Analysis of Mobile Backhaul for 5G using Optical Distribution Network of PON

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Certificate

This is to certify that the thesis titled **"Analysis of Mobile Backhaul for 5G using Optical Distribution Network of PON"** submitted by **Aanchal Khandelwal** for the partial fulfillment of the requirements for the degree of *Master of Technology* in *Electronics & Communication Engineering* is a record of the bonafide work carried out by her under my guidance and supervision at Indraprastha Institute of Information Technology, Delhi. This work has not been submitted anywhere else for the reward of any other degree.

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Abstract

This thesis work provides theoretical analysis of an optical distribution network (ODN) that integrates mobile backhaul network with already existing passive optical network (PON). The need to reduce the cost of laying down new fibers for mobile backhaul networks drives the need for such an integrated architecture that allows sharing of ODN. A wavelength division multiplexing (WDM) combiner is used to stream data from the two arms of the architecture. The PON ODN is considered to have 10 Gbps data rate downstream and 2.5 Gbps rate upstream and a bit error rate (BER) less than 10^{-9}. An analog RF signal at 20 GHz is multiplexed with digital data from this passive optical network. The power budget analysis is done for both arms of the architecture to determine the maximum reach possible. Rise time analysis in PON arm makes sure that the rise time stays within limits for downstream and upstream. Delay analysis for mobile backhaul is done to make sure that the end to end delay in mobile backhaul meets 5G specifications.

In the power budget analysis, it was found that the maximum reach possible for PON arm is 20 km and that for mobile backhaul arm is 30 km. Delay analysis of analog RoF mobile backhaul arm showed that the total end to end delay is 0.26 ms (< 1 ms) and is well within 5G specification. The rise time budget analysis showed that fiber lengths of PON up to 35 km can be met for PON arm. Considering all the analysis, it is concluded that the maximum possible reach of the system under consideration is 20 km.

Keywords: Passive Optical Network (PON), Analog Radio Over Fiber (Analog RoF), Wavelength Division Multiplexing (WDM), Power Budget, Rise Time Budget, Carrier to Noise Ratio (CNR)

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Chapter 1

Introduction

1.1 Motivation

Evolution of 3G and 4G networks over the last decade have led to a significant increase in transmission rate supporting more applications. At the end of the year 2015, global mobile data traffic was 4.4 exabytes per month which rose to 7.2 exabytes per month by the end of 2016 showing a compound annual growth rate (CAGR) of 47% (Fig 1). Of all the mobile traffic in 2016, 4G accounted for 69% of the traffic [1]. This figure is expected to increase to 49 exabytes per month by the year 2021 of which 4G traffic will be more than 75% [1]. Along with traffic, there will be an increase in mobile network connection speed too. The connection speed is expected to increase threefold from 6.8 Mbps (in 2016) to 20.4 Mbps by 2021. Along with 4G, 5G connections will also increase and it is expected to generate 4.7 times more traffic than an average 4G connection [1].

The upcoming generation of 5G demands higher capacity, higher data rate (in multiple Gbps) and lesser delay to meet the quality of service requirements. A 5G connection should meet the following requirements in terms of data rate [2],

- 10 Gbps in indoor and dense outdoor environment
- 100Mbps data rate in urban and suburban environments
- At least 10Mbps data rate in rural areas

5G networks will find applications in vehicular connectivity, traffic safety, infrastructure for smart cities, industrial automation and several IoT (Internet of things) applications. For such applications, it is necessary to have high reliability and end to end latency below 1 ms [2].

From above discussion, it is obvious that the transition from 4G to 5G mobile data services will require a huge increase in transmission rate with low latency. The optical fibers are known to have a huge potential bandwidth of 50THz, immunity to interference and cross talk, low transmission loss (less than 1dB/km) and low cost [3]. These characteristics of optical fibers

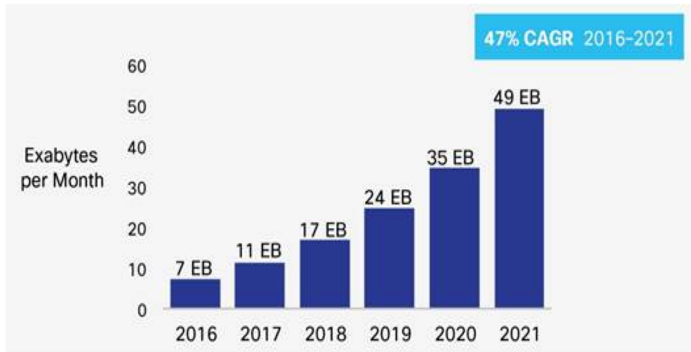

Figure 1.1: Mobile data traffic trend [1]

make them beneficial for connection between central office (CO) and mobile sites.

The need for a system that meets the requirements of high speed, low latency and high bandwidth drives the motivation to use the potential of optical networks. Integration of mobile backhaul with already existing optical distribution networks not only saves the effort of laying down new optical fibers but also saves a lot of money.

Passive optical networks (PON) where transmission takes place between optical line terminal (OLT) and optical network units (ONUs) have been widely used for optical communication. They provide a multi-point to point network in upstream direction and P2MP (point to multi-point) in downstream direction and have been explained in detail in section 1.2.

1.2 Passive Optical Network (PON)

Passive optical network (PON) is a point to multi-point architecture to extend optical fibers to provide FTTx (fiber to the x). The term 'passive' is used because this network involves the use of a passive (unpowered) optical branching devices like passive optical splitters, circulators, isolators and Wavelength-Division Multiplexers/Demultiplexers (WDMs). Such a network therefore requires powered equipments only at source and receiving ends. A typical PON consists of an optical line terminal (OLT), several optical network units (ONUs) or optical network terminals (ONTs), fiber optical splitter and an optical fiber. OLT is the central office and ONUs are the end consumers. Such a network has several advantages [4].

