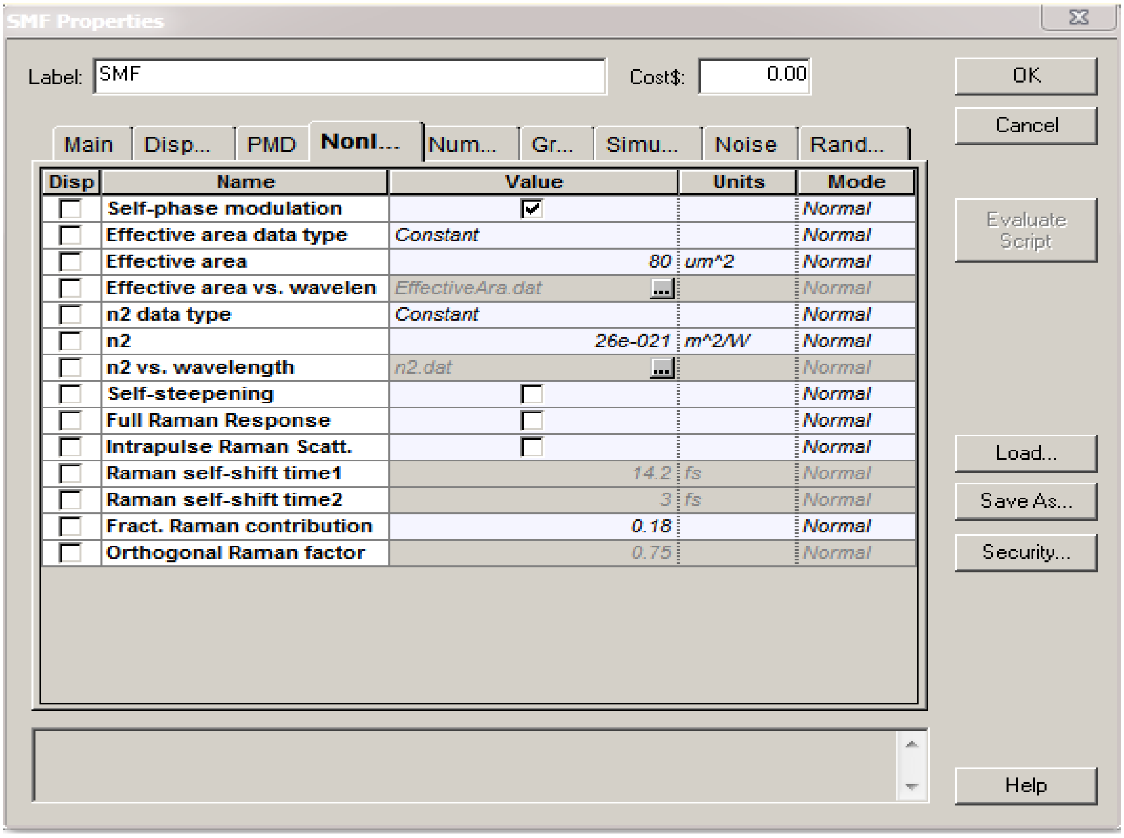

Figure 4-5: Optisystem software non-linearity parameters configuration for SMF

Figure 4-5 shows a configuration of nonlinear parameter of SMF . The effective area is set up to 80 um2; n2, which is the nonlinear index of refraction is configured to 26-21 m2/W; fraction of the nonlinear polarisation, related to the stimulated Raman scattering effect 0.18; Raman self-shift time 1 und 2 are 14.2 and 3 fs.

Equation 4.1 shows the result of the accumulated dispersion in the combined application of DCF and SMF. SMF is configured to a fibre length of 125km; DCF is configured to the negative dispersion of -80ps/nm and used over a 25km fibre length to keep the transmission signal of zero dispersion over the distance.

$$\left(\frac{\frac{16ps}{nm}}{km} \times 125km\right) + \left(-\frac{\frac{80ps}{nm}}{km} \times 25km\right) = 0 \qquad (4.1)$$

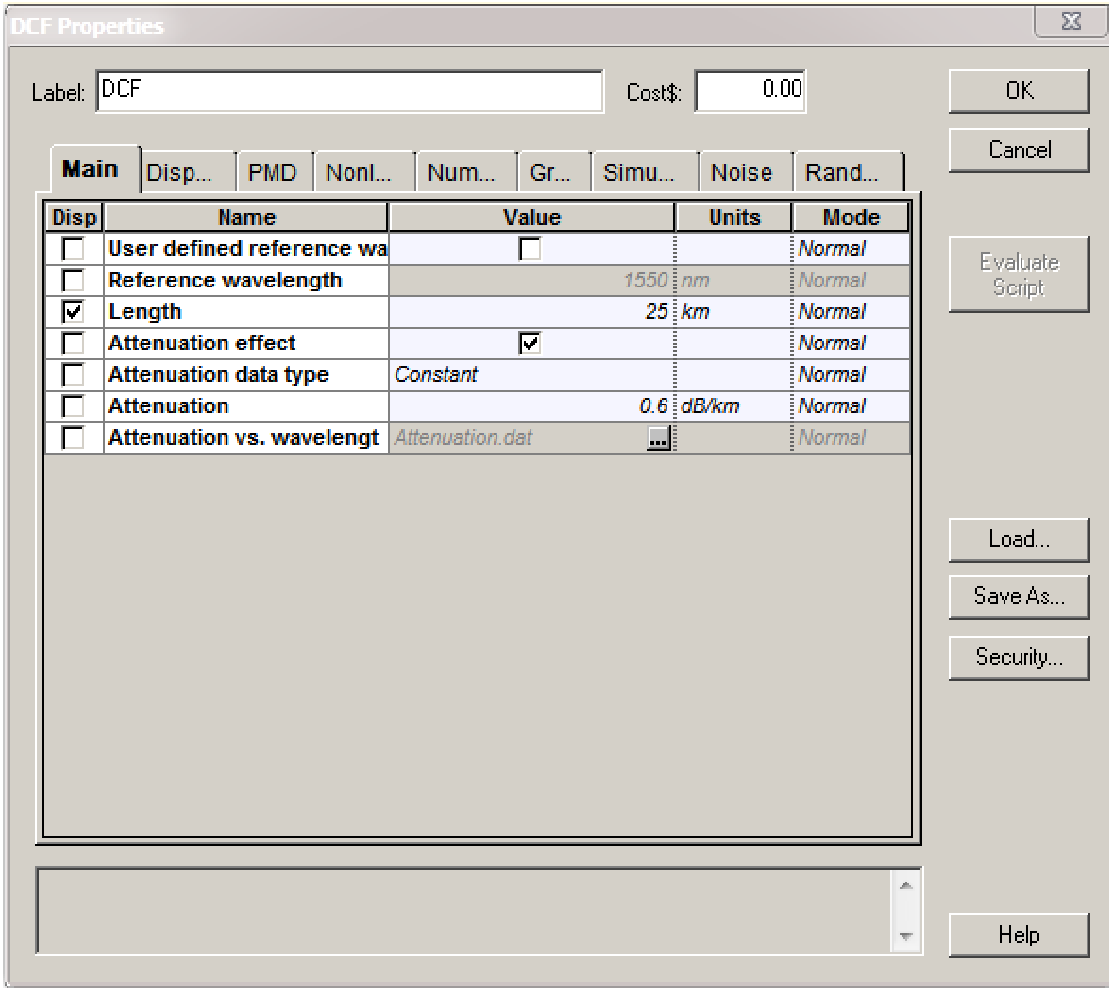

Figure 4-6: Optisystem software main configuration parameters for DCF

Figure 4-6 represents the main configuration for DCF in the Optisystem software. Dispersion effects via long transmission spans can be compensated for by the employment of the DCF. Merely short lengths of DCFs are applied for long transmission distances, because they are designed to hold large dispersion values at the chosen operating frequency. The DCF length is set to 25km with an attenuation of 0.6dB/km, being higher than the attenuation in the SMF, which is 0.2dB/km. The dispersion slop in the SMF ranges at $0.075\frac{ps}{nm^2}/km$, whereas in the DCF at $0.21\frac{ps}{nm^2}/km.$; thus, the DCF length is with 25km shorter than the SMF length with 125km, keeping the signal power attenuations at a minimum and the laser beam at zero dispersion.

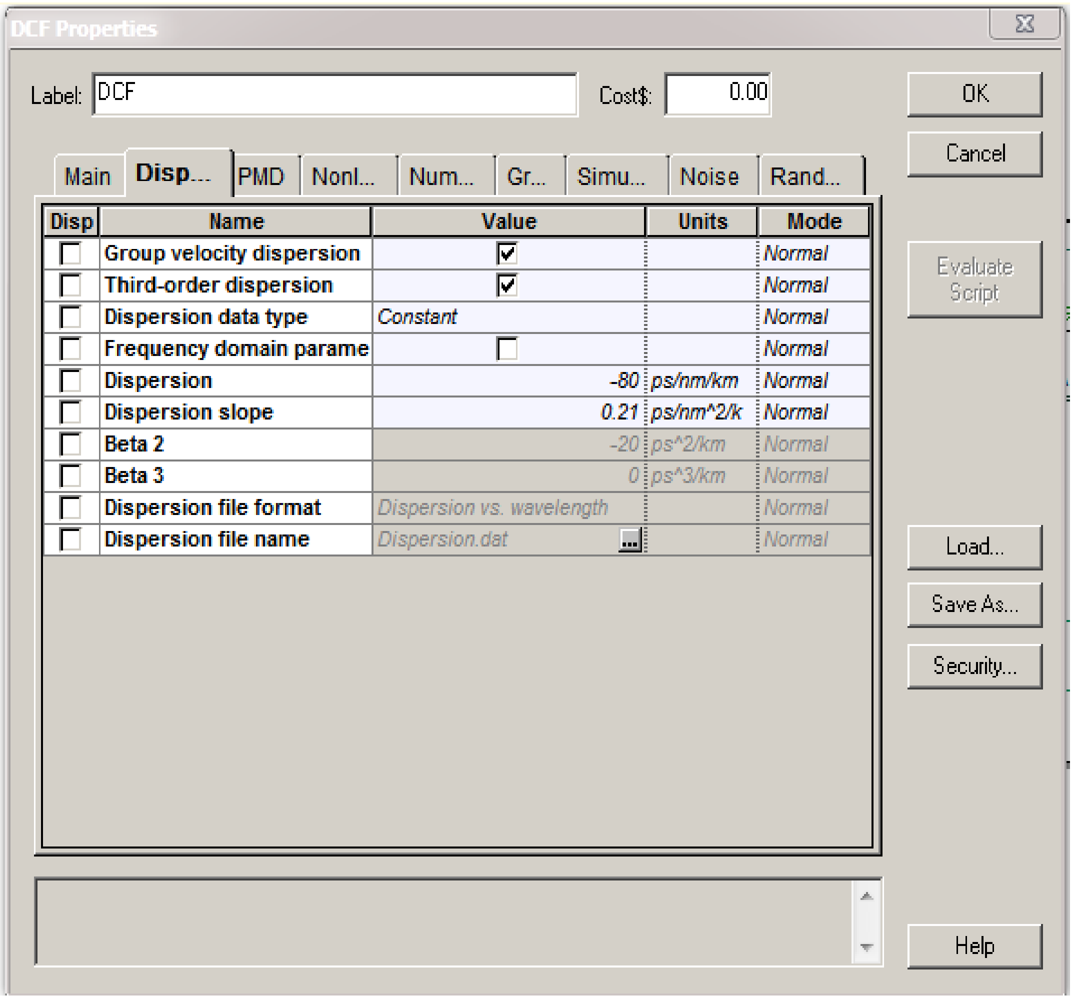

Figure 4-7: Dispersion parameters for DCF

As shown in Figure 4-7, the dispersion is adjusted to -80 ps/nm.km. With this configuration, the accumulated dispersion in SMF (-80 ps/nm.km x 25km= -2000 ps/nm) can be compensated to keep the wavelength of zero dispersion.

The dispersion slope is set at 0.21ps/nm^2.km; and β_2, which stands for the value of group velocity dispersion (GVD) in the frequency domain, ranges at -20 ps^2/km.

The dispersion slope will be sharper with the increment of the transmitting fibre length.

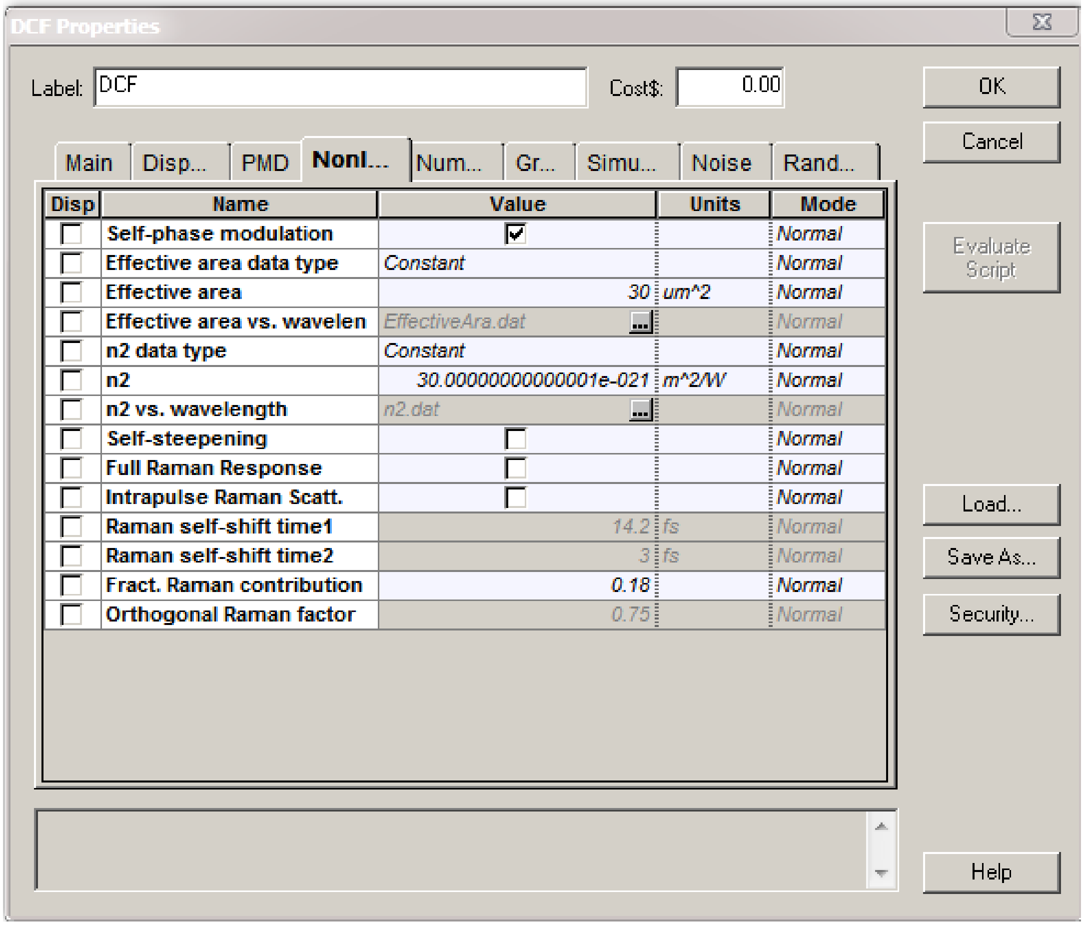

Figure 4-8: DCF nonlinear parameters configuration.

Figure 4-8 shows , the effective area is set to 30 um^2; n^2, which is the nonlinear index of refraction, is configured to 30^{-21} m^2/W; fraction of the nonlinear polarisation, related to the stimulated Raman scattering effect is 0.18; Raman self-shift time 1 und 2 are 14.2 and 3 fs.
The problem of high attenuations in the DCF can be overcome by the deployment of a CFBG with the following parameters: chirped bandwidth $\Delta\lambda$=2 nm; n= 0.0006, and a length of 138 mm. The CFBG minimizes the power loss in the fibre and, together with the DCF, controls the chromatic dispersion.

The optical power is converted to the current electrical signal by a photo detector diode (PIN for dark current 10nA and centre frequency 193.1 THz). The utilisation of the electrical band-pass Gaussian filter sets the electrical signal noise to a minimum and group delay becomes constant for all frequencies. The filter allows signals, within a specified range of frequencies to be heard or decoded in a receiver, while avoiding signals at unwanted frequencies from getting through the centre frequency (f_0). At the WiMAX receiver, the RF signal is demodulated by the Quadrature demodulator. The demodulator implements an analogue demodulator using a carrier generator for Q, and I quadrature components; it consists of two low pass filters with a cut-off frequency configuration of 7GHz. A complex point 1024 FFT, which reduces the complexity of the OFDM system significantly by realizing multi-carrier modulations, implements the OFDMA demodulator. Generating OFDMA symbols with high data rate requires a high-speed FFT processor. Moreover, the portable feature of the OFDMA systems needs an FFT processor, with small size and low power consumption. In the QAM sequence decoder, the bit sequence is split into two parallel sub-sequences; each can be transmitted in two quadrature carriers when building a QAM modulator. This is achieved by using a serial to parallel converter.

4.6 Simulation Results and Discussion

The simulation result clearly show that the fibre attenuation and the chromatic dispersion, which are the main cause for a limited signal transmission length and data bit rate in the RoF, can be controlled by transmitting the WiMAX and LTE signal for 1Gbps bit rate via the compensator modules SMF, DCF and CFBG. The results indicate that the use of a accumulated dispersion compensation method, which consist of two stages, each stage being composed of a triple symmetrical compensator system and, in addition, a CFBG for each system, is the means to control the chromatic dispersion, keep the transmission signal of zero dispersion and to increase the transmission distance to 1800km.

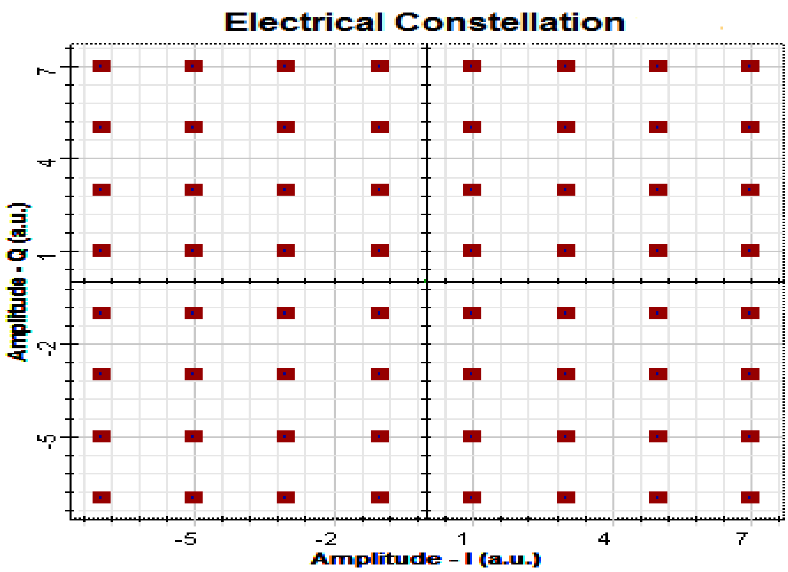

Figure 4-9-a: Electrical constellation for 64QAM WiMAX-Tx and LTE-Tx

Figure 4-9-a illustrates the representation of a signal modulated by a digital modulation scheme. The electrical constellation for the WiMAX and LTE transmitter is a representation of 6 bit(2^6) data per symbol of the 64-QAM modulator for OFDMA 1024; SNR ranges at 108.8 dB. The signal displays clear and free of noise. The signals are transmitted to the WiMAX and LTE-Rx via RoF; firstly, the electrical signal is converted to an optical signal by MZM modulation to the laser beam and subsequently injected into the RoF optic system. At the fibre termination, the PD converts the optical signal to an electrical one, which is then transmitted to the receiver. The Figures 4-10, 4-15,4-16, and 4-17 show the constellation diagrams and RF spectrums of the signal transmission at the LTE and WiMAX receiver.

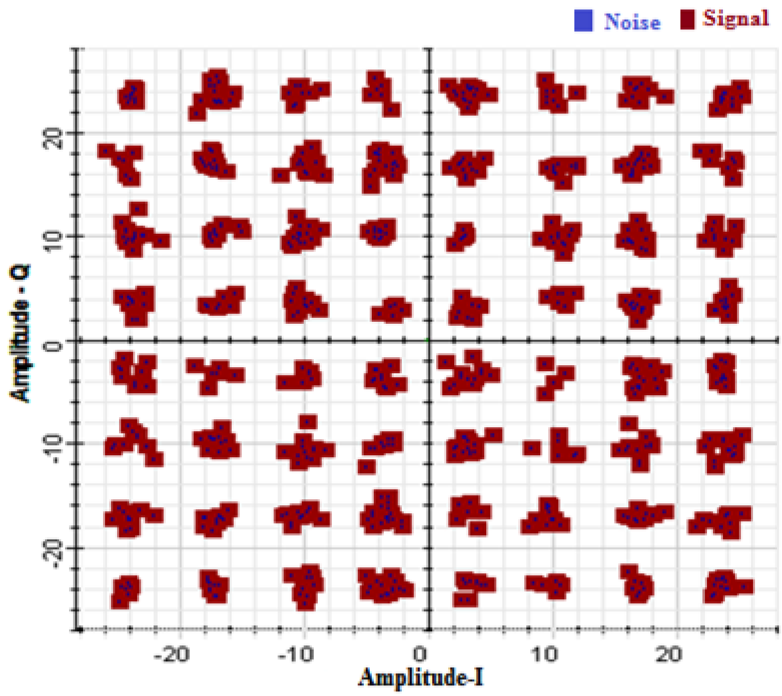

Figure 4-9-b: Electrical constellation for 64QAM at WiMAX-Rx after 1800km

Figure 4-9-b shows the 64-QAM electrical constellation diagram for the WiMAX-Rx. The signal at the receiver is transmitted via RoF over the combined SMF and DCF for a distance of 1800km; it also shows that there is noise included, which is produced by the laser diode and because of power attenuation and signal dispersion in SMF and DCF. As a result, the SNR at receiver degraded from 108.81dB to 24.12dB and OSNR to 26dB at 1800km.

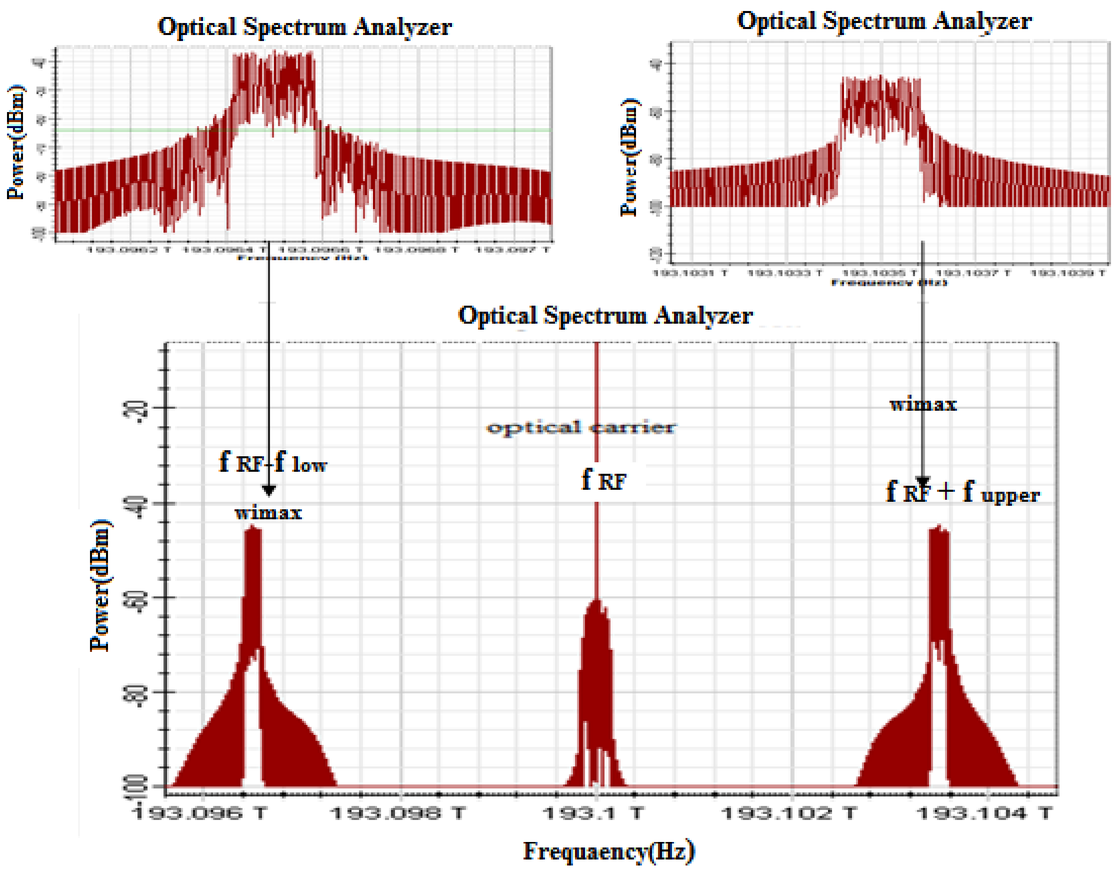

Figure 4-10-a: Optical signal transmission of WiMAX

Figure 4-10-a, illustrates the optical signal transmission of WiMAX; the optical carrier frequency 193.1THz and optical bandwidth 20MHz after WDM-Mux at -10dBm. The Optical Double-Side Band (ODSB) is presented in the carrier f_{RF} =193.1THz. The ODSB signals are generated by external modulation of the lasers (1552.5 nm or 193.1 THz) using MZM; the lower optical sideband is (f_{RF} - f_{low}) and (f_{RF} + f_{upper}) is the upper sideband. The optical signal power ranges at -44dBm.

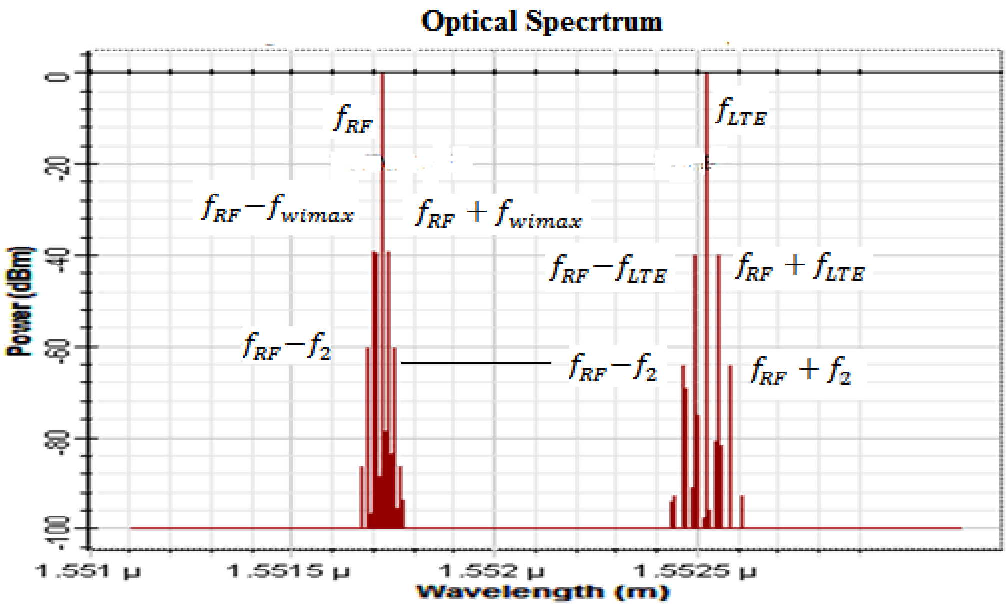

Figure 4-10-b: Optical spectrum ODSB WiMAX and LTE for wavelength

Figure 4-10-b represents the ODSB optical spectrum for the optical carrier of WIMAX and LTE. After LTE and WiMAX are modulated to the laser beam and multiplexed in the WDM-Multiplexer, they are powered in the fibre via two wavelengths; WiMAX at 1551nm and LTE at 1552nm. The carrier frequency f_{RF} ranges of LTE at 193.1THz (1552nm) and WiMAX 193.2THz (1551nm) for a power level of -0dBm. The lower optical sideband $(f_{RF} - f_{wimax})$ and upper optical side band of WiMAX $(f_{RF} + f_{wimax})$ are at a range of -38dBm and for LTE $(f_{RF} - f_{LTE})$ *and* $(f_{RF} + f_{LTE})$ at -40dBm.

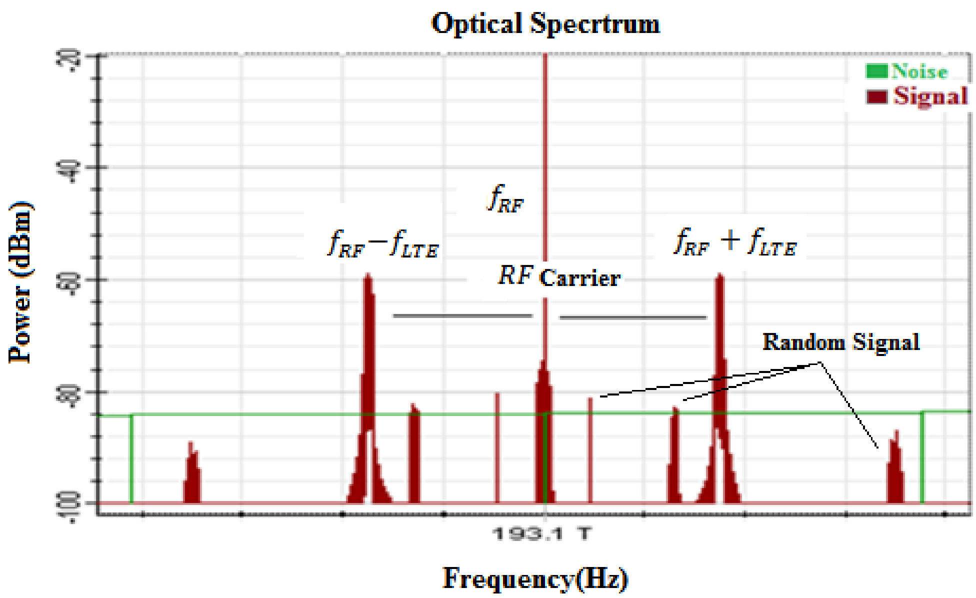

Figure 4-10-c: ODSB of Optical spectrum for LTE after 900km

Figure 4-10-c illustrates the ODSB for optical multiplexer carrier after 900km, which represents the LTE channel. The ODSB is located at the wireless carrier frequency away from the optical carrier. The optical RF carrier is at 193.1 THz; the lower optical sideband is ($f_{RF} - f_{LTE}$) and ($f_{RF} + f_{LTE}$) is the upper sideband. The optical signal travels 900 km of combined SMF-DCF-CFBG and is reflected in the CFBG. The RF power level is at - 20dBm, and the bandwidth of LTE is at -60dBm after 900 km fibre length. The noise, marked in green colour, ranges at -85dBm and there are random signals (white noise) displayed in red colour.

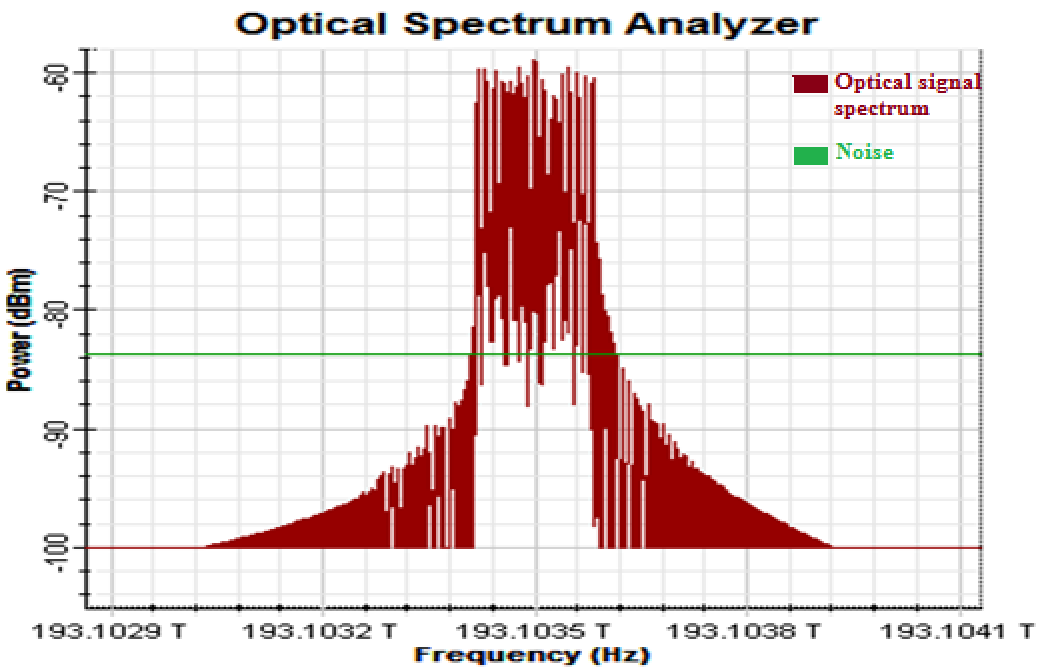

Figure 4-10-d: Optical bandwidth after 1800km.

Figure 4-10-d shows the optical carrier and clear optical bandwidth, which measures 20MHz for WiMAX after 1800km and the carrier frequency is set to 193.1THz. The signal transmission power is measured at a range of -60dBm. The noise ranges at -83dB, which is represented in the green colour and the optical transmission signal is represented in red. Compared to Figure 4-10-a, the optical power penalty is 16-dBm after 1800km, whereas the noise is -85dBm.

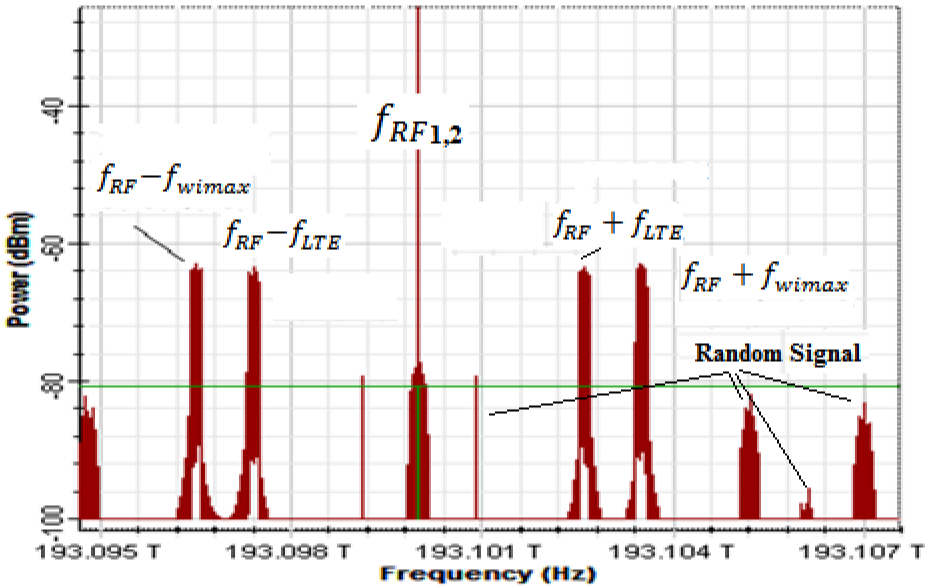

Figure 4-10-f Optical spectrum for LTE and WiMAX after 1800km

In Figure 4-10-f, the optical spectrum of the transmission signal for LTE and WiMAX is shown. LTE and WiMAX have an optical RF carrier in the range of 193.1THz. The ODSB signals obtain all fundamental components in both sidebands, they are presented in the carrier, where f_{RF}= 193.1 THz and (f_{RF}-f_{wimax} , f_{RF}-f_{Lte} , f_{RF} , f_{RF}+f_{Lte} ,f_{RF}+f_{WiMAX}). The power of the sideband of WiMAX and LTE is in the range of -65dBm. The random signals (white noise) are displayed in red colour.

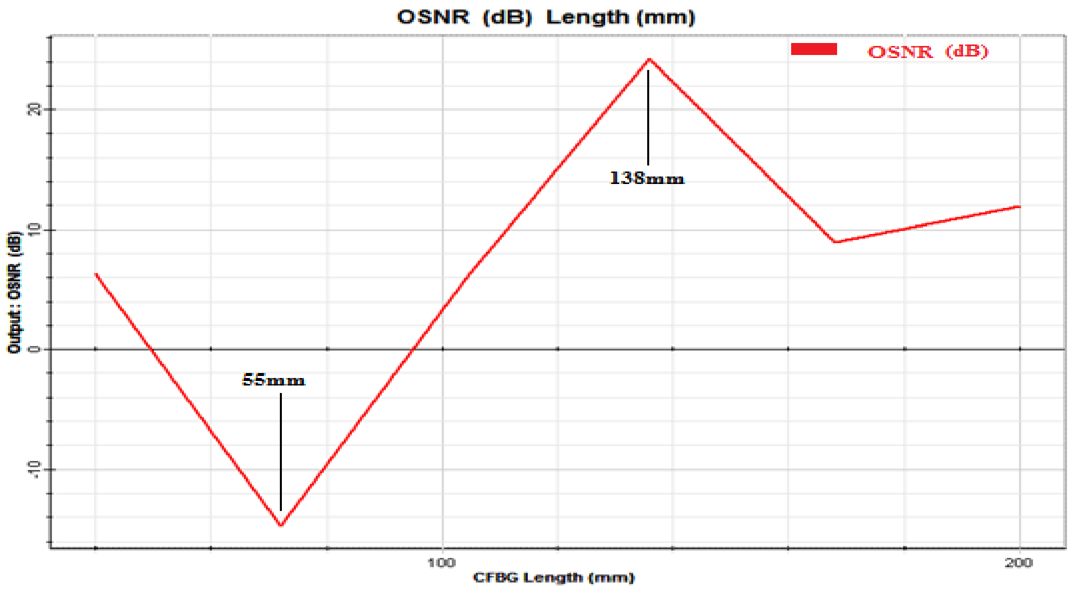

Figure 4-11: OSNR after fibre length of 1800km

The configuration of the CFBG chirp length has an impact on the OSNR. The CFBG offer some potential benefits when compared to DCF, including reduced optical losses, reduced optical nonlinearity, and the possibility of full dispersion slope compensation. Figure 4-11 illustrates the changing chirp length and its improvement of the OSNR; after 1800km transmission range, the OSNR output is with 26dB higher when the chirp configuration is 138mm than with a chirped grating set to 55mm. The setup shows the best OSNR results for for the CFBG configration parameter of 138mm to improve the signal itransmission of the system.

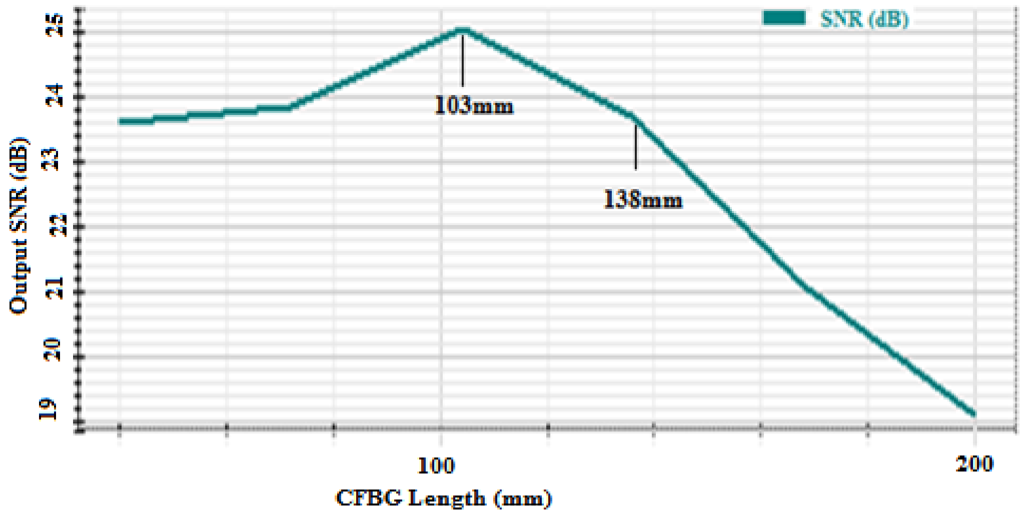

Figure 4-12: SNR output for different chirp lengths after 1800km

Figure 4-12 illustrates the magnitude of SNR for the configured chirp lengths of CFBG from 10- 200mm. The SNR at receiver measures 25dB when the chirp is configured to 103mm and 23.8dB when configured to 138mm. This means that the signal quality can be controlled by changing the CFBG chirp length.