- Long reach
- Use of passive components (like splitters, circulators, multiplexers, AWG etc.) instead of active components and thus these components do not require power
- High bandwidth and data rates

Variants of PON include TDM-PON (Time Division Multiplexing PON), WDM-PON (Wavelength Division Multiplexing PON) and TWDM-PON (Time and Wavelength Division Multiplexing PON). In this thesis work, WDM-PON has been used to multiplex digital and analog data from the two arms for both upstream and downstream on a single mode fiber.

Figure 1.2 shows a typical architecture of WDM PON where downstream data from OLT is multiplexed and transmitted to ONU. An arrayed waveguide grating (AWG) is used as an optical demultiplexer in downstream direction and as a multiplexer of different wavelength streams from different ONUs in upstream direction. A circulator is used to facilitate upstream and downstream transmissions.

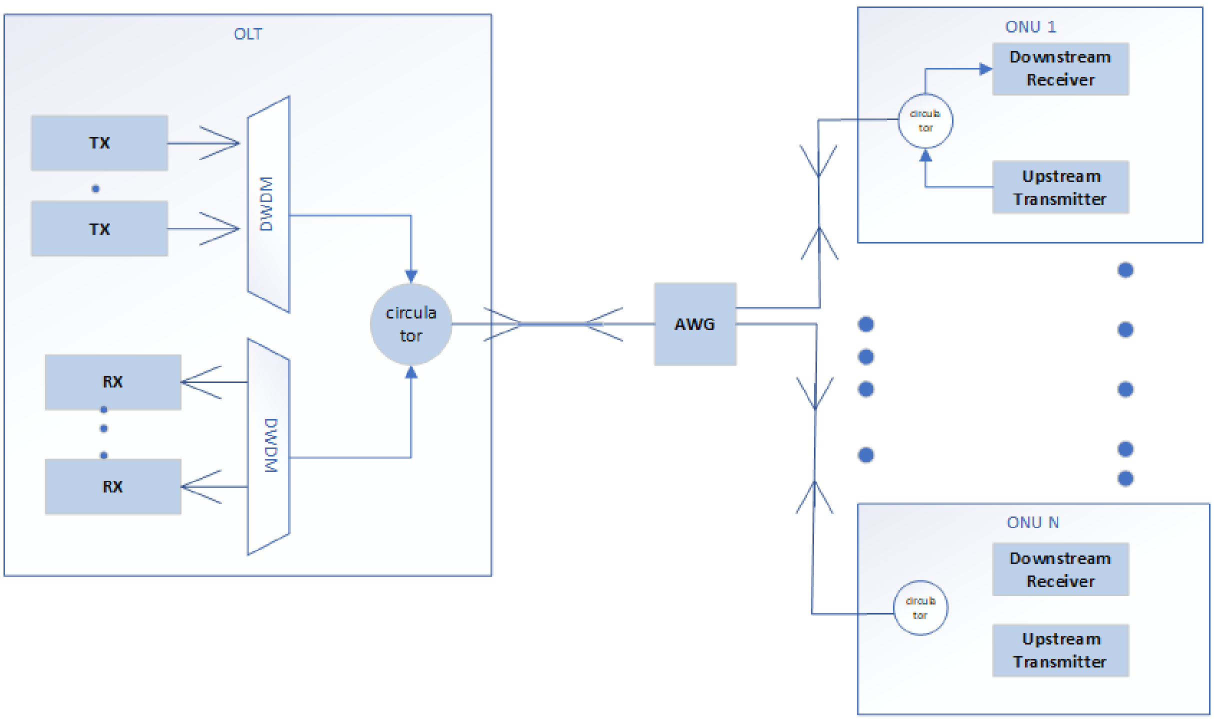

Figure 1.2: WDM PON

1.3 Analog Radio over Fiber

Radio over fiber helps in seamless integration of optical and wireless communication systems. The concept of analog RoF (AROF) involves an RF signal being transmitted from the centralized control station (CCS) to remote antenna unit (RAU) over the optical fiber using an optical carrier. At the transmitter, the RF signal modulates an optical carrier and at the receiver, the RF signal is recovered using an OE downstream converter. Figure 1.3 shows the configuration of analog RoF.

1.4 Wavelength Division Multiplexing (WDM)

WDM is a multiplexing technology in which multiple optical carriers of different wavelengths can be multiplexed in a single optical fiber. WDM facilitates bidirectional communication over a

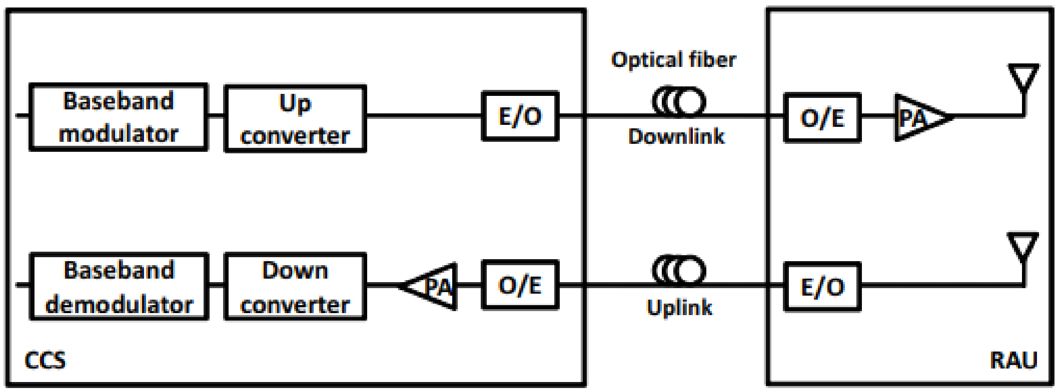

Figure 1.3: Analog RoF

single optical fiber (upstream as well as downstream). There are three types of WDM techniques, Normal WDM, Coarse WDM (CWDM) and Dense WDM (DWDM). Normal WDM involves two wavelengths (1330 nm and 1550 nm) on one fiber. WDM with less than eight active wavelengths is CWDM. It is used for short range communications. DWDM is for systems more than eight active wavelengths per fiber and is used for long-haul transmissions.