TABLE 4-2: TOTAL POWER AND SNR OF WIMAX-TX

Electrical Carrier Analyzer

	Total Power (dBm)	Signal Power (dBm)	Noise Power (dBm)	SNR (dB)
Min value	-100	-100	-100	0
Max Value	8.8122203	8.8122203	-100	108.81222
Ratio max/min	108.81222	108.81222	0	108.81222
	(Hz)	(Hz)	(Hz)	(Hz)
Frequency at min	0	0	0	0
Frequency at max	3.5e+009	3.5e+009	3.5e+009	3.5e+009

The optical signal, which is a combination of LTE and WiMAX, is separated in the WDM-DEMUX and converted to an electrical signal by the photo diode. Each signal, LTE and WiMAX, is demodulated at the receiver and returned into a digital signal by the OFDMA-Demodulater. Table 4-2 illustrates the signal power and SNR of WiMAX-Tx, which is modulated to the laser beam and injected into RoF. The RF is at 3.5GHz; the signal power's maximum value ranges at 8.812dBm and maximum value for SNR is at 108.8dB.

TABLE 4-3: TOTAL POWER AND SNR OF WIMAX-RX

Electrical Carrier Analyzer

	Total Power (dBm)	Signal Power (dBm)	Noise Power (dBm)	SNR (dB)
Min value	-100	-100	-100	0
Max Value	-7.5421934	-7.5589891	-31.676432	24.117443
Ratio max/min	92.457807	92.441011	68.323568	24.117443
	(Hz)	(Hz)	(Hz)	(Hz)
Frequency at min	0	0	0	0
Frequency at max	3.5e+009	3.5e+009	3.5e+009	3.5e+009

Table 4-3 illustrates the total power and SNR of WiMAX-Rx for RF 3.5GHz; the signal power is at 92.46 dBm and SNR at 24.12dB; the noise power increased from 0 to 68.32dBm, due to the risen power attenuation and noise from the laser diode. The SNR difference between transmitter and receiver is 84.68dB, which means that the signal degraded over the transmission distance of 1800km. The power degradation measures 16.37dBm, so the power consumption of the system ranges at a low level.

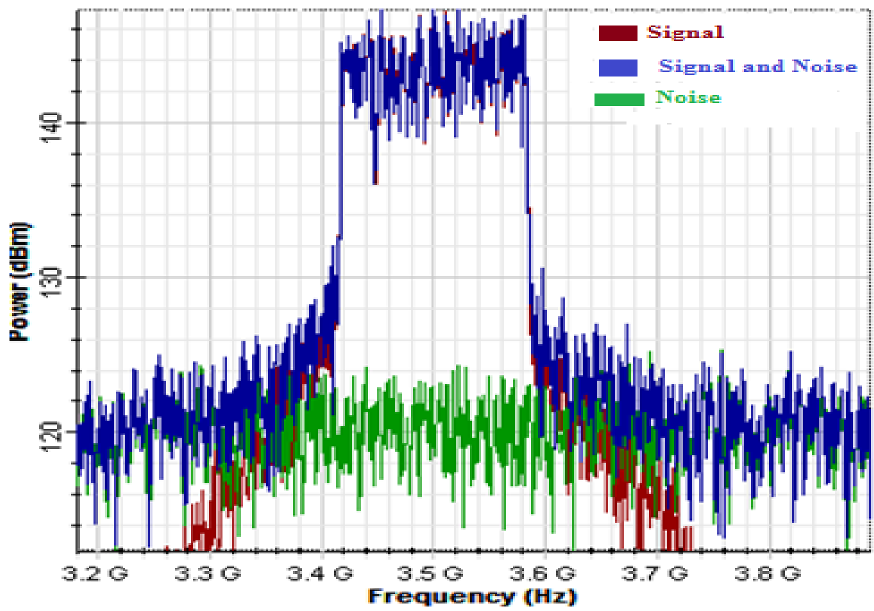

Figure 4.13: RF Spectrum of 3.5GHz-WiMAX-Rx for fibre length 1800km

Figure 4-13 represents the RF spectrum at the WiMAX receiver for RF 3.5GHz and 20MHz bandwidth; the signal is deployed over the triple compensators module SMF-DCF-CFBG for a span of 1800 km; the RF power is measured at 148dBm and the SNR is measured at 24.117dB. The blue colour refers to the signal including noise. The green spectrum area refers to the noise and the red to the signal without noise.

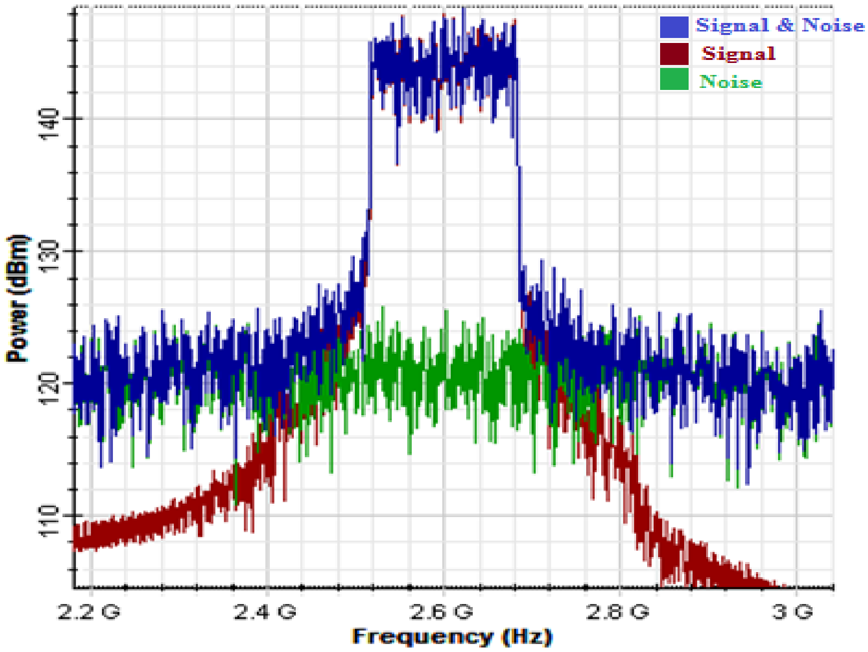

Figure 4.14: RF Spectrum of 2.6GHz-LTE-Rx for fibre length 1800km

In Figure 4-14, the clear RF spectrum at the LTE receiver is shown for LTE –RF 2.6GHz and 20MHz bandwidth; the signal is deployed over the triple compensators module SMF-DCF-CFBG for a length of 1800 km; the RF power is measured at 146dBm and SNR at 24.12dB. The blue colour refers to the signal including noise. The green spectrum area refers to the noise and the red to the signal without noise.

The optical amplifier EDFA is used for a total of 393.6dB for the signals transmission via 1800km; the RF spectrum for both, WiMAX and LTE at the receiver, is clear and satisfactory. As mentioned before, the EDFA only can compensate for the low power loss in a signal; the task of the DCF is to keep the signal in the position on zero dispersions and the CFBG minimizes the power losses in the signals. Thus, the signals reach a transmission distance of 1800km.

4.7 Chapter Summary

In this chapter , an approach for transmitting RF signals via Radio over fibre, using a WiMAX and LTE systems downlink deployed over a triple compensation scheme, consisting of SMF, DCF and CFBG was proposed. The DCF parameters were configured to compensate the accumulated dispersion in SMF and CFBG; thus, reducing the power loss and chromatic dispersion in the fibre also obtaining high values of OSNR and SNR.

The simulation results indicate the system's ability, transmitting a WiMAX-OFDMA and LTE- OFDMA signal of 128 subcarriers with an FFT of 1024 for a 3.5GHz and 2.6GHz carrier frequency via RoF for a fibre length of 1800km successfully. The bandwidth parameter was set to 20MHz; WiMAX and LTE were transmitted via RoF with a bit rate to 1Gbps with 64-QAM.

The comparison of the CFBG's chirp lengths from 10mm to 200 mm proved the best OSNR result with a 138mm chirp at 26dB and SNR at 24.117dB. Combining the SMF with a DCF dispersion configuration of -80ps ps/nm.km and additionally with a CFBG chirp of 138mm, can control the chromatic dispersion affecting the fibre.

The power amplifier used a total of 393.6dB for the transmission of the optical signal over a span of 1800km. Thus, a much lower power budget is needed for the WiMAX and LTE downlink than for the WiMAX transmission over 5 km, where the BS antenna consumed 43 dBm per km. Furthermore, the data bit rate could be increased to 1Gbps, and the bandwidth spectrum stayed relatively constant over the long fibre distance.

The results for SNR and OSNR are highly satisfactory; the power consumption is low between the input and output of the fibre.

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Chapter 5

Efficient Transmission of WiMAX, LTE and CWDM Channels via GPON-RoF

5.1 Overview

Optical-wireless access technologies have been considered the most promising solution to achieve effective delivery of wireless and baseband signals. They increase the bandwidth and extend the transmission distance at a lower power budget and environmentally friendly. In order to simplify the design, a gigabit passive optical network (GPON) is applied to the RoF system, which is able to provide much higher total bandwidth at a longer connection distance. The integration of an 18 channel coarse wavelength division multiplexing (CWDM) in the GPON,

In this chapter, the deployment of a combined wireless system, 3.5GHz WiMAX, 2.6GHz LTE and baseband signals with a bit rate of 2.5Gbps downlink and 1.25Gbps uplink in GPON-CWDM via RoF technology is demonstrated. The signals are transmitted to the bidirectional splitter-32 for 160km bidirectional SMF length and from the splitter to the WDM-DEMUX for 50km SMF length. The CDF and CFBG are utilised to overcome the problem of chromatic dispersion and power attentions in the SMF fibre. As a result, an extension of the transmission distance to 600km is achieved. Furthermore, the results indicate open eye diagrams, a clear RF and bandwidth spectrum and consultation diagram as well as low-energy consumption; Q- factor, SNR and OSNR have improved.

5.2 Introduction

Fibre optic technology is supposed to be the best solution for an expanding market for high-speed broadband services and high-bandwidth capacities at economical prices, because it offers virtually unlimited bandwidth potential. Additionally, it is widely considered the ideal solution for the delivery of broadband access to the last mile, which means the space between the carrier's central office (CO) and the subscriber's location in a network. One of the most significant developments within the fibre optic technology is a cost-effective passive optical network (PON) which is a point-to-multipoint fibre to the premises (FTTP) network architecture, facilitating a single optical fibre to provide different premises. Consisting of an optical line terminal (OLT) at the provider's central office (CO), a splitter and several optical network units (ONU) in the end user's area, PON is able to reduce capital expenditures. A minimised amount of fibre and central office equipment simplifies operations [11] .

Main standards for PONs are Broadband passive optical network (BPON), Ethernet PON (EPON), and Gigabit PON (GPON) [105] all operating with minimum power consumption. The passive optical splitters in PONs are deployed to allow a singular optical fibre to serve typically 32 –128 ONUs, where each unit can provide broadband service for 120 to 240 users [106].
BPON is the first generation in PON with a specification of a delivery bit rate of up to 622 Mbps download speed and 155 Mbps upload speed. The splitter in BPON fibre is connected to 32 users; each simultaneously can offer 40 Mbps down - and 10 Mbps upload speed.

A new addition to the Ethernet family is EPON, which has been selected as the standard large-scale FTTH introduction on the market. EPON is expected to offer a competitive solution for broadband network access, due to the ubiquitous adoption of Ethernet-based network equipment The system supports a bit rate of 1.25 Gbps bandwidth in both downstream and upstream directions; the splitter is capable to support 16 remote ONUs with each ONU providing average 60 Mbps sustainable bandwidth [107]**.** Nevertheless, BPON and EPON are still not flexible enough for HDTV and other high bandwidth applications.

The need for significant bandwidth as well as transmission distance led to the development of an improved network topology called GPON. The role of GPON systems in the progress of high- speed PONs is significant, due to the ability to deliver extremely high bit rates. Simultaneously, they assist in the transmission of supporting formats such as IP and TDM [108] as well as WDM and CWDM at high levels of performance. The upstream rates range up to 2.5 Gbps and downstream up to 1.25Gps [109]; the splitter supports 32-128 ONU. The heart of a GPON system is the OLT, performing key functions such as traffic scheduling, buffer control and bandwidth allocation. The power splitter receives data from the OLT via fibre after several kilometers of fibre length and subsequently supports 32 ONU; each ONU receives multiple wavelengths from the splitter. The ONU is capable to support the user over a remote antenna unit (RAU) by delivering a RF signal or as baseband directly connected to the device.

The Media Access Control (MAC) regulates communication between the OLT, ONU and all optical network terminals (ONTs), and they can only transfer data back upstream to the OLT when permission has been given.

High bandwidths devices, like HDTV, require up to 20Mbps, and the average Standard Definition Television (SDTV) stream currently uses up to 6Mbps. Each subscriber in fibre-to-the-home (FFTH) access network would need an average bandwidth of 50–60 Mbps to use broadband services such as HDTV, HD video streaming, and interactive online gaming simultaneously [106]. In order to meet these future needs, GPON using CWDM offers the possibility to extend the currently available 2.5Gbps by four times. CWDM is a wavelength division multiplexing (WDM) technology, which assembles several signals on laser beams at different wavelengths for transmission along fibre optic cables, with a channel spacing of 20nm. This spacing is, compared to DWDM, quite wide and, therefore, less accurate and less expensive lasers can be applied. A vigorous control of the laser drift is not needed, because of the wide channel spacing. The cost-effective CWDM technology is ideal for the expanding fibre capacity up to 18 channels in metro fibre applications. The fact, that the laser can operate un-cooled, gives the CWDM an advantage in means of energy consumption [16].

As described in this chapter, GPON-CWDM utilises Radio over Fibre to integrate LTE, WiMAX, and baseband signals. The deployment of optical fibre links to dispense RF signals from a central station to Remote Antenna Units (RAUs) possesses an extremely low signal loss; 0.2 dB/km for the wavelength of 1550 nm.

Both WiMAX and LTE base stations consume a high amount of energy transmitting the signal from 300m up to 5km. The path loss of WiMAX–RF 3.5GHz between a base station antenna with a height of 30m and a 2m high subscriber's station antenna ranges at 165dB; and of LTE 158dB for the transmission range of 4900m only[110]. Therefore, a solution has to be developed to address transmission cost and the limitation of signal delivery.

In this chapter, the simulation of the deployment of WiMAX-RF 3.5GHz, LTE-RF 2.6GHz wireless systems and 18 wavelengths as baseband signals across CWDM channels in GPON via a RoF system is proposed. LTE and WiMAX are carried over RF, transmitted to the RAU and converted to fibre optic signals. The optical CWDM wavelength and the RF signal are multiplexed by the WDM, and simultaneously delivered via fibre; firstly, to a length of 160 km and then to 210km. Controlling the chromatic dispersion in SMF, the combination of SMF, DCF and CFBG is applied; thus, the signal could be transmitted over a length of 600km. Section 5.3 describes the different types of passive optical network; related work is presented in Section 5.4; Section 5.5 explains the experimental configuration of the simulation design of GPON via RoF for a fibre length of 210km and the extended fibre length of 600km. The setup of the GPON-CWDM via RoF and integrated WiMAX and LTE is described in Section 5.5.1; the results are discussed in Section 5.6; and finally, in Section 5.7 the chapter is summarized.

5.3 Related Work

Several researchers [82][96][111–118] have integrated PON systems in optical system architectures to enhance capacity and services for next-generation networks. Shen et al [118] propose different architectures for the integration of EPON and WiMAX in order to utilise the advantages of increased bandwidth of fibre communications, in combination with the mobile and NLOS performance of wireless communications. EPON is used as a backhaul connecting different WiMAX base stations. The researchers found the integration to be helpful, realizing fixed mobile convergence and providing additional positive aspects, like better capacity utilisation and support of QoS; simplification of network operations , and providing wired and wireless broadband access services through a single passive optical network. A novel architecture for next-generation OFDMA-based PONs is proposed in [113].

The experimental results of this approach show that the chosen setup is able transmitting the integrated 10 Gbps OFDMA and three 20 MHz RF signals over 20 km, down- and upstream.

Milosavljevic et al [116] presented the interoperability of standard WiMAX and GPON using overlapping radio cells. They demonstrate the transmission of multiple un-coded IEEE802.16d channels through a single RF subcarrier at rates of 50 Mbps downstream and 15 Mbps upstream via GPON and WiMAX microcell links. They reached a transmission distance of 21 km. Kantarci et al [96] propose an energy-efficiency structure and design for hybrid fibre-wireless access networks. In this structure, the optical back-end consists of a WDM-PON, and the wireless front-end is a 4G broadband access network. The researchers attempted to develop power saving clusters (PSCs) consisting of fibre rings linking different hybrid access networks. The PSC permits the OLTs to sleep and allocates the accumulated traffic among the working segments in the ring. Simulation results show, applying this approach enables power savings in a range between 20% and 45%.

This research utilises a GPON-CWDM system for the deployment of a combined wireless system, 3.5GHz WiMAX, 2.6GHz LTE and baseband signals CWDM 18 channel with a bit rate of 2.5Gbps downlink and 1.25Gbps uplink in via WDM-RoF technology. The signals are transmitted to the bidirectional splitter-32 for 160km bidirectional SMF length and from the splitter to the WDM-DEMUX for 50km SMF length. The CDF and CFBG are utilised to increase the transmission length to 600km.

5.4 Passive Optical Network (PON) Technologies

The Passive Optical Network architecture is the leading technology for fibre to the home respectively, fibre to the premises (FTTH/FTTP) technology. Most telecommunication networks today are active networks like VDSL, DSL, and cable, which apply active components in their equipment, being placed in the network backbone, central office, the neighbourhood infrastructure and the customer premises. Active components in the PON system are situated only in the central office and the customer premises; the neighbourhood infrastructure obtains a passive light transmission device, the optical splitter, which divides the data stream of one bi-directional light source, into individual links connected to each customer [119]. The PON architecture is a form of fibre optic access network, where the fibre transfers traffic between the network side (service node interface) and the user's home network side (the user-to-network interface).

In the optical domain, the optical line termination (OLT) ceases the fibre at the side of the network, and the optical network unit (ONU) terminates the fibre at the user side. An optical distribution unit (ODN), like an unpowered optical splitter, which facilitates a single optical fiber to serve 16 to 128 premises, sits between the OLT and the ONU [15], as illustrated in Figure 5-1.