1.5 Power Budget analysis

This involves allocating available optical power to various impairments and losses that might result in optical loss while the signal is being transmitted from source to destination and is done to ensure that minimum required signal strength is received by the user.

1.6 Rise Time Budget analysis

Similar to power budget analysis, rise time budget analysis is done to determine the dispersion limitation of an optical fiber link. Detailed analysis has been given in chapter 5.

In [6], an architecture has been proposed that involves integration of mobile backhaul networks with already exisiting PON systems. Such an architecture will reduce the cost of laying down new fibers as the optical distribution network (ODN) is being shared between PON and mobile backhaul using a WDM set up.This provides an economical solution for mobile backhaul networks as the already deployed PON can be used. The challenge here is that the already existing PON systems use many wavelengths leaving limited wavelengths for mobile backhaul. This raises the need for using spectrally efficient techniques for modulation like orthogonal frequency multiplexing division (OFDM). Figure 1.4 shows a block diagram of the architecture.

In this thesis work, mathematical analysis has been done for such an architecture. Power budget analysis has been done for PON in chapter3 to determine the maximum possible length of fiber in a passive optical network following XG-PON2 standards. Carrier to noise ratio (CNR) for varying fiber lengths in mobile backhaul has been analysed and calculated in chapter 4 to estimate the maximum reach of the system. In chapter 5, rise time analysis of the PON arm has been done to make sure that the system meets the rise time budget for both downstream as well as upstream. Also, end to end delay analysis has also been done in chapter 6 to make sure that the integrated architecture meets the latency limitation of 5G. This is followed by final conclusion of the study in chapter 7.

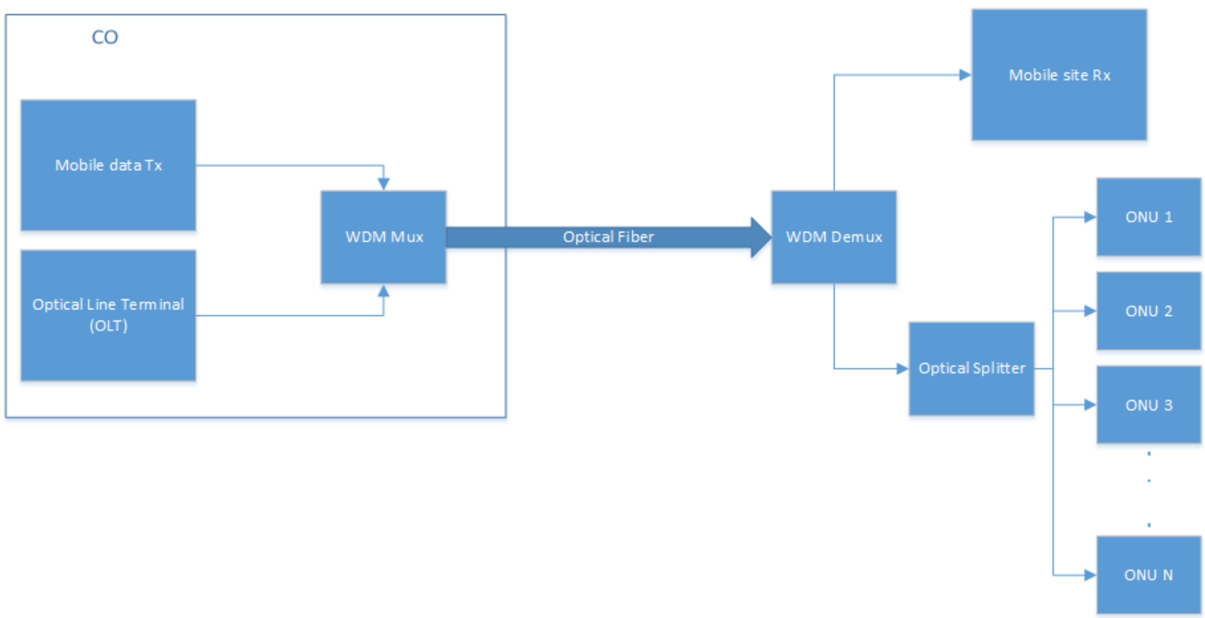

Figure 1.4: ODN sharing architecture

Chapter 2

Architecture

A detailed structure of the mobile backhaul network integrated with PON in ODN sharing scheme is shown in Figure 1.4. Both the mobile backhaul and PON share the same central office (CO) and the data streams from both these arms are combined using wavelength division multiplexer and transmitted through optical fiber. At the end of optical fiber, an arrayed waveguide grating (AWG) can be used as a wavelength demultiplexer to demultiplex the two data streams.

The digital data from PON arm is passed through a passive optical splitter with a split ratio N varying from 16 to 1024 and received by ONUs (optical network units) connected at the receiver side as shown in the figure. The data rate for dowsntream and upstream data in PON is considered to be 10 Gbps and 2.5 Gbps respectively according to XGPON nominal class 2 standard (Fig. 3.1). From figure 3.1, the minimum transmitted power for DS is 4 dBm and US is 2 dBm. The minimum power that should be received at the photodetector is -28 dBm and -29.5 dBm respectively. A photodetector at the ONU converts optical to electrical signal. The mobile data is an analog RF signal transmitted at 20 GHz, modulated by optical carrier from laser diode and transmitted over single mode fiber. It is then received by a photodetector that converts the signal back to electrical. OFDM has been used to make it spectrally efficient. The specifications for NR (new radio or 5G) OFDM have been given in table 3.1.

Class	Direction	ONU	ODN	OLT
Nominal 2	2.5G US	Min Tx power = 2 dBm	Max loss: 31 dB	Min Rx power : − 29.5 dBm
	10G DS op. 1	Min Rx power: -28 dBm (APD Receivers)	Max loss: 31 dB	Min Tx power: 4 dBm
	10G DS op. 2	Min Rx power: -21.5 dBm (Pin-PD Receivers)	Max loss: 31 dB	Min Tx power: 10.5 dBm

Figure 2.1: XGPON nominal 2 class G.987.2 standard

For theoretical analysis, erbium doped fiber amplifier (EDFA) is used at the receiver side to boost the optical signal intensity. An avalanche photodiode (APD) is considered in the analysis of the architecture as it is known to result in higher SNR (signal to noise ratio) because of its multiplication gain [7]. Laser diode is considered for optical source and is assumed to work in dynamic range.

Chapter 3

Power Budget Analysis

As discussed in previous section, the minimum transmitted and received power values for US and DS have been shown in figure 2.1. Following equation 3.1, the power budget available for DS and US is 32 dB and 31.5 dB respectively.

$$Power\_budget = P_{Tx} - P_{Rx} \tag{3.1}$$

Taking into account various noise impairments that may result in power loss in transmission, an analysis has been done to estimate the maximum reach possible. The following subsections talk about impairments due to inter-channel crosstalk, chromatic dispersion, polarization mode dispersion, rayleigh backscattering and jitter. The numerologies for every parameter considered for analysis is given in table 3.1.

3.1 Inter-channel crosstalk

Imperfect demultiplexing by AWG may result in inter-channel cross talk for a multichannel transmission. The inter channel crosstalk power penalty is given by equation 3.2 [8],

$$P_c = -5\log(1 - \frac{10^{\frac{-C_c}{10}}}{N-1} Q^2 (\frac{ER+1}{ER-1})^2), \tag{3.2}$$

where $Q = \sqrt{2} erfc^{-1}(2 \cdot BER)$, BER is the bit error ratio, ER is the linear extinction ratio and C_c is the inter channel cross talk given by equation 3.3 [8],

$$C_c = \Delta P_{ONT} + d_{MAX} + \log(2 \times 10^{\frac{-I_A}{10}} + (N-3) \times 10^{\frac{-I_{NA}}{10}}), \tag{3.3}$$

where ΔP_{ONT} is the maximum signal power difference, d_{MAX} is the largest differential path loss, I_A (dB) is the adjacent channel isolation value, I_{NA} (dB) is the non- adjacent channel isolation value of AWG and N is the the number of channels in WDM-PON. Table 3.1 lists the value of all the values assumed for analysis.

3.2 Rayleigh Backscattering (RB)

Refractive index variations within the glass fiber with distance causing Rayleigh Scattering [12]. The scattering loss (in Napers) at wavelength λ is given by equation 3.4 [12],

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T \tag{3.4}$$

where, n is the refractive index, k_B is the Boltzmann's constant, T_f is the fictive temperature, p is the photoelastic coefficient and β_T is the isothermal compressibility.

3.3 Chromatic dispersion (CD)

Each wavelength travels at a different speed inside SMF causing dispersion. The power penalty induced in transmission fiber due to chromatic dispersion is given by equation 3.5 [10],

$$P_{dispersion} = -10\log(1 - 5.195 B^2 L^2 [0.18 B_o^2 D^2]) \tag{3.5}$$

where, B_o is the optical bandwidth, L is the transmission distance, B is the data rate and D is the dispersion value.Table 3.1 lists the values considered for calculation of power penalty due to CD.

3.4 Polarization Mode Dispersion (PMD)

For first order PMD, the power penalty is directly proportional to differential group delay (DGD) and is given by the following equation 3.6 [11],

$$Penalty_{PMD}[dB] = 26\gamma(1-\gamma)\frac{\delta\tau^2}{T^2} \tag{3.6}$$

where $\delta\tau$ is the DGD, 0< γ <1 is the relative power launched in two pricipal states and is assumed to have a uniform distribution with its mean value $(\gamma(1-\gamma)) = \frac{1}{6}$ and T is the pulse width (T= frac1B). From [11], the expression of power penalty evaluates to 0.062 dB.

3.5 Jitter

In high speed optical fiber transmission systems, time jitter is a major issue caused when transition from one symbol to other occurs earlier or is delayed because of pulses being spaced closed together [12]. According to ITU-T G.987.2 [20], jitter tolerance is defined as the peak to peak amplitude of jitter at input XG-PON that causes 1 dB power penalty. Assuming jitter being equal to jitter tolerance, we can say that power penalty due to jitter will not be more than 1 dB.