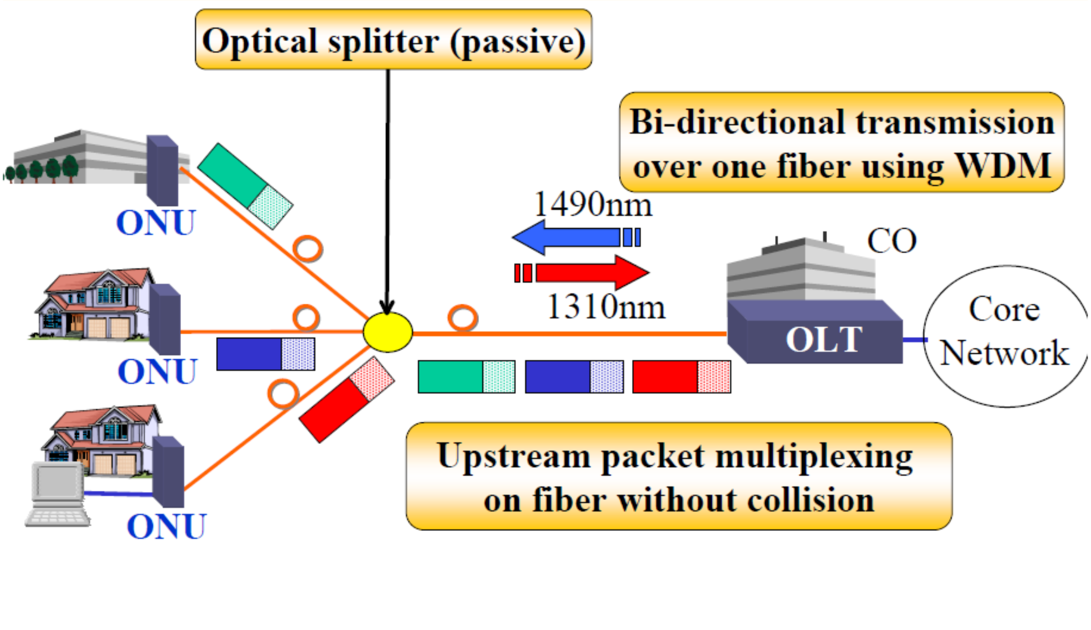

Figure 5-1: PON Technology to the home [120].

Figure 5-1 shows, the OLT is located at the service provider and connected to the different ONUs via a 1:32 splitter. The ONUs are connected to the subscribers.

The maximum fiber length between OLT and ONU, also called logical reach, depends on different parameters. Fiber attenuation, the optical power of the laser, component insertion loss, dispersion, other nonlinear effects, photo detector sensitivity, margin and expected signal performance are forming the optical budget, which determines the optical reach. Scalability and expansion are important characteristics of FTTP networks; therefore, they are designed to identify and accept newly added ONUs. Wavelength division multiplexing allows the PON to carry multiple wavelengths over the fibre link. With the ITU-T (G.694.2) specification, the cost-effective CWDM system of 18 optical channels over the full range of 1261–1621 nm is set as standard for metropolitan networks and is well suited for the access application PON. Generally, the PON technology is increasingly popular, because it decreases cost by reducing the number of required fibre and office equipment. In recent years, networking companies worldwide invested hugely in FTTP respectively PON technology [15]. For example, in the UK, BT is planning to provide FTTP and FTTC (fibre to the cabinet) to almost two thirds of homes and business premises by 2015 [121].

For other Europe countries, the FTTP penetration was expected to exceed between 2005 and 2008 from 2.5 million to 6.5 million buildings, with Denmark and the Netherlands as leading countries with approximately 76% respectively 66% of homes being powered with FTTP [106]. The PON technology includes three main specifications, APON/BPON, EPON and GPON, which are described in the following sections.

5.4.1 APON / BPON

ATM-based PONs (APONs) behave like usual Asynchronous Transfer Mode (ATM) networks; being designed in the mid- 1990s, they are an alternative to the telephone- and cable-based access networks in means of cost-effectiveness. APONS were developed to support ATM with defined data rates by ITU-T G.983.1 standard, published in 2005, of 1244.16-Mbps downstream and 622.08-Mbps upstream [122]. An APON can be employed for the provision of voice over IP, voice over ATM, high-speed Internet connection and video on demand services; symmetric or asymmetric downstream and upstream transmission rates can be implemented. As ATM encodes data into small cells of the same size, the cells are scrambled to make them readable for a single ONU only. For the upstream transmission, the APON system uses the wavelength of 1310nm, and to avoid collision, only one ONU can transmit cells at a time in the upstream direction [122]. The downstream operates with the wavelengths of 1490nm for transmitting ATM traffic, and 1559nm, which is used for video distribution. The G.983.1 standard makes use of other unidirectional fibers, operating at 1310 nm also possible. The maximum distance between an ONU and an OLT ranges at 20km; the minimum supported splits of the passive optical splitter are 16 or 32, and an APON can maintain a minimum of 64 ONUs.

The characteristics of APON were broadened to Broadband PON (BPON) under the same standard ITU-T G983.1 and an additional band for the downstream transmission was added. The BPON architecture enables a wide range of broadband services, like access to the Ethernet and video distribution.

5.4.2 Ethernet Passive Optical Network (EPON)

EPON is specified under the IEEE.802.3ah Ethernet for the first mile standard. With data rates of 1.25 Gbps for the downstream at a wavelength of 1490 nm and upstream transmission at 1310 nm, EPON is able to support triple-play services [123]. In contrast to the ATM technology, where data is sent in small-sized cells, Ethernet broadcasts data packets, including video etc. As Ethernet has over rounded the ATM technology, EPON is an emerging access network technology, which provides a cost-efficient strategy deploying fibre links between the central office and the subscriber premises [124]. Bandwidths requirements for next-generation applications, such as high-definition IPTV distribution and multimedia delivery systems, are huge, therefore, an amendment of the existing standard, the 10 Gigabit Ethernet passive optical network (IEEE 802.3av), was approved in 2009. The 10G EPON is compatible with the 1G EPON systems and offers symmetric 10G downstream and upstream links as well as asymmetrical 10G upstream and 1G downstream links [125].

5.4.3 Gigabit Passive Optical Network (GPON)

To enlarge BPON and EPON capabilities meeting the growing demand for higher speeds on the access network, a format was developed to carry multiple-sized data packets efficiently at gigabit per second rates. GPON is standardised in the ITU-T G.984 series of recommendations. The architecture enables the transport of high-quality voice, high-bandwidth IPTV, and data. The GPON standard specifies the information security mechanism. Advanced Encryption Standard (AES), protecting data from being modified, disclosed, utilised or destroyed unauthorized [119].

Today it is one of the supreme point-to-multipoint fibre technologies, due to several advantages over other access systems. GPON networks are deployed massively all around the globe and are, therefore, economically attractive specifically for mobile carriers. Not only the ability to transmit downstream data rates of nearly 2.5Gbps but also the upstream quality of service (QoS) and service level agreement (SLA) create a value of GPON [126]. The PON technology applies WDM, utilising one wavelength for the downstream and another one for the upstream signal transmission. Thus, new network services can be provided with the same fibre capacity. The WDM enhancement prefers the wavelengths range from 1530 to 1605 nm, due to low attenuation in commonly deployed standard single-mode fibre, and it complies with the gain window of the erbium-doped fibre amplifier (EDFA)[123].

5.5 Simulation Design of GPON-CWDM via RoF and Discussion

The following sections present the simulation design of the transmission system using OptiSystem 9.1 and OptiGrating software. Section 5.5.1firstly describes the architecture consisting of GPON and CWDM via RoF for a fibre length of 160km to the splitter and subsequently, to ONU and 50km to WDM-DEMUX, which is in total 210km. Secondly, the advantage of transmitting combined LTE, WiMAX, and 18 wavelengths baseband in GPON via RoF is discussed. In Section 5.5.2, GPON and CWDM via RoF for the extended network signal transmissions distance of 600km is proposed.

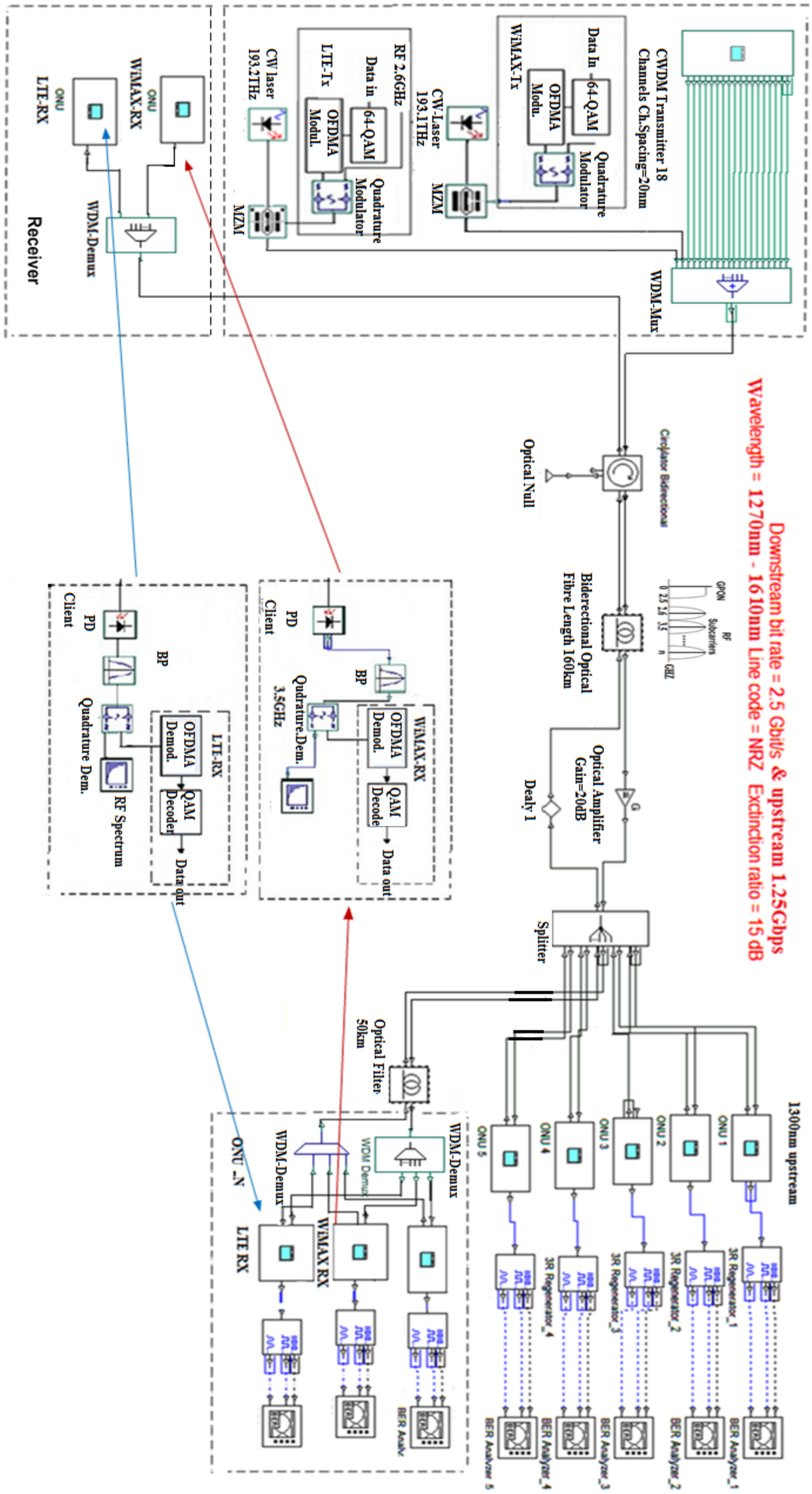

Figure 5-2: WiMAX and LTE combined with baseband and transmitted via GPON CWDM-RoF system

5.5.1 GPON-CWDM via RoF for fibre length of 210km

In Figure 5-2, the tree topology of the experimental configuration is displayed. The downstream direction starts from the GPON head end and optical line terminal (OLT). As mentioned in Section 5.2, the OLT is the heart of GPON, it supports 2.5Gbps downstream data to the splitter-32. The network is called "passive optical network" because the optical splitter does not need external electrical power to operate. The OLT consists of CWDM, WDM-MUX, WDM-DEMUX LTE-Tx, LTE-Rx, WiMAX-Tx, and WiMAX–Rx. CWDM systems have channels at wavelengths spaced 20 nm apart, compared with 0.4 nm spacing for DWDM. The laser emissions occur on eighteen channels at eighteen defined wavelengths: from 1611 nm, 1591 nm, 1571 nm, 1551 nm, 1531 nm, 1511 nm, 1491 nm, 1471 nm and down to 1271 nm. The wavelength inexactness or variability (tolerance) in a CWDM laser reaches up to ± 3 nm, whereas, in a DWDM laser, the tolerance is much narrower.

The LTE supports scalable multiple transmission bandwidths including 1.4, 3, 5, 10, 15, and 20 MHz The target peak data rate via RoF system is for both systems (WiMAX and LTE) 1Gbps whereas 100 Mbps in the wireless system and 54Mbps for WiMAX. The modulation schemes on the physical layer range from QPSK over 16QAM to 64QAM and can be amended quickly to different subcarriers to appropriate the various reception conditions of subscribers. The system is set up with Mobile WiMAX, due to its transmission scheme (OFDMA) and increased scalability of the actual physical layer parameters.

In the following, the successful transmission of WiMAX 64QAM OFDM and LTE 64 QAM OFDM channels via a combined GPON and RoF system is demonstrated. WiMAX 64QAM and LTE 64QAM channels as a function of the RF drive are transmitted into the two Mach-Zehnder modulators (MZMs) in the OLT. The CW laser diode has an average output power of 3 dBm for laser frequency 193.1 THz. A line width of 10 MHz, relative noise dynamic of 3dB and a noise threshold of -100dB. The CW-1 laser diode emits a light wave (193.1 THz) into an optical input of the MZM-1, where WiMAX-RF is modulated to the laser. The CW-2 emits a light wave (193.2 THz) to MZM-2, where LTE-RF is modulated to the laser and subsequently, powered as an optical wave into the fibre; firstly, launched into WDM-MUX. The WDM technique, on the one hand, is used to guarantee signal transparency for different radio signal formats and to prevent interference with the GPON-CWDM spectrum.

On the other hand, the laser emission wavelengths are opted for a 20 nm pitch CWDM grid to operate signals to/from the required base station. Firstly, the 18-channel CWDM wavelength is launched into WDM-MUX, which powers the combined LTE, WiMAX of CWDM wavelength into the bidirectional SMF for 160km to the splitter-32. The bidirectional splitter as a coupler divides the optical signal to one, two, or more fibres. These are employed to distribute the downstream 2.5Gbps data from and to the OLT to ONUs and WDM-DEMUX to combine the upstream 1.25Gbps data from individual ONUs and WDM-DEMUX to a single OLT. Every ONU is capable to support 24 end users with up to 100Mbps, and can be used in a Fibre-to-the-Premises (FTTP) case as an interface to the copper fibre, or in a fibre-to-the-curb (FTTC) case; it can also be used in the Fibre-to-the-Neighbourhood (FTTN). This component evenly splits the signal input power to N output ports. The S-parameters for the splitter are [77]:

$$S_{o_{iI_I}} = \left[10\, log\frac{1}{N} - \propto\right]^{<0^0} \tag{5.1}$$

Where α is the parameter insertion loss (dB), N is the number of output ports and the output port index.

Finally, the WDM-DEMUX is connected to the splitter via SMF length 50km. This technology provides an attractive solution for the first mile because of the fact, that it does not require any signal division. Moreover, WDM systems allow individual users to use their own wavelength channel; LTE-Rx at wavelength 1552 nm and WiMAX-Rx at wavelength 1551nm. At the WiMAX and LTE receivers the Quadrature demodulator, which implements an analog demodulator using a carrier generator for Q and I quadrature components, demodulates the RF signal; it consists of two band-pass filters. 7GHz cut-off frequency of low-pass filter is configured; the OFDMA demodulator is implemented by a complex point 1024 FFT. The upstream baseband and wireless signals of 1.25Gbps travel from the user to the ONU and subsequently to the OLT via a splitter. The WiMAX-Tx and the LTE-Tx for wavelength 1300-1320nm are deployed from WDM-MUX via 50 km SMF length to the splitter, from there via 160km bidirectional fibre to the OLT. In the OLT, the WDM-DEMUX separates the signals. The PIN converts the optical into electrical signals, which radiate through the RAU to the LTE and WiMAX receiver.

5.5.2 SMF, DCF, and CFBG Extended GPON Network for Fibre length 600km.

The following section describes the simulation setup of the GPON network for the increased transmission distance. The system is broadened by the deployment of the triple compensators technique SMF-DCF and CFBG.

The 64-QAM WiMAX OFDMA and the 64-QAM LTE OFDMA downstream are transmitted as RF signals to the fibre. The WiMAX–RF spectrum ranges at 3.5GHz and LTE-RF at 2.6 GHz comprising 128 subcarriers and 20MHz bandwidths. Figure 5-3 illustrates the schematic of the simulation setup of WiMAX and LTE via RoF, including the dispersion model techniques SMF, DCF, and CFBG. In this simulation, the base station deploys the data of the WiMAX and LTE to the fibre system as a RF signal 3.5GHz and 2.6GHz; firstly, to the remote antenna unit as an electrical signal. Subsequently, the signal is converted into a fibre optic signal by modulating the RF to the laser beam, which a laser diode has powered into the MZM and from there into the WDM.

The optical signal then is multiplexed with CWDM wavelength and is powered to the RoF system. The RoF system consists of part 1, comprising a DCF (25 km), SMF (125 km) SMF (125 km) and DCF (25 km), connected to the CFBG, which is added after every 300 km. The CFBG is used because of the high- power attenuations in DCF also to minimize the energy loss in the fibre optic system and to control the chromatic dispersions in conjunction with the DCF. The CFBG chirped bandwidth is $\Delta\lambda$=2 nm, n=0.0006 and has a length of 125 mm.

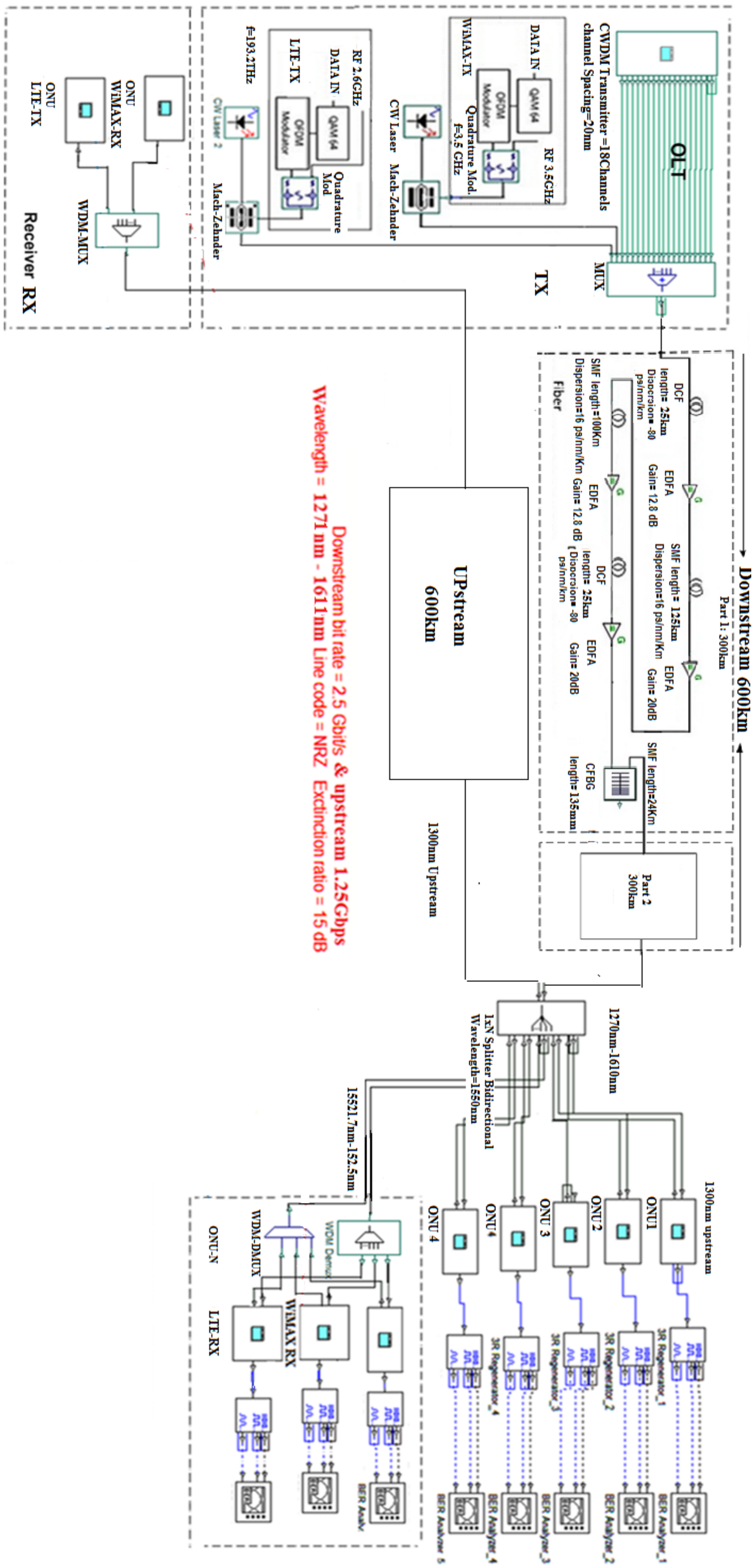

Figure 5-3: Downstream and upstream of GPON/CWDM network via RoF, using SMF, DCF and CFBG for fibre length 600km

The described layout allows an adjustment of the positive dispersion signal in SMF; thus, the signal transmission can be increased to 600km fibre length. The SMF dispersion parameter is 16 ps/nm/km and signal attenuation is 0.2dB/km; therefore, fully accumulated dispersion is 16×125=2000 ps/nm. DCF is configured to negative dispersion -80ps/nm/km at 1552nm to neutralize the positive signal dispersion in SMF.

The bidirectional splitter supports multiple wavelengths for one ONU as the ONU is able to support 24 users and the WDM, which subsequently provides the user with up to 16 channels. The upstream transmission signal of 1.25Gbps travels from the user to the ONU and then to the OLT via a splitter at wavelengths of 1300nm and 1320nm. Afterwards, it travels from the WiMAX-Tx and the LTE-Tx to the OLT WiMAX-Rx and LTE-Rx via the splitter and a bi-directional fibre. A photo detector diode in the ONU (PIN for dark current 10nA and centre frequency 193.1 THz) converts the optical power into the current electrical signal. As mentioned before, the utilisation of the electrical band-pass Gaussian filter sets the electrical signal noise to a minimum and group delay becomes constant for all frequencies.

5.6 Simulation Results and Discussion

The following section presents the simulation results; firstly, regarding the fibre link of 210km and secondly, for the increased span of 600km.

5.6.1 GPON/CWDM Based RoF for a SMF length of 210km

In this section, the signals of WiMAX-RF and LTE-RF as analogue channels and 18- CWDM channels as digital are modulated and converted to the optical channels then multiplexed in WDM-Multiplexer and transmitted over GPON-RoF system for a bidirectional SMF for fibre length of 160km to the bidirectional splitter. In the bidirectional splitter transmitted to the ONUs directly and from splitter via bidirectional SMF for fibre length of 50km to WDM-DEMUX, which is in total a fibre length of 210km in this system. In the WDM-DEMUX, the wavelengths carrying LTE and WIMAX are separated and subsequently transmitted to the LTE and WiMAX-Rx.

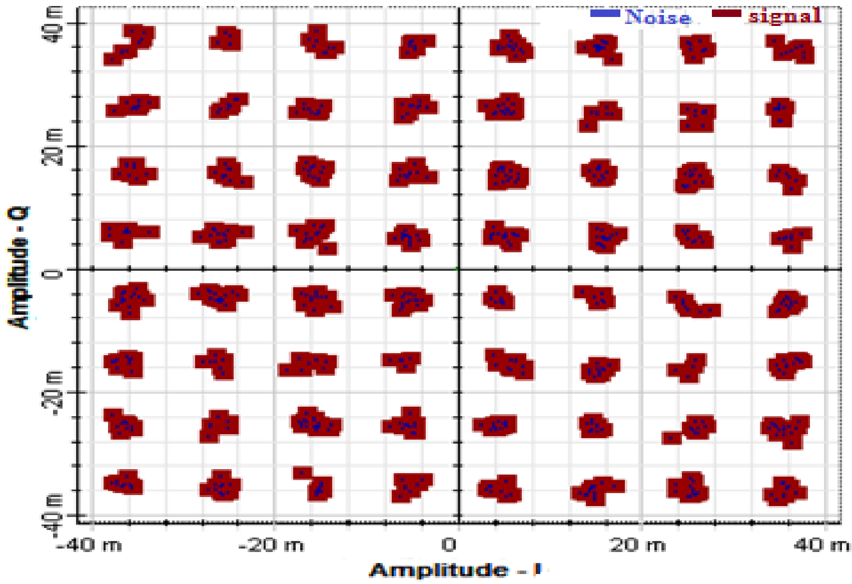

Figure 5-4-a: 64 QAM signal constellation diagram of WiMAX for 20km fibre length

Figure 5-4-a shows the 64-QAM electrical constellation diagram for the 3.5GHz WiMAX-Rx. The signal at the receiver is transmitted via RoF over bidirectional SMF for a distance of 20km. It also shows that there is noise included, which is produced by the laser diode and because of power attenuation and signal dispersion in SMF. The baseband signal obtains a little noise, which refers to white noise. The types of noise in the fibre optic system caused by the laser diode can be divided into noise threshold and dynamic noise. The types of PD noise are called thermal noise and shot noise. In the bidirectional SMF, the optical signal becomes weak after 20km, due to power attenuation and signal scattering as well as chromatic dispersion, which affects the signal quality.

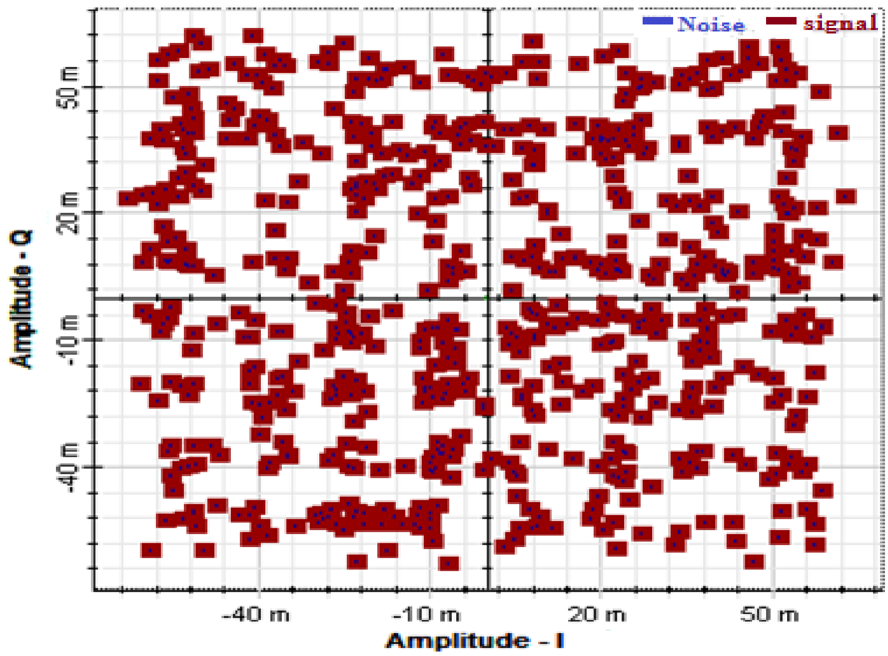

Figure 5-4-b: 64 QAM signal constellation diagram of WiMAX for 210km fibre length

Figure 5-4-b shows the 64QAM scheme for the SMF after 210km fibre length; the signal constellation displays unclear as a result of the high standard of noise, due to the high power loss in SMF. The signal transmission span is limited, because of the positive dispersion of 16ps/nm/km, which is the reason for the light pulse to spread. This spreading or broadening of the pulse leads to signal distortion or loss per km. In this figure, the signal quality is low, compared to Figure 5-3, due to rising power attenuation per km and noise.

The EDFA can only amplify the optic signals, which obtain minimum power loss. Therefore, the DCF and CFBG are used to increase the signal transmission, by controlling the signal spreading in SMF.

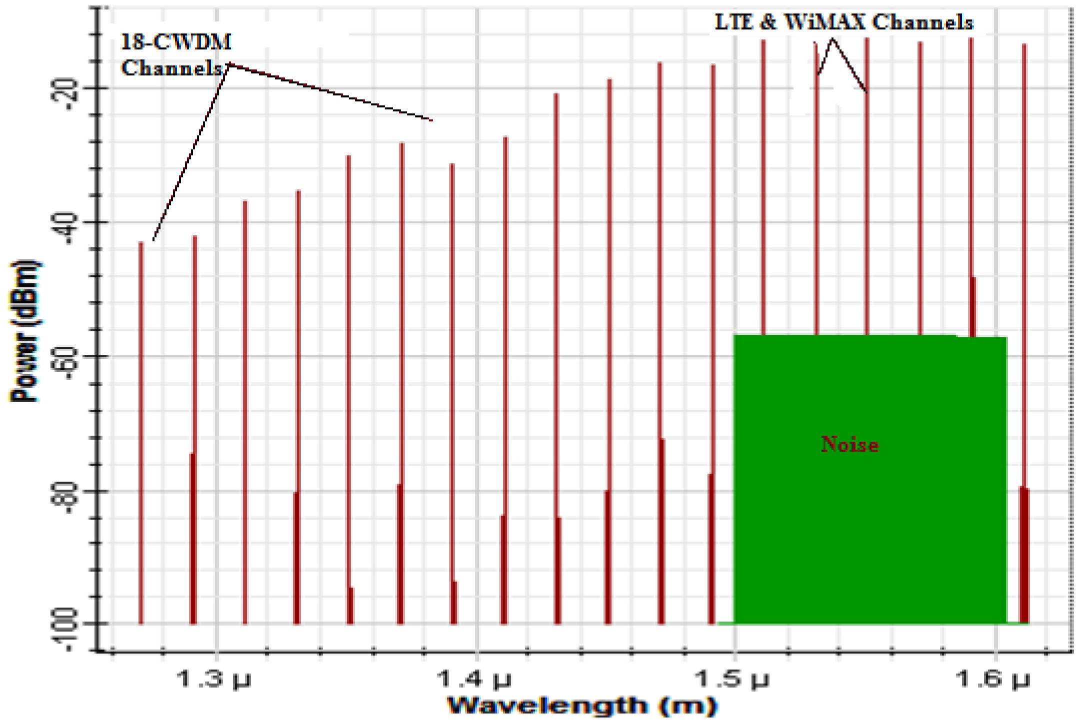

Figure 5-5: Optical emission spectrum for 2.5 Gbps for combined 18 channels CWDM signal, WiMAX-Tx and LTE-Tx for SMF length 210km

Figure 5-5 illustrates the optical emission spectrum for 2.5 Gbps for the combined 18 channels CWDM signal, which represent the digital signal, also WiMAX and LTE-Tx, which represent the analogue signal. The CWDM offers a favourable approach of delivering 2.5 Gbps to the access network. The WDM-Mux powered into the bidirectional SMF for the fibre link of 210km. The WDM multiplies fiber capacity by multiplexing optical light signals of different wavelengths onto SMF; the fibre wavelengths ranges from 1271 to 1611nm, which carry baseband (digital signal) and analogue signals (LTE and WiMAX-RF). The power level for the wavelength 1271nm ranges at -46dB but from 1550nm to 1622nm, it ranges at -15dB, due to the fact that the power attenuation is higher at the wavelength from 1271nm to 1382nm. As described in Chapter 2.4.1, this physical character of fibre optic is called Low water peak.

The WiMAX-RF wavelength is 1552.5 nm and LTE-RF is 1551.7nm; the green area in the displayed spectrum refers to noise, which occurred from the wireless RF signal and the laser diode. Laser diodes usually entail relatively intensive noise. The spectrum also shows that the energy level is independent of the wavelength.

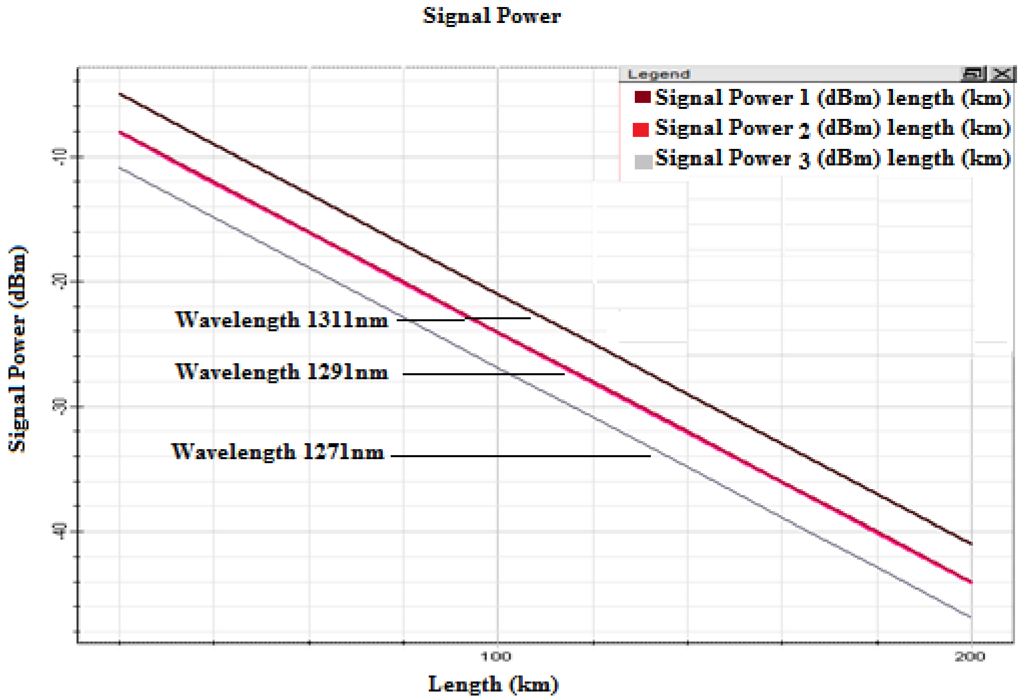

Figure 5-6: Signal power attenuation of 8 channels in SMF; dBm per km

As shown in Figure 5-6, the signal power loss after the SMF length of 210km ranges from -41 to -46dBm for different wavelength. The signal transmission of the optical signal over bidirectional SMF reaches 160km length via RoF to the bidirectional splitter, then from the splitter via bidirectional SMF length 50km to the WDM-DEMUX, which is in total a length of 210km. The measured signal power for the wavelength of 1271nm at the receiver ranges at -46dBm, for 1291nm decreases to -43dBm, and for 1311nm to -41dB. This result proves the power level in the optical system is dependent on the wavelength.

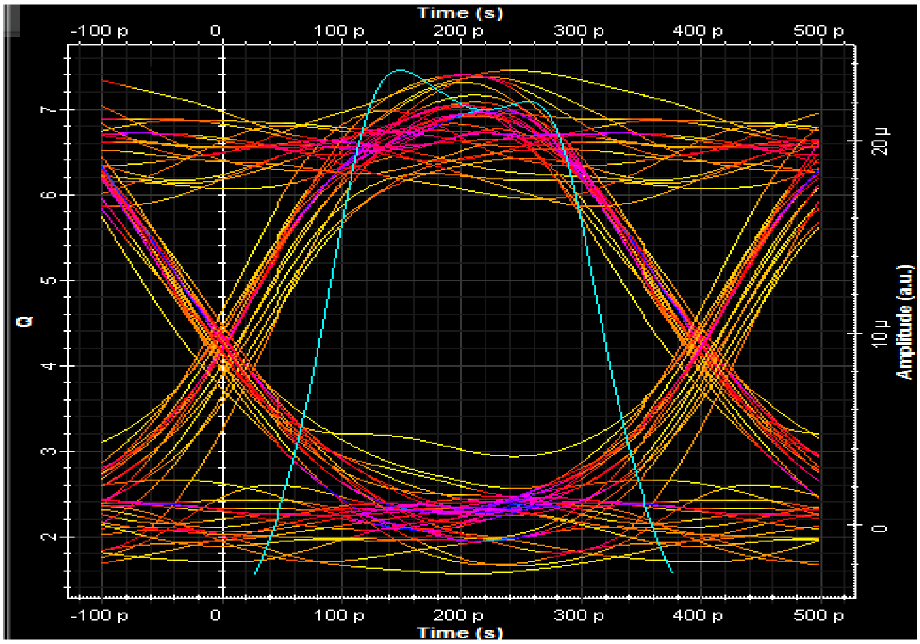

Figure 5-7-a: Eye diagram and Q-factor after splitter for the ONU multiple wavelength for a fibre length of 160 km

The eye diagram, as an useful tool for the qualitative analysis of signals in digital transmission systems, presents in Figure 5-7-a a wide eye opening diagram of the ONU for wavelength 1551nm and bidirectional SMF length of 160km; the Q factor is measured at the range of 7.452. The splitter supports multiple wavelengths, each ONU obtains a wide eye diagram opening with a minimum of noise, which represents a high signal-to-noise ratio (SNR) and a low jitter. Additionally, there is a rapid progress when centred to 400ps, equal to 2.5GHz; the wavelength has different dispersion factors.

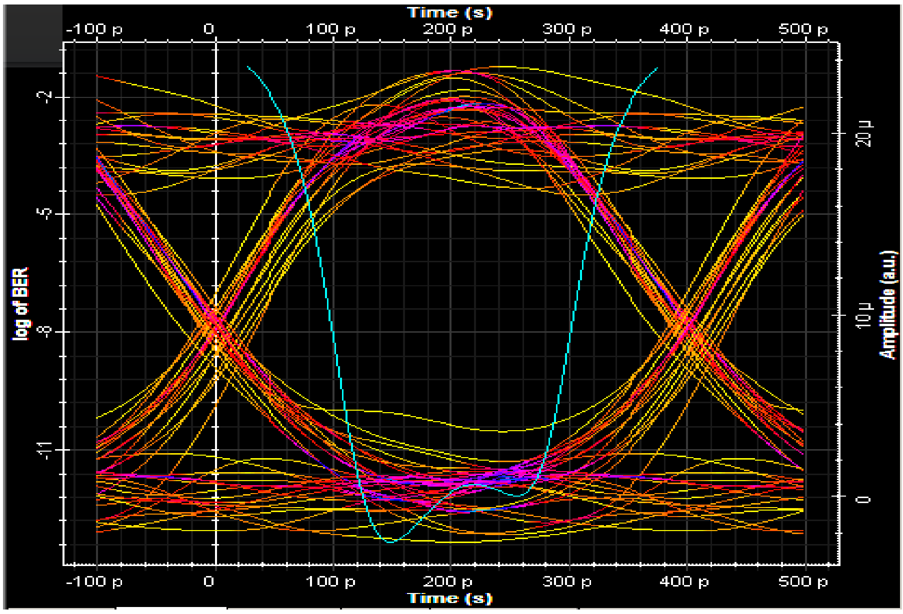

Figure 5-7-b: Eye Diagram and Bit error rate for bidirectional SMF 160

The down-converted 2.5Gbps electrical eye diagram is shown in Figure 5-7-b. The pulse width of the 2.5Gbps signal carried by the optical millimetre-wave (1551nm) is approximately 400 ps for OSNR 21.96dB. The BER curves and is measured at the level of   4.5e-14 with a minimum of noise after the signal transmission via RoF in the CWDM-GPON system for the bidirectional SMF length of 160km to the ONU. In addition, it presents a wide-open eye for the ONU for the channel of 1551nm wavelength.