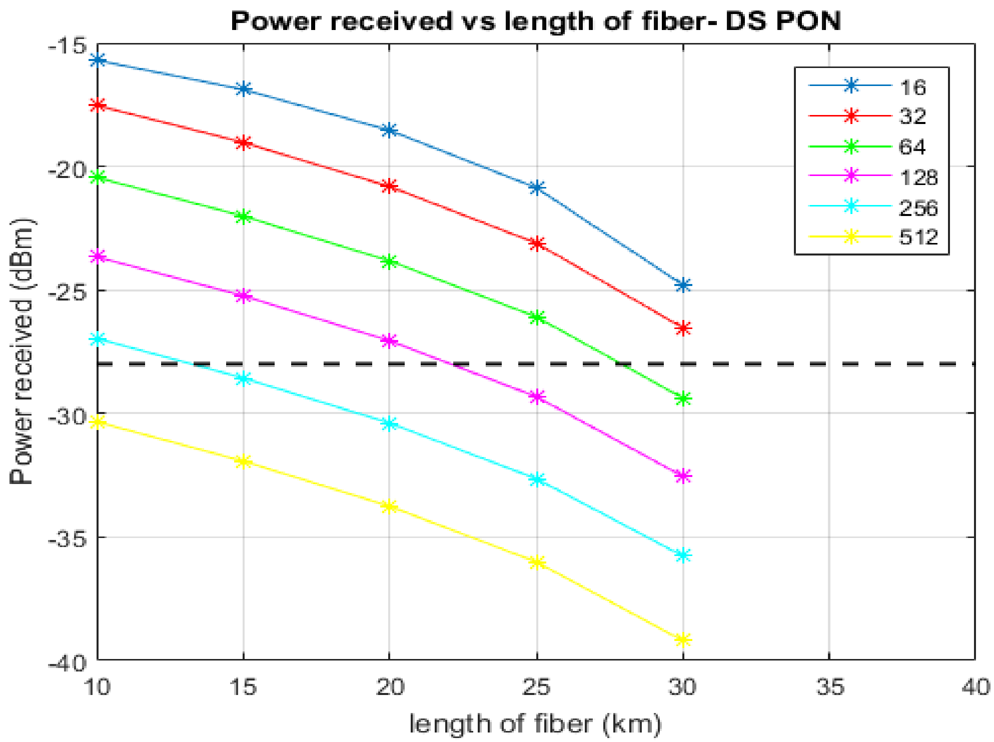

Figure 3.1: PON DS- Received power

From equations 3.2, 3.4, 3.5 and 3.6, power penalty for each impairment can be calculated. Power loss due to each impairment can then be evaluated according to the expression $P_{impair} = 10^{-\frac{penalty}{10}} \dot{P}_{transmitted}$ [12]. Considering insertion loss due to power splitter given by equation 3.7 and fiber loss given by equation 3.8, power received for DS and US for varying lengths and split ratios is plotted in figure 3.1 and 3.2 respectively.

$$Loss_{insertion} = 0.8 + 3.4 \log_2 N, \tag{3.7}$$

$$Loss_{fiber} = \alpha l \tag{3.8}$$

where α is the attentuation constant (0.2 dB/km) and l is the fiber length

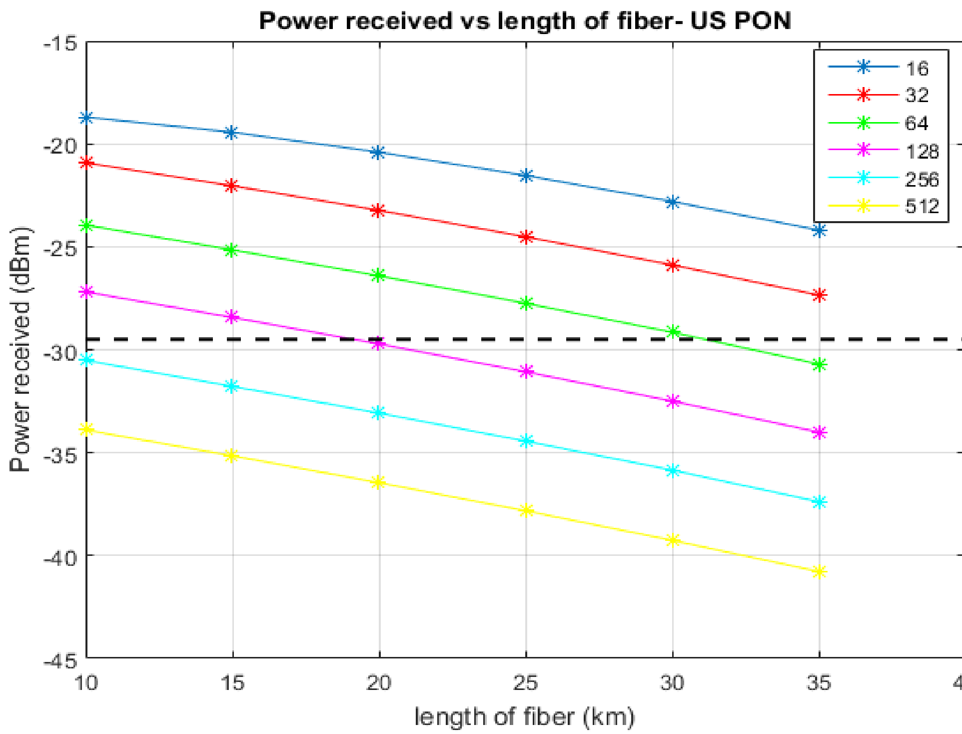

Figure 3.2: PON US- Received power

Table 3.1: Specification and parameter values used in analysis

ΔP_{ONT}	5 dB
ER	6.6
I_A	23 dB
I_{NA}	30 dB
N	varies from 16 to 1024
d_{MAX}	$length\ of\ fiber \times fiber\ loss$
fiber loss	0.275 dB/km
Q	4.24 (for $BER = 10^{-9}$
T_f	1400 K
β_T	$6.8 \times 10^{-11} m^2/N$
p	0.286
n	1.45
λ	1550 nm
α_{scat}	0.148 dB/km
B	10 Gbps DS, 2.5 Gbps US
B_o	0.8 nm
D	-17 ps/nm-km
Frequency of transmission in RoF	20 GHz [21]
Sub carrier spacing	15 KHz [21]
Signal bandwidth	80 MHz [21]
FFT size	8192 [21]
Number of sub carriers	4800 [21]
K_3	2.58, inferometric modulator [22]
m_o	4 % [22]
V_b	0.5 V [22]
P_o	-14 dBm
R_{rb}	-33.2 dB [23]
α	0.2 dB/km
f, frequency of RoF signal	20 GHZ
β	0.05
Core diameter of Corning SMF fiber	8.2 μm
χ_{1111}	6x$10^{-15} m^3/W - s$ [12]
n_2	1.48
λ	1550 nm
$P_i = P_j = P_k$	4 dBm
η	5-10% [12]
M	10
R	9

Chapter 4

CNR analysis for mobile backhaul

Mobile backhaul signal is transmitted using the radio over fiber set up. Impairments due to IMD-RAM, IMD-OFDM, PMD, FWM, RBS and photodetector noises have been analysed and the numerical value of parameters used in analysis has been given in table 3.1.