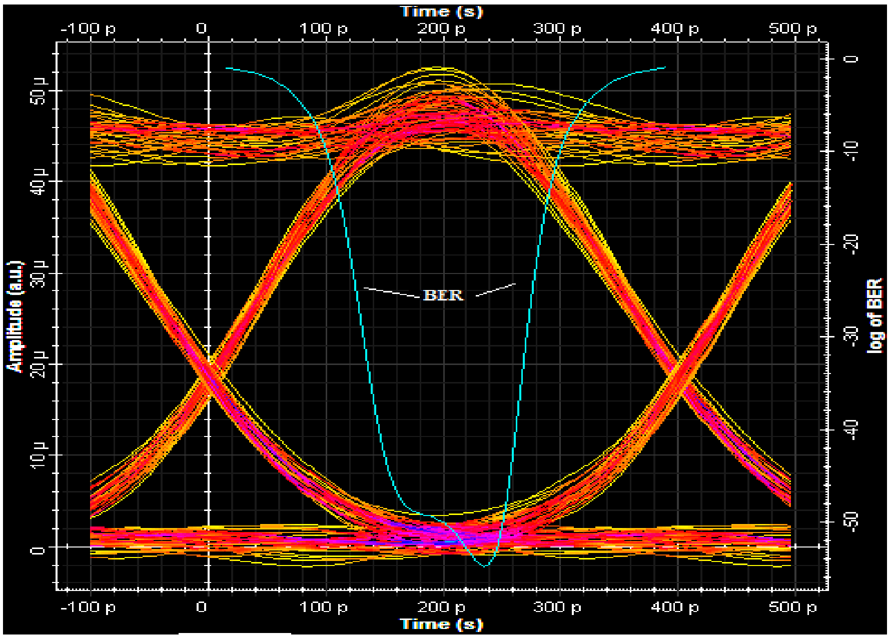

Figure 5-8-a: Eye Diagram and BER for WDM -ONU after SMF length of 210km

Figure 5-8-a shows a down-converted 2.5Gbps electrical wide-open eye diagram for the ONU after WDM-DEMUX; the BER is measured at the range of at 1.719e-55 for the time of 400ps and the Q-Factor is 15.64. From the splitter, the various wavelengths are powered into the 50km SMF length; the transmission length from GPON via splitter to WDM-DEMUX is 210km. The WDM-DEMUX provides individual wavelength to the user via RAU, which covers a micro cell area of 1552.5 nm.

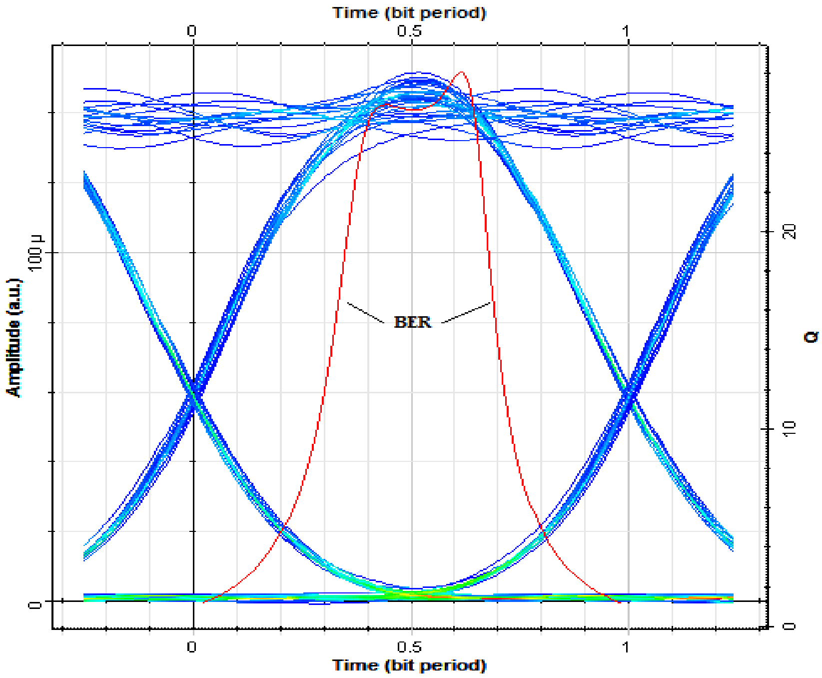

Figure 5-8-b: Eye diagram and Q-Factor after 210km

Figure 5-8-b shows a down-converted 2.5Gbps electrical wide-open eye diagram for the ONU after WDM-DEMUX; the Q-factor performs satisfactorily with a measurement of 28.64 for the time of 400ps and for OSNR 21.85dB. From the splitter, the various wavelengths are powered into the 50km SMF length; the transmission length from GPON via splitter to WDM-DEMUX is 210km. The WDM-DEMUX provides individual wavelength to the user via RAU, which covers a micro cell area of 1552.5 nm.

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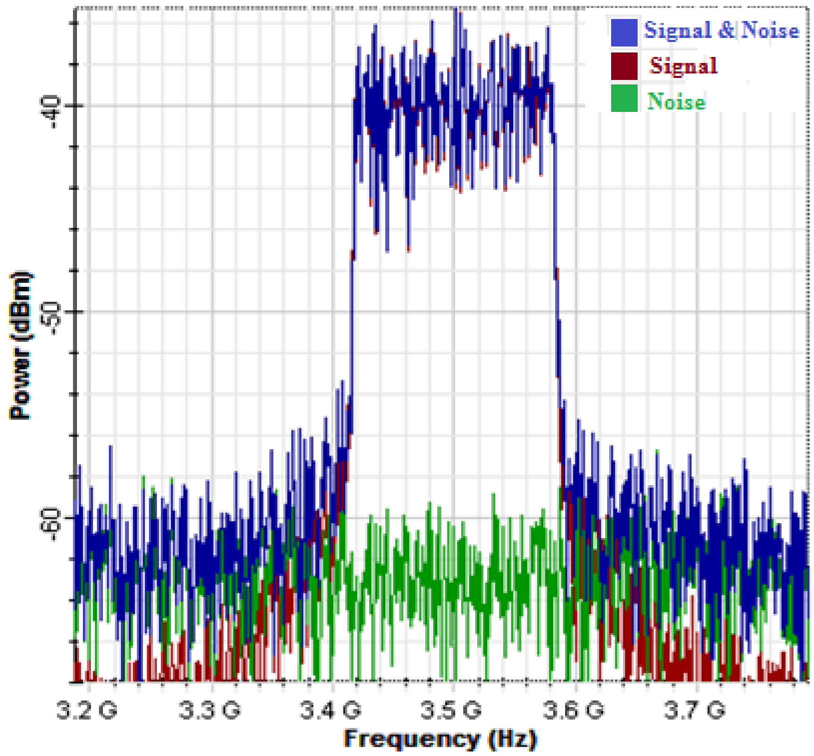

Figure 5-9-a: Downstream RF spectrum of WiMAX-Rx after SMF 210km

Figure 5-9-a illustrates the downstream RF spectrum of 64-QAM WiMAX-Rx for 3.5GHz carrier frequency and a bandwidth of 20MHz. The blue coloured spectrum area refers to signal and noise, the green to noise, and the red to the signal without noise. The signal is transmitted via bidirectional SMF length of 160km to the splitter and from there via bidirectional SMF length 50km to the WDM-DEMUX, where the optical signal is separated to the WiMAX wavelength 1552.5nm and LTE 1551.7nm. Subsequently, the optical signal is converted to an electrical signal in the PD and transmitted to the WiMAX receiver. The power amplitude measures -44dBm and the OSNR 21.85dB.

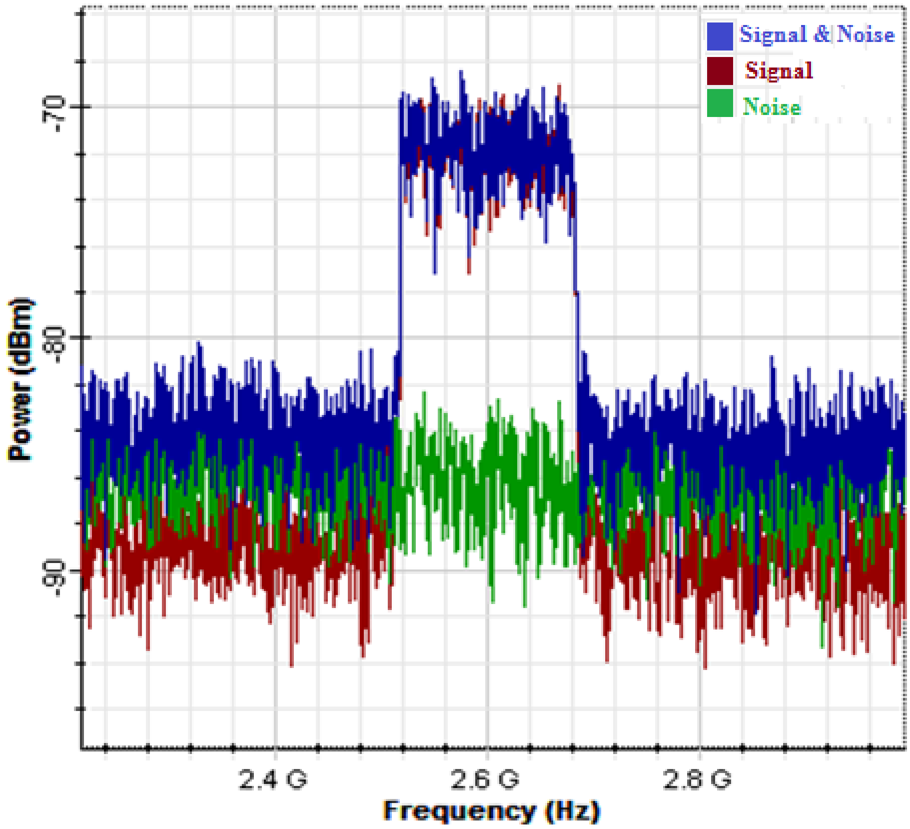

Figure 5-9-b: Downstream RF spectrum of LTE-Rx after SMF 210km

Figure 5-9-b illustrates the downstream RF spectrum of 64-QAM LTE-Rx 2.6GHz carrier frequency and a bandwidth of 20MHz. The blue spectrum area refers to the signal and noise, the green to the noise and the red to the signal without noise. The signal is transmitted via the bidirectional SMF length of 160km to the splitter and from splitter via bidirectional SMF length 50km to the WDM-DEMUX. The WDM-DEMUX separated the optical signal to the LTE-wavelength 1551.7nm. Then the optical signal is converted to the electrical in the PD and transmitted to the LTE receiver. The power amplitude measures -70 dBm and OSNR 21.85dB.

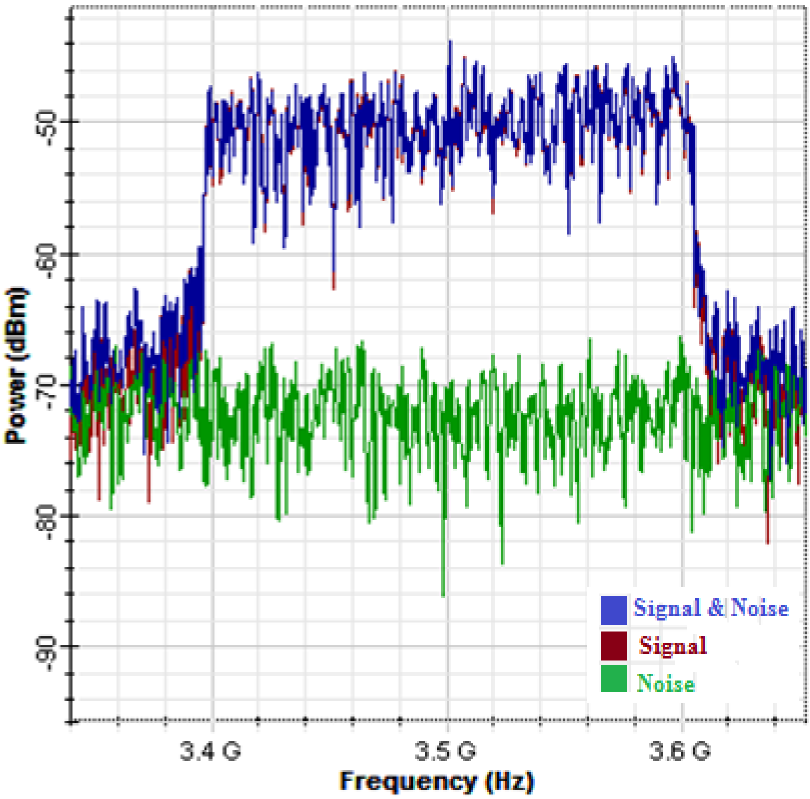

Figure 5-9-c: Upstream RF spectrum of WiMAX-Rx

Figure 5-9-c illustrates the RF spectrum upstream of 64-QAM WiMAX-Rx for 3.5 carrier frequency and a bandwidth of 20MHz. The blue colour refers to the signal and noise, the green spectrum area to the noise and the red to the signal without noise. The signal is transmitted from the user via the bidirectional SMF length of 50km to the bidirectional splitter and from there via bidirectional SMF length 160km to the WDM-DEMUX. The WDM-DEMUX separates the optical signal to the WiMAX-wavelength 1300nm. The PD converts the optical signal to the electrical: subsequently, the electrical signal is transmitted to the WiMAX base station. The power amplitude measures -45dBm.

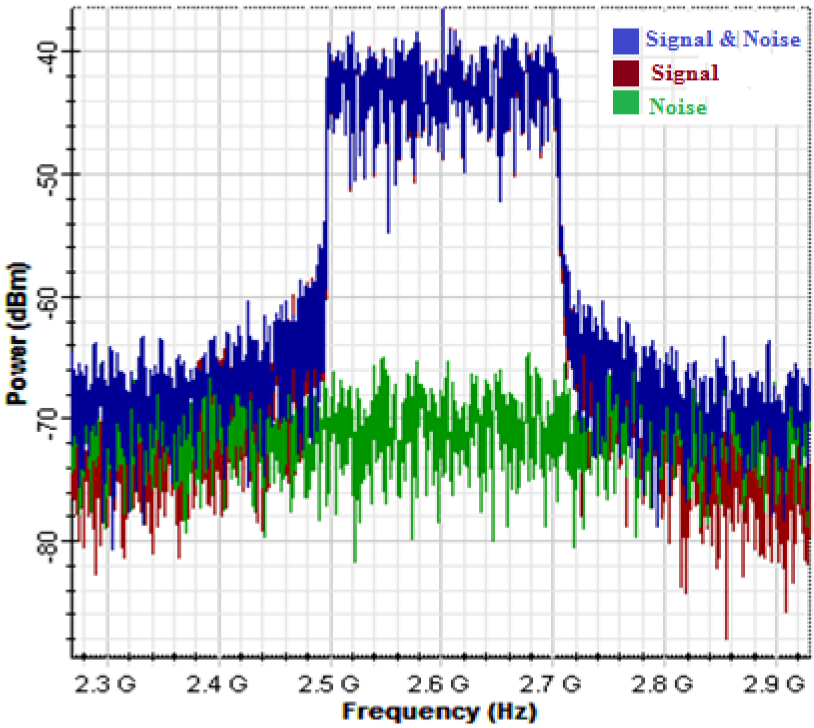

Figure 5-9-d: Upstream RF spectrum of LTE-Rx

Figure 5-9-d represents the RF spectrum upstream of LTE-Rx for 2.6GHz carrier frequency and a bandwidth of 20MHz. The blue spectrum area refers to the signal and noise, the green to the noise and the red to the signal without noise. The signal is transmitted from the user via the bidirectional SMF of 50km length to the bidirectional splitter and from there via bidirectional SMF length 160km to the WDM-DEMUX. The WDM-DEMUX separates the optical signal to the LTE-wavelength 1320nm. The PD converts the optical signal to the electrical, which then is transmitted to the LTE base station. The power amplitude measures for LTE-Rx -40dBm.

The optical signal-to-noise ratio (OSNR), as a crucial and basic system design analysis, designates the quality of the signal in an optical network by identifying the ratio of the signal power to the signal noise power. The OSNR depends on the bit rate, which means, the higher the bit rate, the higher the required OSNR. A function of the OSNR, the so-called Q- factor, frames a qualitative description of the receiver output; Equation 5-2 defines OSNR.

$$OSNR(dB) = 10log \frac{P_{signal}}{P_{noise}} + 10 \ log \frac{B_m}{B_{ref}} \qquad (5.2)$$

Where P_{signal} is the average signal power; B_{ref} is an optical reference bandwidth normally 0.1 nm at 1550; P_{noise} is the optical noise power; B_m is the noise equivalent bandwidth of an optical spectrum analyzer. The noise occurs at the transmitter laser diode from an erbium-doped fibre amplifier (EDFA). OSNR is measured to test the qualification of individual channels.

TABLE.5-1-A: OSNR AFTER 160KM FIBRE LENGTH

Frequency (THz)	Input OSNR (dB)	Output Signal (dBm)	Output OSNR (dB)
188.43021	95.991313	-11.008945	22.070897
190.82906	95.858411	-11.141822	21.883632
193.28979	95.991494	-11.008602	21.960329
195.8148	95.857409	-11.142859	21.770274
198.40666	95.991901	-11.008347	21.84696

The following Table 5-1-a shows the optical RF frequency via 160km SMF to the splitter also for each frequency the input and output OSNR of the SMF link end, and the output signal power in dBm. The highest OSNR occurs at the wavelength of 1591nm (188.43THz), because of the low water peak standard SMF, which refers to the low-power loss at the wavelengths 1550 nm to 1591nm. The lowest OSNR is at the wavelength 1531nm (195.81nm), due to the low water peak standard SMF. The difference between the OSNR at the input and the end of the SMF after 160km is 73.92dB.

TABLE 5-1-B : OSNR AFTER 210KM FIBRE LENGTH

Frequency (THz)	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
188.43021	-10.040243	-32.002975	21.962732
190.82906	-10.173425	-31.948587	21.775162
193.28979	-10.040107	-31.892063	21.851956
195.8148	-10.174921	-31.836266	21.661344
198.40666	-10.040265	-31.77844	21.738174

Table 5-1-b presents the OSNR at WDM-DEMUX after the splitter for SMF 50km length; the average power loss at the splitter is 73.43dbm. A power loss of 0.11dB can be recognized for the span from the splitter to the WDM-DEMUX. As a result, the highest OSNR occurs at the wavelength of 1591nm (188.43THz), because of the low water peak standard SMF, which refers to the low-power loss at the wavelengths 1550 nm to 1590nm; high-power loss arises at the wavelengths from 1371nm to 1391nm. The frequencies from 188.4THz to 198.4THz stand in relation to the wavelengths from 1591nm to 1511nm, as shown in the following equation:

$$\lambda = \frac{c}{f} \tag{5.3}$$

Where c is the light speed in vacuum 2.99792458 × 108 m/s ,λ stands for wavelength and f is optical frequency.

5.6.2 RoF Based GPON - CWDM System for Transmission of LTE/WiMAX/ Baseband over 600km

The transmission range obtains a limit, due to the signal dispersion. With shorter wavelength, the channel loss increases, so the transport distance and the light separation ratio are limited. In order to operate with a low energy budget used by the thermal management of the network, the CWDM is employed; the spacing is 20nm between the channels and so much greater than the DWDM spacing of typically 3.2 nm. The compensation of the chromatic dispersion in the system is needed to achieve an increase of the transmission distance to a fibre span of 600 km, covering a large area and distributing multiple clients. Additionally, the signal needs to be adjusted, and the power attenuations in SMF reduced. Thus, the combined compensators SMF, DCF and CFBG are applied to fulfil these requirements. As shown in Figure 5-2, the DCF is set up to -80ps/nm.km, due to SMF dispersion specific of 17ps/nm.km at 1552nm, which shortens the path of the transmitted signal. DCF has the potential to accumulate the signal dispersion of zero also to limit chromatic dispersion. As a result, DCF is capable to increase the extent of signal transmissions. The chirped fibre Bragg grating is used, because of the high- power attenuation of the DCF of 0.6dB/km. The CFBG behaves like a tuneable signal transmitter and reduces the power attenuations in the SMF and DCF; also, it works like an optical filter.