4.1 Analysis of impairments

4.1.1 Inter modulation distortion-RAM (IMD-RAM)

Third order intermodulation products (IMD3) produced by combining several RFs may fall inside the alloted RF channel hence reducing the SNR. This optical noise is given by expression 4.1 because of 3 tones (i,j,k) [16].

$$N_{i\pm j\mp k} = \frac{3}{2} \cdot \frac{K_3}{3!} \cdot V_b^3 \cdot m_i m_j m_k \cdot P_o \tag{4.1}$$

where, m_i is the optical modulation index (OMI) of the i^{th} RF channel, V_b is the bias voltage of the modulator, K_3 is the 3^{rd} order modulator non-linearity parameter and P_o is the average received optical power.

4.1.2 Inter modulation distortion - OFDM (IMD-OFDM)

The non-linearity of the modulator may generate inter-modulation distortion noises due to beating between OFDM subcarriers. The intensity of distortion because of IMD3 at RF channel l is given by equation 4.2 [17],

$$I(l) = \frac{1}{6}d_{l-1}^2 + \frac{2}{3}d_l^2 + \frac{1}{6}d_{l+1}^2 \tag{4.2}$$

where, d_i^2 is the relative amplitude of IMD noises given by equation 4.3,

$$d_i^2 = \frac{(P_o \kappa_3 m_o^2 V_b^3)^2}{2} \cdot \mathcal{M}(N) \tag{4.3}$$

m_o is the OMI of a single OFDM subcarrier and $\mathcal{M}(N)$ is the total number of IMD3 products generated by N equally spaced OFDM subcarriers.

4.1.3 Rayleigh Backscattering (RBS)

Interference of the reflected modulated wave with the Rayleigh back scattering incident wave generates noise which leads to degradation of SNR. The power spectral density (PSD) of RBS noise is given by equation 4.4 [18],

$$N(f) = \frac{10R_{rb}^2(2\alpha L + e^{-2\alpha L} - 1)}{9} \cdot (S(f) * S(f)) \tag{4.4}$$

where, S(f) is the PSD of the output of laser, α is the fiber attenuation (0.2 dB/km), L is the length of optical fiber and R_{rb} is the RBS reflectance of the fiber.

$$S(f) = \frac{1}{\sqrt{2\pi}\sigma_f} exp\frac{(f - f_o)^2}{2\sigma_f^2} \tag{4.5}$$

4.1.4 Polarization mode dispersion (PMD)

PMD causes misalignment between polarizations of the optical carrier and its RF leading to RF power fading. The SNR penalty caused by this is given by the equation 4.6 [19],

$$\delta = cos(\pi \cdot f \cdot \tau) \tag{4.6}$$

where,
$\tau = \beta\sqrt{(L)}$ is the differential group delay, β is the PMD coefficient of the fiber and L is the length of optical fiber.

4.1.5 Four wave mixing

When three wavelength channels (say ν_i,ν_j,ν_k) near the zero-dispersion point interfere, they produce a fourth intermodulation product (ν_{ijk}) at frequency given by $\nu_{ijk} = \nu_i + \nu_j - \nu_k (i, j \neq k)$. Power$P_{ijk}$ generated at frequency ν_{ijk} due to interaction of signals at frequencies ν_i, ν_j and ν_k with input powers P_i, P_j and P_k respectively is given by equation 4.7 [12],

$$P_{ijk}(L) = \eta(\mathcal{P}\kappa)^2 P_i(0)P_j(0)P_k(0)exp(-\alpha L) \tag{4.7}$$

where κ is the nonlinear interaction constant given by [12],

$$\kappa = \frac{32\pi^3\chi_{1111}}{n_2\lambda_c}(\frac{L_{eff}}{A_{eff}}) \tag{4.8}$$

η is the efficiency of four wave mixing, $\mathcal{P}$ is the degeneracy factor ($\mathcal{P}$=6 for three waves mixing), ,P_i, P_j, P_k are the fiber input powers at frequencies ν_i, ν_j and ν_k respectively, χ_{1111} is the third-order nonlinear susceptibility, n is the refractive index of the fiber, L_{eff} (equation 4.9) and A_{eff} (equation 4.10) are the effective length and effective cross-sectional area of the fiber respectively.

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \tag{4.9}$$

$$A_{eff} = \pi r^2, \tag{4.10}$$

r is the radius of core (see Table 3.1)

Taking into account the above noise impairments and photodetector noises like shot noise, dark current, surface dark current and thermal noise (explained in next section) , the CNR (carrier to noise ratio) at receiver can be expressed by equation 4.11 [12].

$$\frac{C}{N} = \frac{0.5(mRMP)^2}{Noise_{photodetector} + Noise_{impairments}} \tag{4.11}$$

where m is the modulation index (typical value is 0.25-0.5), R is the unity gain responsivity, M is the photodetector gain and P is the received optical power. The CNR varying with fiber length is shown in figure 4.1. The US signal will hold the same noise parameters as the DS and it can be considered as reciprocal of the DS scenario. Therefore, figure 4.1 also represents the CNR curve for US RoF.

4.2 Photodetector Noise

Noise in photodetector arises due to statistical nature of the photon to electron conversion process and the thermal noises associated with the amplifier circuitry [12]. For InGaAs APD, following receiver noises can cause impairments [12].

4.2.1 Shot noise

Shot noise is the result of statistical nature of the production and collection of photoelectrons when an optical signal is incident on a photodetector. The mean-square value of shot noise current is given by the following equation [12],

$$i^2_{shot} = 2qI_pB_eM^2F(M) \tag{4.12}$$

In the above equation, I_p is the average value of photocurrent given as $I_p = \mathcal{R} \cdot P_{in}$, $\mathcal{R}$ is the

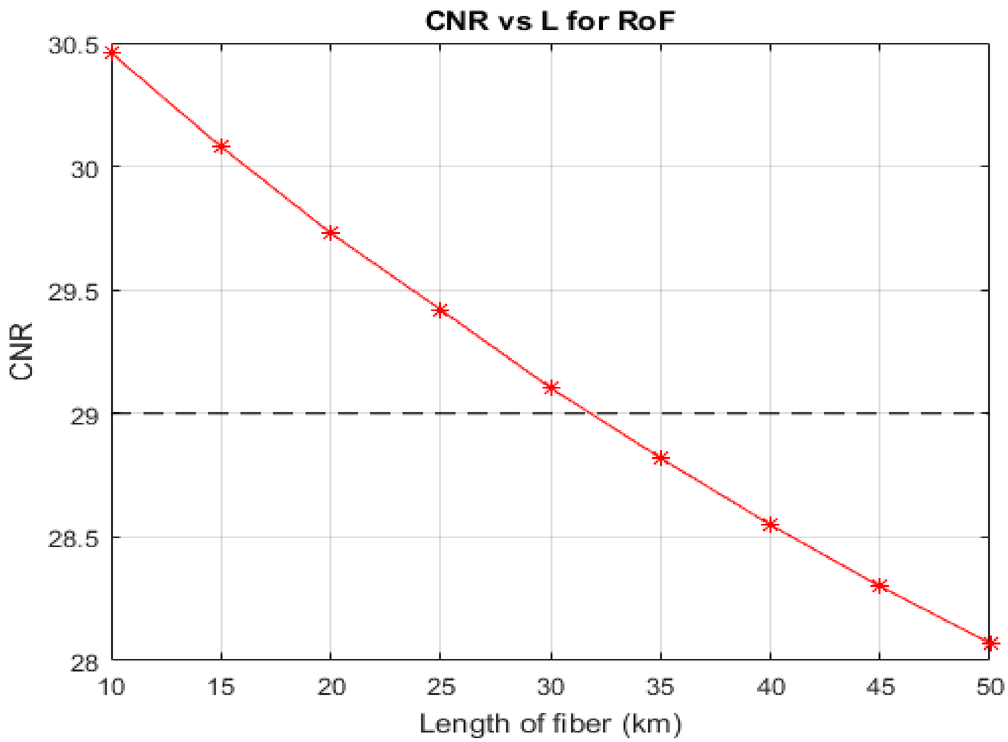

Figure 4.1: Carrier to noise ratio

APD responsivity, P_{in} is the incident optical power, B_e is the receiver bandwidth, M is the APD gain and F(M) is the noise figure defined in section 3.3.1.

4.2.2 Dark current

Dark current is the residual current that flows through the bias circuit of the photoelectric device when there is no incident light on the photodiode. The mean square value of this current is given by the following equation [12],

$$i_{DB}^2 = 2qI_dM^2F(M)B_e \tag{4.13}$$

where I_d is the primary detector bulk dark current and ranges from 10-50 nA at M=10 [12].

4.2.3 Surface dark current

Also known as surface leakage current, it is the result of leakage current and its mean square value is given by [12],

$$i_{DS}^2 = 2qI_lB_e \tag{4.14}$$

where I_l is the surface leakage current.

4.2.4 Thermal noise

Also known as Johnson noise, thermal noise is the result of the load resistance R_L and contributes a mean-square noise current given by the following equation [12],

$$i_T^2 = \frac{4k_B T}{R_L} B_e \tag{4.15}$$

where, k_B is the boltzmann's constant and T is the absolute temperature. The value of R_L is assumed to be 200 Ω for the analysis.

Chapter 5

Rise Time Budget Analysis

In digital systems, rise time budget analysis becomes critical to determine the dispersion limitation. In the ODN sharing scheme considered here, it plays a major role in PON arm to determine the maximum possible reach of the system. The total rise time (t_{sys}) for single mode fiber is given by equation 5.1 [12],

$$t_{sys} = \sqrt{t_{rx}^2 + t_{tx}^2 + t_{GVD}^2} \tag{5.1}$$

where, t_{rx} is the transmitter rise time and it depends on the light source and its drive circuitry (typical value is 25 ps) , t_{rx} is the receiver rise time given by equation 5.2 and t_{GVD} is the group velocity dispersion rise time given by equation 5.3 [12].

$$t_{rx} = \frac{350}{B_e} \tag{5.2}$$

where B_e is the 3-dB electrical bandwidth of the receiver assumed to be 20 GHz here.

$$t_{GVD} = |D|L\sigma_\lambda \tag{5.3}$$

where D is the dispersion coefficient (17 ps/nm-km), L is the length of fiber and σ_λ is the half-power spectral width of the source whose typical value is 0.1 nm for laser source [12].

The allowed rise time $t_{available}$ is given by $t_{available} = 0.7/B_{NRZ}$ where B_{NRZ} is the bit rate of NRZ signal (10 Gbps for DS and 2.5 Gbps for US). Therefore, the maximum allowable rise time degradation for DS is 0.07 ns and for US is 0.28 ns. From equations 5.2 and 5.3, t_{sys} can be calculated. Table 5.1 shows the theoretically calculated value of rise time for various fiber lengths.

Table 5.1: Rise time analysis

Component		Rise time
t_{tx}		25 ps
t_{rx}		17.5 ps
t_{GVD}	10 km	0.017 ns
	15 km	0.0255 ns
	20 km	0.034 ns
	25 km	0.0425 ns
	30 km	0.051 ns
	35 km	0.0595 ns
	40 km	0.068 ns

Table 5.2 shows system rise time evaluated according to equation 5.1.