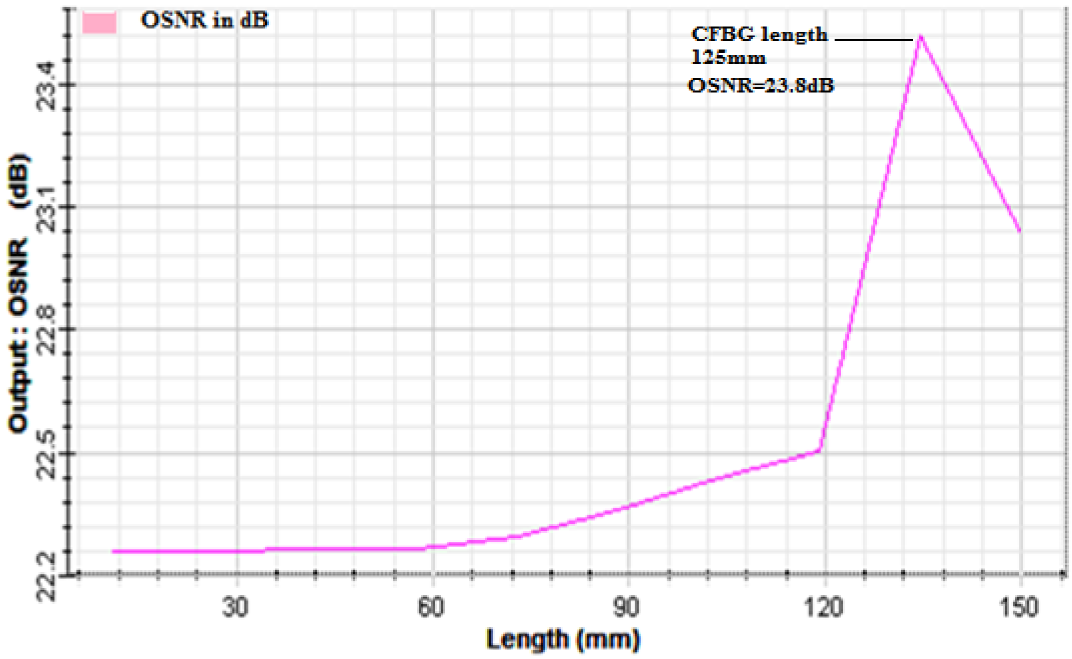

Figure 5-10: OSNR for CFBG chirp length in mm

Finally, the CFBG chirp is set up to 125mm to achieve a high OSNR. Figure 5-10 demonstrates the measuring of OSNR for signal transmission after 600km of a combined SMF, DCF, and CFBG. The 20-30mm CFBG chirp length provides the lowest OSNR at 22.2dB, and 125mm chirp length provides the highest OSNR at 23.8dB. High level of OSNR means low BER and satisfying transmission signals quality.

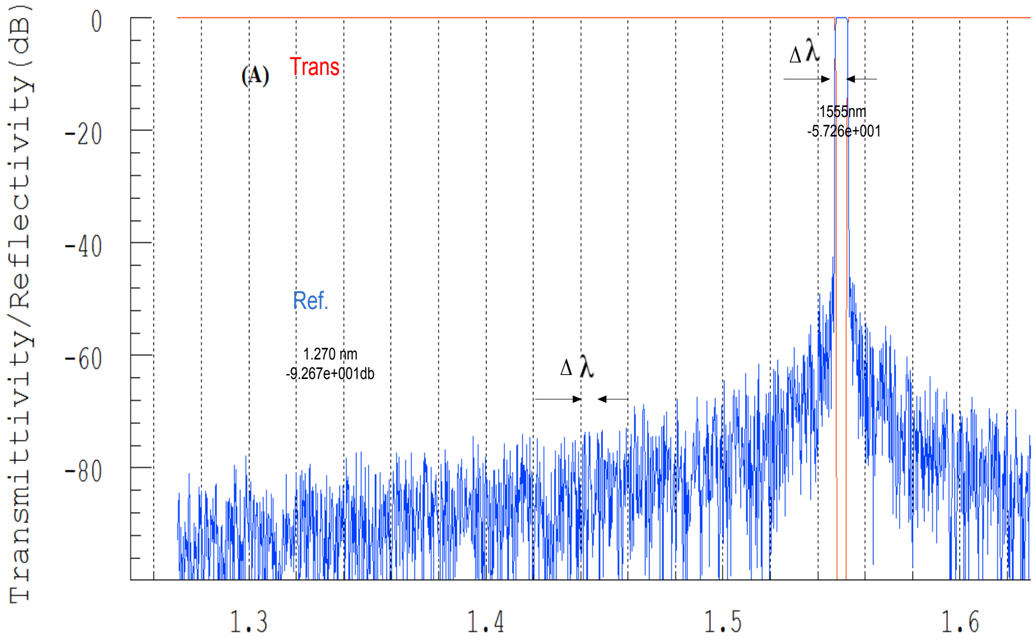

Figure 5-11: Transmittivity and reflectivity of wavelengths from 1.2µm – 1.6 µm

Figure 5-11 illustrates the transmittivitiy and reflectivity of the wavelength period in CFBG for the chirp length of 125mm. The CFBG is used as a filter for the optical power signal in the SMF and DCF for wavelengths from 1271-1611nm. The red area represents the signal transmission and the blue the reflected wavelength. The wavelengths 1271nm and 1550nm are the reflected wavelength at -92.67dB and -57.62dB. In Equation 5.3, the reflection, defined at a specific position, is the ratio of reflected power to input power.

$$R = \frac{P_f}{P_{in}} \qquad (5.3)$$

Where Pf is the reflected power and Pin is the input power.

The chirp period function is Λ= 0.533766 µm for chirped bandwidth Δλ=2 nm. The chirp period is specified as a variance of the grating period along the distance. The total chirp stands for the difference between the first and the last grating period. The Grating Period Chirp means the grating period modulation depending on the distance, as expressed in Equation 5-4.

$$\Lambda(z) = \Lambda_0 - \frac{z - \frac{L}{2}}{L}\,\Delta \qquad (5.4)$$

Where Λ(z) is the period chirp function; Λ_0 is the centre of chirp; L stands for the grating length, and Δ means the total chirp [104]. Accordingly, it is possible to reconstruct an unknown grating with the knowledge of the reflection coefficient only.

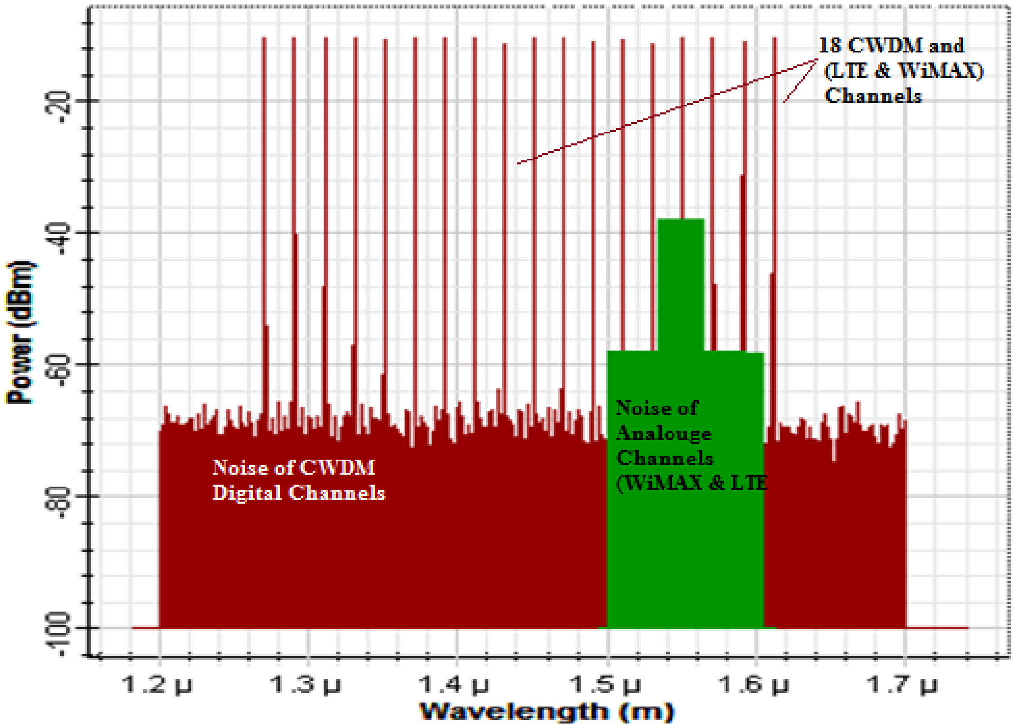

Figure 5-12: Optical spectrum 18 channels CWDM in GPON- and LTE-RF, and WiMAX-RF for the distance of 600km

Figure 5-12 displays the downlinks of optical modulation in the signals multiple transmission channels over a splitter based GPON fibre network, using CWDM technology to provide 18 channels transmitters. The channel spacing in CWDM is 20nm, which guarantees low-power consumption of the system and allows transmitting two wireless systems, LTE-RF at channel wavelength 1552.5nm and WiMAX-RF at channel wavelength1551.7 nm, over 600km. In the simulation, the GPON system obtains the capacity to deploy CWDM technology via RoF to provide up to 18 baseband wavelengths and 2 wireless systems, using the same fibre infrastructure

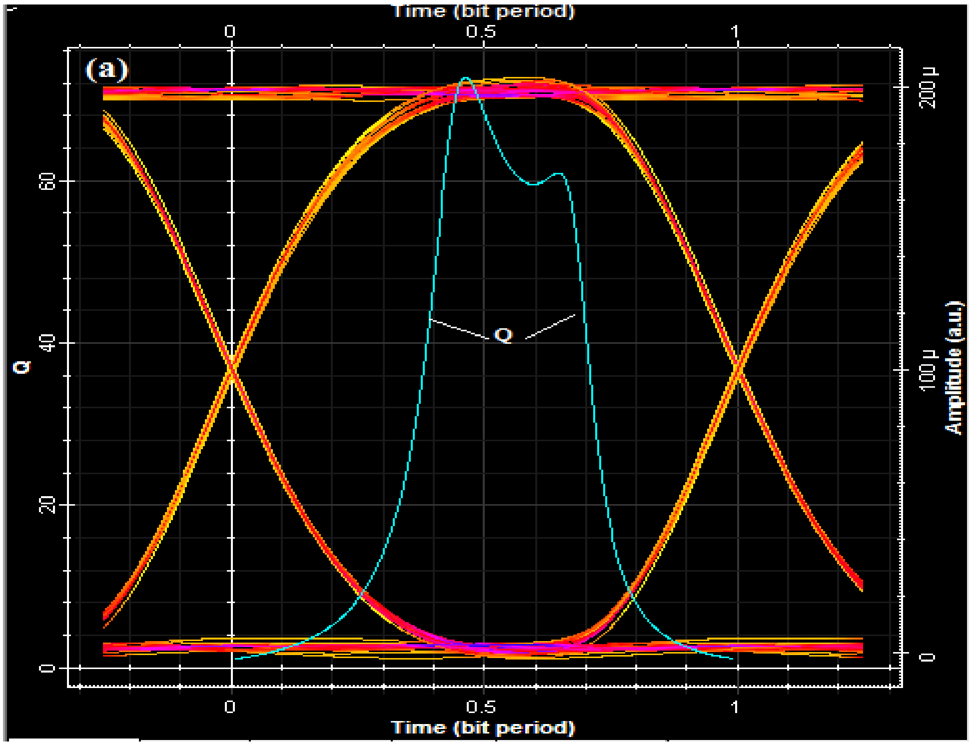

Figure 5- 13-a: Downstream eye diagram for Q-factor after 300km of combined SMF, DCF, CFBG fibre

Figure 5-13-a shows a clear open eye diagram of the downstream 2.5Gbps CWDM channels after 300km transmission via the triple compensation system (SMF-DCF and CFBG) to the bidirectional splitter and from there to the ONU. In the ONU, the PD converts the optical signal to an electrical signal, which then is transmitted to the users. This result indicates a satisfactory performance without distortion in the diagram; the Q-factor ranges at 72.

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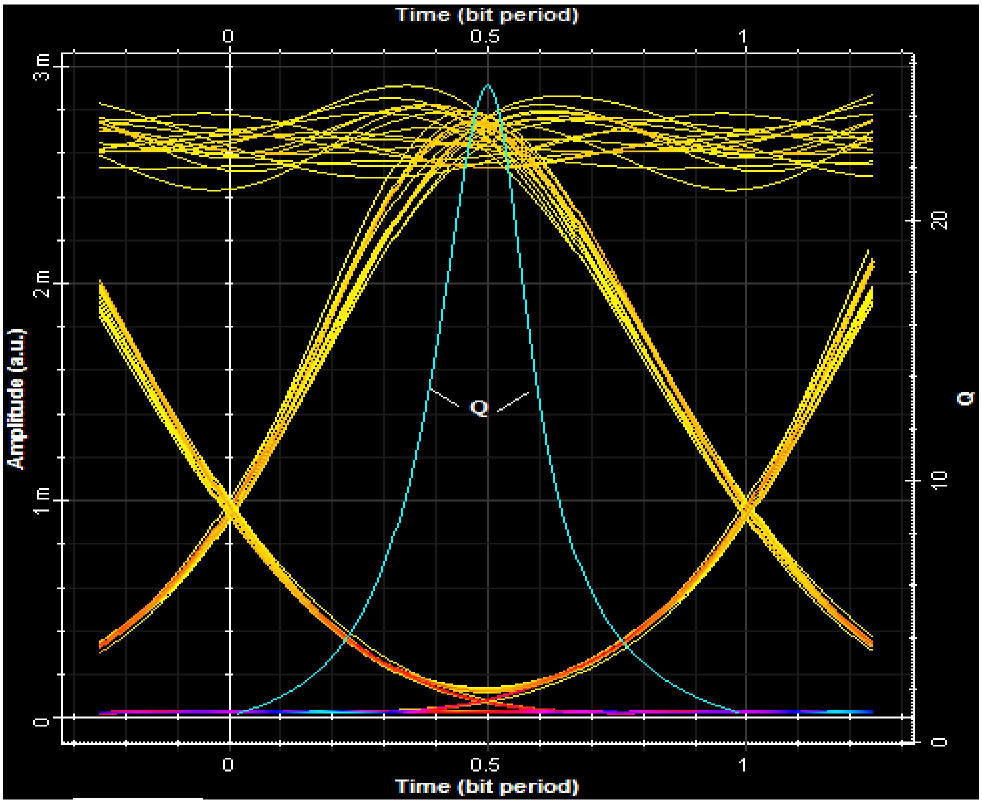

Figure 5- 13-b: Downstream eye diagram for Q-factor after 600km of combined SMF, DCF, CFBG fibre length

The performance of the 2.5Gbps CWDM module features a slight degradation after 600km, Figure 5-13-b shows a clear open eye diagram of the downstream 2.5Gbps CWDM channels after 600km transmission via the triple compensation system (SMF-DCF and CFBG) to the bidirectional splitter and from there to the ONU. In the ONU, the PD converts the optical signal to an electrical, which subsequently is transmitted to the users. This result indicates a satisfactory performance without overlaps in the diagram; the Q-factor measures 25.17.

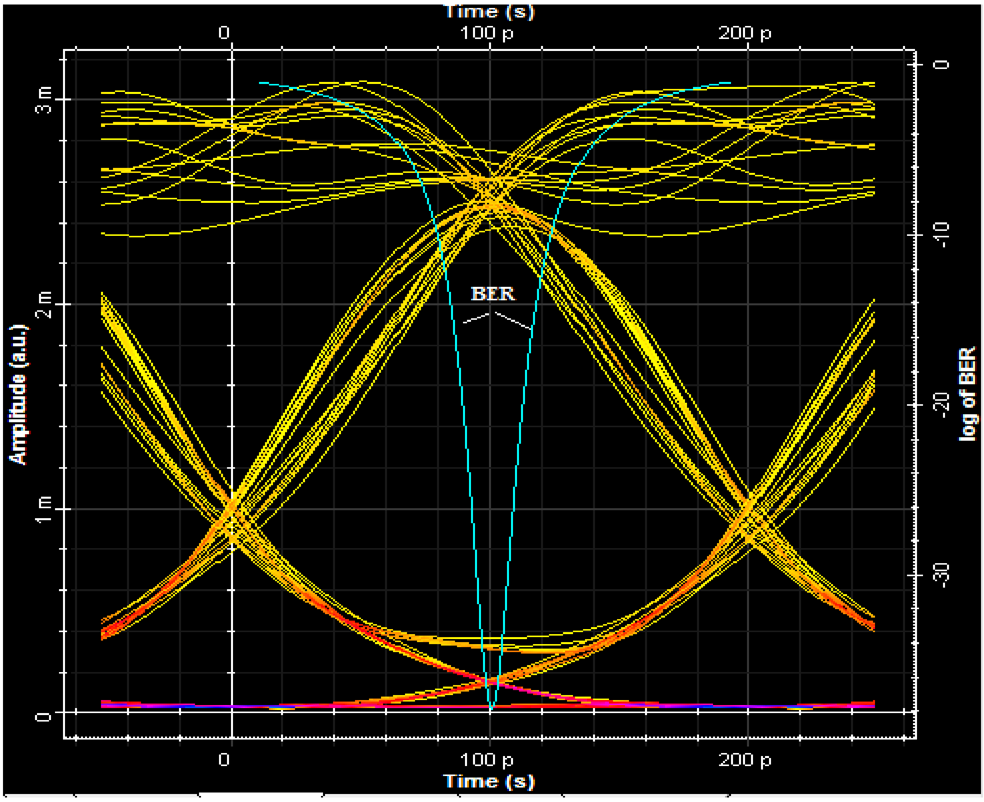

Figure 5-13-c: Downstream eye diagram for BER after 600km of combined SMF, DCF and CFBG fibre length.

Figure 5-13-c represents a clear open eye diagram of the downstream 2.5Gbps GPON-CWDM channels via the RoF system. The optical signal is transmitted via the triple compensation system (SMF-DCF and CFBG) to the bidirectional splitter for a length of 600km. From the splitter, the optical signal is transmitted to the ONU, where the PD is located, which converts the optical to an electrical signal. Subsequently, the electrical signal is transmitted to the users. The BER ranges at 10e-38 and the Q-factor is measured at a range of 12.93.

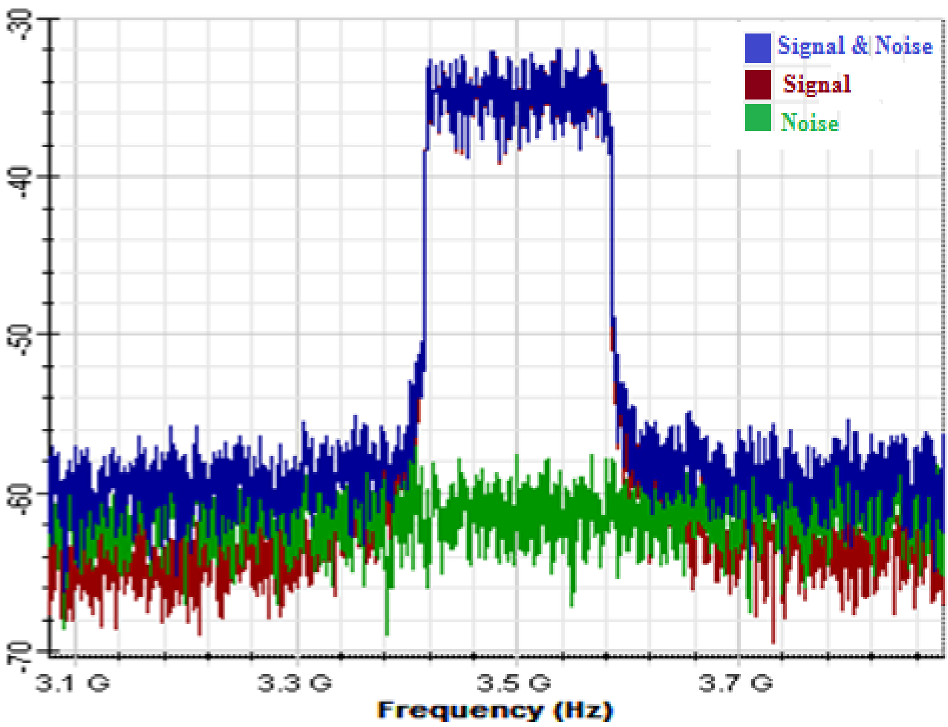

Figure 5-14-a: Downstream RF spectrum of LTE-RF after 600 km transmission

Figure 5-14-a presents the downstream RF spectrum of the 64-QAM LTE-Rx for 2.6GHz carrier frequency and a bandwidth of 20MHz after 600km fibre length. The blue spectrum area indicates the signal with noise; the green refers to the noise and the red to the signal without noise. The transmission span is consisting of the combined SMF, DCF and CFBG components. The signal is transmitted via the bidirectional SMF-DCF and CFBG length of 600km to the bidirectional splitter and then to the WDM-DEMUX. In the WDM-DEMUX, the optical signal is separated to the LTE-wavelength 1551.7nm and subsequently, the optical signal is converted to the electrical in the PD. The wavelength of 1551.7nm conveys the LTE-RF of 2.6GHz, the RF power measures a level of -35dBm.

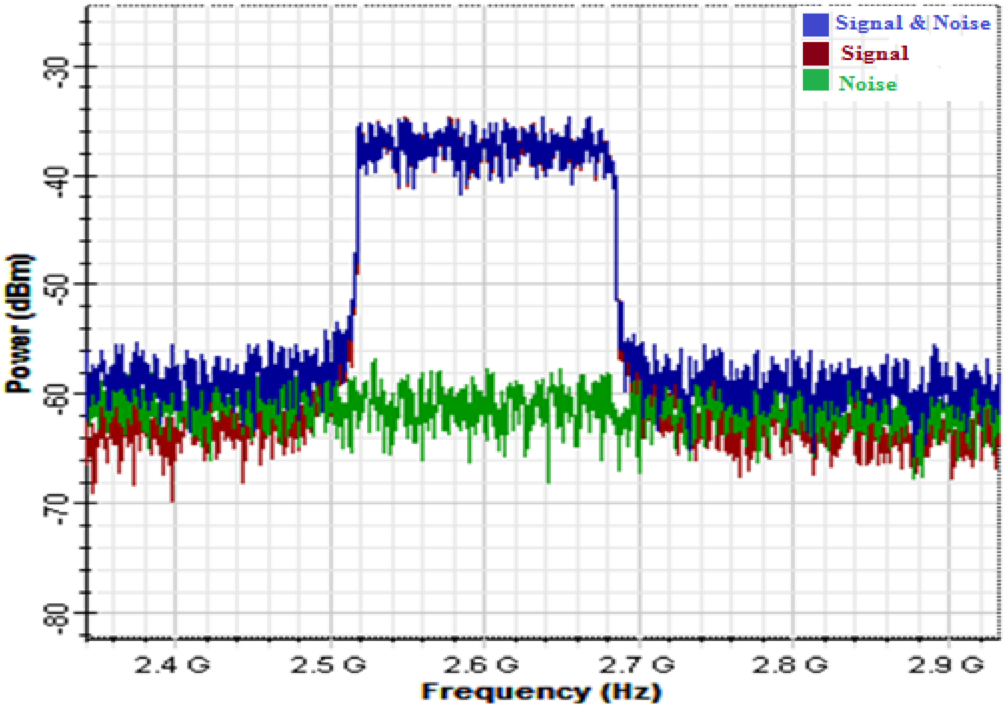

Figure 5-14-b: Downstream RF spectrum of WiMAX-RF after 600 km transmission

Figure 5-14-b displays the downstream RF spectrum for the 64-QAM WiMAX-Rx; for 3.5GHz carrier frequency and a bandwidth of 20MHz after 600km fibre length. The fibre length is consisting of combined SMF, DCF and CFBG. The signal is transmitted via bidirectional SMF-DCF and CFBG length of 600km to the bidirectional splitter and from the bidirectional splitter to the WDM-DEMUX. In the WDM-DEMUX separated the optical signal to the LTE-wavelength 1552.5 nm carries 3.5GHz centre frequency then the optical signal converted to the electrical in the PD. The blue colour indicates the signal with noise. The green spectrum area refers to the noise and the red to the signal without noise. The RF power level is at –33dBm after 600km.

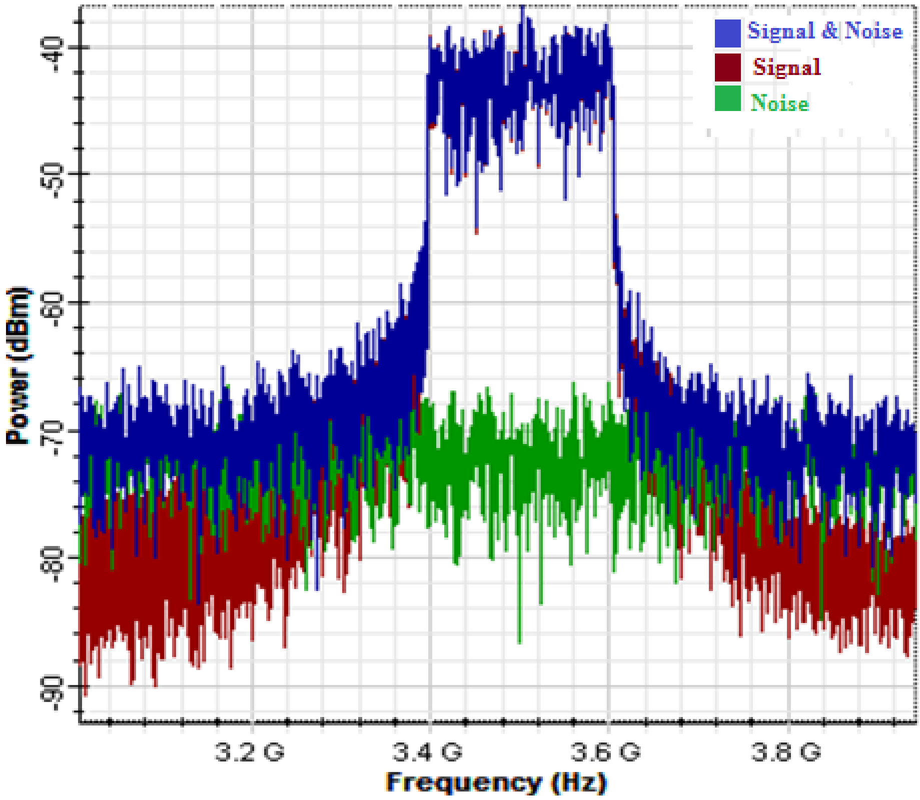

Figure 5-14-c: Upstream RF spectrum for WiMAX- RF

Figure 5-14-c illustrates the upstream RF spectrum of the WiMAX-Rx 3.5GHz carrier frequency and bandwidth 20MHz. The blue spectrum refers to the combined signal with noise, and the green only to noise. The signal is transmitted from the user via the bidirectional splitter and from there via bidirectional SMF-DCF and CFBG for the length of 600km to the WDM-DEMUX, where the optical signal is separated to the LTE-wavelength 1300nm. The PD converts the optical signal to the electrical, which subsequently is transmitted to the WiMAX base station. The upstream optical wavelength 1320nm carries the WiMAX signal. The RF power level is at –40dBm after 600km

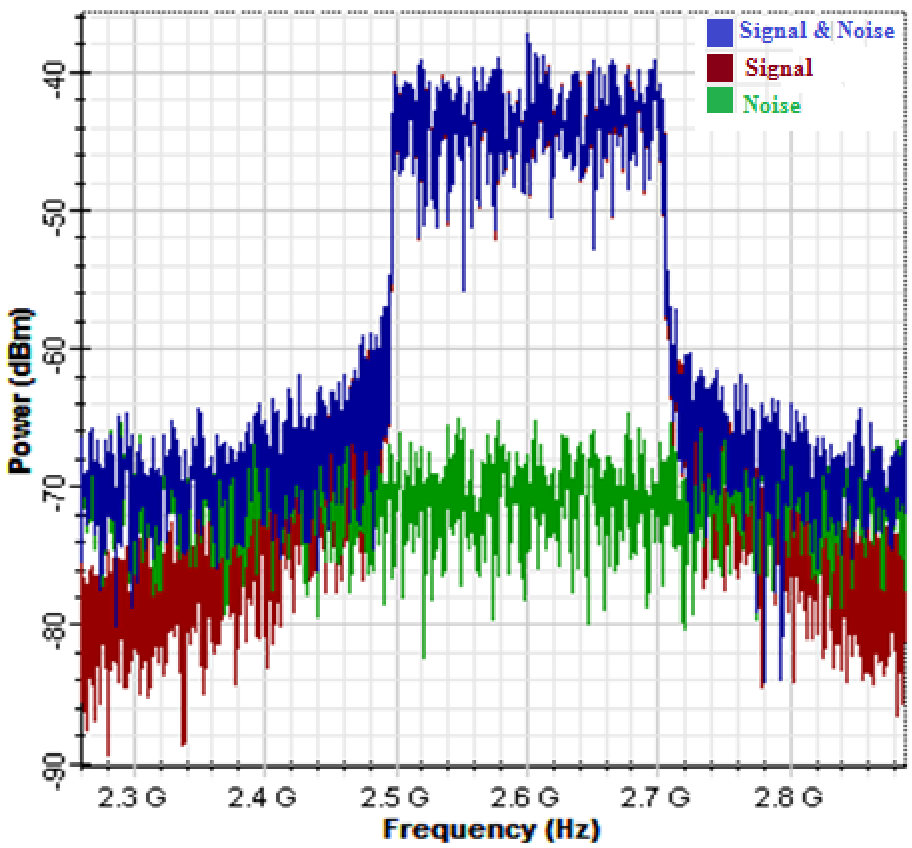

Figure 5-14-d: Upstream RF spectrum for LTE- RF

Figure 5-14-d shows the RF spectrum upstream LTE-Rx 2.6GHz carrier frequency and bandwidth 20MHz. The signal is transmitted from the user via the bidirectional splitter and from there via bidirectional SMF-DCF and CFBG for a length of 600km to the WDM-DEMUX. In the WDM-DEMUX, the optical signal is separated to the LTE-wavelength 1320nm. The PD converts the optical signal to the electrical, which then is transmitted to the LTE base station. The upstream optical wavelength 1300nm carries the LTE signal. The blue spectrum refers to the combined signal and noise, and the green only to noise at a power level of -40dBm after 600km. The power amplifier uses 151.2dB for the entire transmission length of 600km.

5.7 Chapter Summary

In this chapter, the simulation of a combined wireless system (WiMAX, LTE) RF spectrum, and baseband with a bit rate of 2.5Gbps downlink and 1.25Gbps uplink in GPON-CWDM via RoF system was described.

The signals travelled via bidirectional SMF length 160km to the bidirectional splitter-32 and from there being transmitted directly to the ONUs also to the WDM-DEMUX via bidirectional SMF for fibre length of 50km, which is in total a fibre length of 210km in this system. In the WDM-DEMUX, the optical signal is separated to the LTE and WiMAX wavelength.

The deployment of a different network topology utilising the DCF and CFBG in combination with SMF overcame the problem of chromatic dispersion and power attenuation in the SMF fibre. Thus, an extension of the transmission distance to 600 km was achieved. The results showed a satisfying OSNR, BER, wide-open eye diagram also clear RF spectrum.

The optical power amplifier for the extended length used 151.2dB, which is an exceptionally small amount compared to the signal transmission via air for an even much shorter distance. The path loss of WiMAX–RF 3.5GHz, between the 30m high base station antenna and the 2m high subscriber's station antenna, ranges at 165dB for the distance of 5km.

In the simulation, the described network topology has demonstrated its capacity deploying effectively wireless respectively, baseband signals with GPON/CWDM technology via RoF for a length of 600km with a low power budget.

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Chapter 6

Conclusion and Future Work

6.1 Conclusion

In this chapter, the research work is summarized and concluded with the achievement of the research objectives. Subsequently, future work is proposed and discussed.

The research work aimed to find solutions for the demand of continuously increasing quantity of data and the rising amount of energy needed to transfer this data by applying Radio over Fibre. The thesis provided three contributions, addressing simulations of green radio communication network systems, based on RoF for wireless access and baseband channels.

Firstly, the performance of WiMAX signals distributed via RoF for different fibre length, utilising symmetrical compensator techniques, which overcame the transmission limits caused by dispersion, was presented. Concerning the parameter of power consumption for the transmission of WiMAX via air, where the BS used 43dB/km, the transmission via RoF from 20km to 180km used only 65dB and employing the compensator components SMF-DCF-FBG increased the signal transmission distance from 180 to 410 without increasing the power. Applying an amended triple symmetrical compensators technique, SMF-DCF-CFBG, for fibre length 792km used 192dB; the results for OSNR were 26.63dB, SNR 31.32dB and the data bit rate was increased to 120 Mbps.

Secondly, the delivery of LTE and WiMAX signals via WDM-RoF employing the triple compensators technique over a fibre length of 1800km, data bit rate 1Gbps , consuming 393.6dB, was demonstrated. Finally, the performance of the simultaneous transmission 2.5 Gbps downlink and 1.25 Gbps uplink of analogue (WiMAX and LTE) and digital 18-CWDM signals via GPON based RoF was investigated. The setup utilized bidirectional SMF to 210km and splitter 1-32. The triple compensators component was applied to increase the fibre span to 600km for a power budget of 151.2dB.

Sending data via a RoF system was proven from comprehensive simulations to achieve high quality signal transmission spectrums, increased transmission distances and low power consumption. The findings of this research work can contribute to the provision of wireless Internet globally with significantly reduced energy consumption per bit and a reduction in network operating costs to operate profitably.

6.1.1 Performance of WiMAX Signals Distributed via RoF Applying Symmetrical Compensators

In the first simulation design, a 54Mbps WiMAX IEEE 802.16-2005 signal was transmitted via air to calculate the power attenuation and transmission distance. The transmission range was set from 100m to 5km , which resulted in a power attenuation of -28dB for 900m, -50dB for 2000m and -189.67dB for 5km. This was a very short transmission distance and huge power consumption; therefore, the signal delivery via RoF was investigated.

Accordingly, a 3.5GHz and 64QAM WiMAX system for OFDM 1024 and subcarrier 128 to deliver 54Mbps per channel signal transmission was simulated; firstly, via RoF-SMF only for a distance from 20km to 140km for an optical power amplifier configured to 35dB. The signal at the receiver became corrupted at 140km fibre length; thus, the power amplifier was increased to 65dB, but at 180km, the signal became corrupted again. However the optical power amplifier was increased, the signal quality did not improve, due to chromatic dispersion; the positive dispersion in SMF increased with every kilometre and led to the boarding and scattering of the signal.

In order to control the dispersion in SMF keeping the fibre signal at zero dispersion, the DCF has been used, which resulted in the signal span being increased to 288km with the power amplifier constantly at 65dB. A further increase of the transmission span was not possible, due to the DCF attenuation of 0.6dB/km in the fibre. Hence, the FBG was employed, which works like a tuneable signal and controls the power attenuation compensating chromatic dispersion.

The application of the symmetrical compensators consisting of DCF-SMF-SMF-DCF-SMF and FBG enabled an increase of the transmission distance to 410km. All three configurations used the same amount of power, 65dB, whereas the fibre span could be increased by more than 100 per cent through the employment of the DCF and FBG.

Finally, a further extension of the transmission distance to 792km was achieved with a different setup, the deployment of a 120Mbps mobile WiMAX signal for 64-QAM via RoF applying the triple compensators architecture, each one consisting of a 264km long DCF-SMF-DCF-SMF-SMF-CFBG. With this setup, the power consumption ranged at 192dB and OSNR at 26.63dBm; thus, the aim to achieve a high signal transmission quality over a long fibre span at a low-power budget has been achieved. The RF spectrum displayed clear bandwidths for WiMAX and the constellation diagram clearly showed 6bit (64QAM).

6.1.2 Performance of LTE and WiMAX Signal transmission via WDM-RoF for a length of 1800km

The second contribution investigated simulation designs deploying two mobile wireless systems, WiMAX OFDMA and LTE OFDMA signals of 128 subcarriers with an FFT of 1024 for a 3.5GHz and 2.6GHz carrier frequency via WDM-RoF for a fibre length of 1800km. The WDM has extended the RoF capacity, because it offers more than one light beam (wavelength) in the same fibre cable. Each wavelength carries a wireless channel, thus the data bit rate can be extended.

The triple compensation scheme, consisting of SMF, DCF and CFBG, was applied. The CFBG was utilised instead of FBG, because of its high efficiency to control signal attenuation, chromatic dispersion and light scattering over a long distance. The comparison of the CFBG's chirp lengths from 10mm to 200 mm proved the best OSNR result with a 138mm chirp. Combining the SMF with a DCF dispersion configuration of -80ps ps/nm.km and additionally with a CFBG chirp of 138mm, can control the chromatic dispersion affecting the fibre. The bandwidth parameter was set to 20MHz; WiMAX and LTE was transmitted with the bit rate of 1Gbps with 64-QAM. The power consumption between the input and output of the fibre ranged at 393.6dB; therefore, the power budget for the WiMAX and LTE downlink was much lower than for the WiMAX transmission for 5 km, where the BS antenna consumed 43dB/km.

The results for input SNR ranged at 108.8 dB and output SNR at receiver at 24.1dB ; the RF spectrum displayed clear bandwidths and for both, WiMAX and LTE, the constellation diagram clearly represents 6bit (64QAM).

6.1.3 Performance of WiMAX, LTE and CWDM Channels via GPON-RoF

The third contribution studied a comprehensive simulation design to enhance the data bit rate and enlarge the coverage area using a low energy budget. The setup deployed digital and analogue signals utilizing Wavelength-Division-Multiplexing (WDM) for Gigabit Passive Optical Networks (GPON) for downlink 2.5Gbps and uplink 1.25Gbps. Eighteen digital CWDM channels and two analogue signals (2.6GHz LTE and 3.5GHz WIMAX) were transmitted as digital signals via the GPON system; firstly, muxed in WDM and subsequently, transmitted via RoF utilising bidirectional fibre optic cables to the bidirectional splitter. The bidirectional splitter is a passive component, which works mechanically, supporting 32 ONU and each ONU supports 24 users. The CWDM was utilised, due to the wide channel spacing of 40nm, which contributes to energy savings of up to 60 per cent of the optical network energy budget compared to DWDM.

Firstly, the signal was delivered over 160km SMF to the splitter-32 and the ONU-24 and from the splitter over 50km bidirectional SMF to and from the LTE and WiMAX receiver.
The transmission range was extended to 600 km through the deployment of the SMF-DCF and CFBG, in combination with the SMF, compensating for the chromatic dispersion and power attenuation in the SMF.

According to the simulation results, the optical power amplifier used 151.2dB for the link of 600km, which is compared to the path loss of 3.5GHz WiMAX-RF of 165dB a relatively small amount. The eye diagram showed open for a distance of 300km and 600km; the RF spectrum displayed clear bandwidths for both WiMAX and LTE, also the constellation diagram clearly represented 6bit (64QAM).

6.2 Future Work

The simulations described in this thesis, regarding the deployment of the RoF system with changing applications, transmission lengths and data bit rates have shown promising results. All five simulation setups demonstrated the successful propagation of WiMAX respectively LTE signals via RoF over an increasingly long fibre span and with low-energy consumption. However, the next step to confirm and support these achievements would be an experimental setup with measurements on a fibre system.

6.2.1 WiMAX- Femtocell via RoF

In future research projects, it would be interesting to implement a WiMAX -Femtocell instead of a BS via radio over fibre because it has several advantages for the user and the provider, as well. As a 4G technology, the femtocell can be used in microcell and pico-cell areas also indoors; the normal cell radius ranges between 50-100m [51]. Within the building, the femtocell offers a better coverage and additional services for the user. For the network operator, the femtocell provides a cost-effective means to enhance the coverage and service.

6.2.2 Sleep Mode in the RoF System

In the area of green radio communications, the future research work could focus on the design of a sleep mode system, addressing the necessity of extra power savings of high bit rate and long transmission range fibre networks. Normally, the fully on power in a RoF system means that the CW laser diode needs 6dBm, and the EDFA 10dBm 24 hours a day, 365 days a year independent from the user's enquiry. A sleep mode operation would allow significant savings in means of energy consumption, due to a switch- off- power mode for the device when there is no data enquiry to be transmitted.

In regard of the necessary hardware being used for this operation, the FPGA Altera Stratix 1.2VDC would be a suitable candidate. For this device, a long-life rechargeable battery would provide the FPGA with the energy needed when the optical system is in sleep mode, and recharge when the system is working.

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