Table 5.2: Total rise time for different fiber lengths

L (km)	10	15	20	25	30	35	40
$t_{sys}(ns)$	0.0349	0.0398	0.0457	0.0523	0.0594	0.0669	0.0745

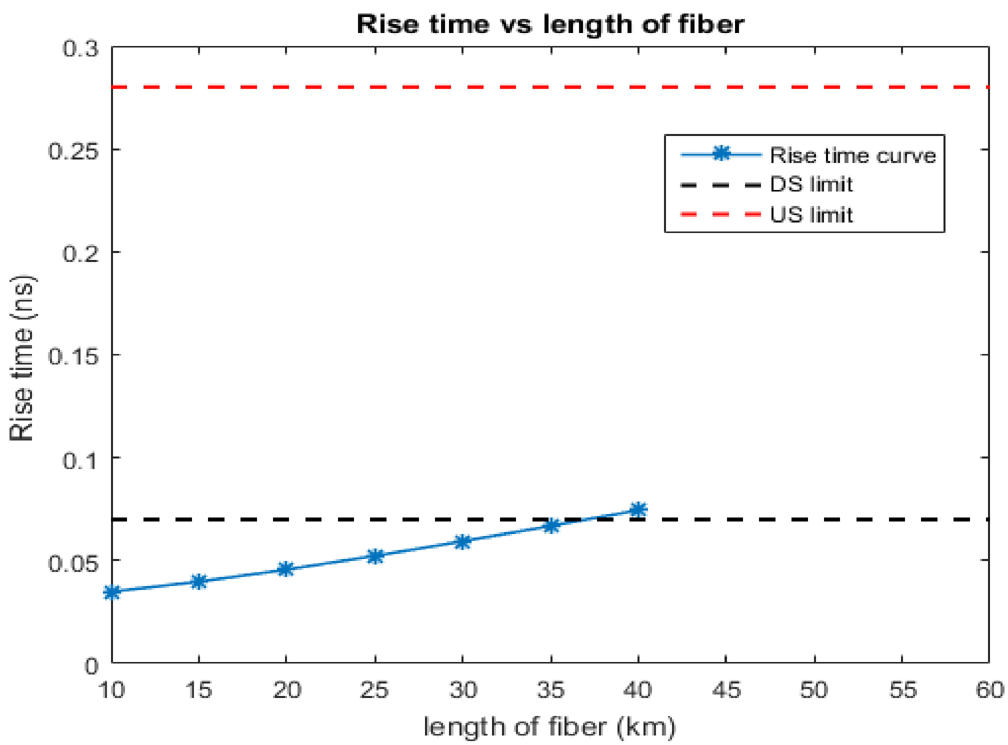

Figure 5.1: Rise time for different fiber lengths

Figure 5.1 shows that for fiber lengths up to 35 km, rise time budget is met for both US and DS data.

Chapter 6

Delay analysis

The transmission of mobile signal requires end to end latency to be less than 1 ms to follow 5G specifications. This sections discusses and analyses the factors and delays that contribute to overall end to end delay of the mobile backhaul arm of the architecture.

6.1 Group delay

Light travels slower in fiber optic cable than in vacuum because of difference in refractive index of light in free space and in glass. This results in fiber delay or group delay. The expresssion for group delay is given as [13],

$$\tau_g = \frac{N_{ge}}{c} \tag{6.1}$$

where, N_{ge} is the group index of SMF ($N_{ge} = 1.4682$ at $\lambda = 1550$ nm for Corning SMF-28e optical fiber).

6.2 Processing delay

Various optical components used in the architecture such as WDM multiplexer/demultiplexer, circulator, optical amplifiers and transponders contribute to total delay. These are all passive devices and hence can be considered as a passive waveguide. Therefore, same rules apply for them as for fiber and their delay can be given by the following expression [15],

$$Delay = \frac{n}{c} \cdot t \tag{6.2}$$

where, n is the refractive index of fiber (n = 1.468) and t is the length of the waveguide.

A circulator is typically 50 mm in length and 5.5 mm in diameter. According to [14], length of waveguide in a WDM Mux/Demux component is 49 mm.

Erbium-doped fiber amplifier (EDFA) is commonly used as an optical amplifier and consists of a 10-30 m long optical fiber which has been lightly doped with erbium. A 30 m long Er^{+3} doped optical fiber is assumed for calculation of $delay_{EDFA}$.

Another component that adds up to delay is a transponder which changes the signal coming from the customer to a signal reasonable for transmission over the WDM link and an approaching signal from the WDM link to an appropriate signal toward the client. According to [15], transponders contribute to a delay ranging from 5-10 μs.

Table 6.1 lists all the delays and their values evaluated from equations 19 and 20.

Table 6.1: Delay

Group delay, τ_g	0.24 ms
$Delay_{circulator}$, $\tau_{circulator}$	0.245 ns
$Delay_{MUX/DEMUX}$, $\tau_{MUX/DEMUX}$	0.24 ns
$Delay_{EDFA}$, τ_{EDFA}	147 ns
$Delay_{transponder}$, $\tau_{transponder}$	10 μs

Assuming one circulator, two units of WDM Mux/Demux (one for multiplexing and other for demultiplexing), two units of EDFA and two units of transponders (one at transmitted and other at receiver end), the total delay is given by equation 6.3.

$$\begin{aligned} Delay_{total} =& \tau_g + (\tau_{circulator} + 2 \times \tau_{MUX/DEMUX} \\ & + 2 \times \tau_{EDFA} + 2 \times \tau_{transponder}) \end{aligned} \quad (6.3)$$

$$\begin{aligned} =&(0.24 \times 10^6 + 0.245 + 2 \times 0.24 + 2 \times 147+ \\ & 2 \times 10 \times 10^3)ns \\ =&0.26ms \end{aligned}$$

The above calculation shows that end to end delay for mobile backhaul is 0.26 ms which is less than the required limit of 1 ms.

Chapter 7

Conclusion

This thesis work included extensive theoretical analysis of the considered ODN sharing architecture based on power budget analysis of PON and mobile backhaul, delay analysis of mobile backhaul and rise time budget analysis of mobile backhaul. A common conclusion for the maximum reach possible can be drawn from figures 3.1, 3.2, 4.1 and 5.1. From power budget analysis, it was found that a maximum of 20 km of fiber length can be supported independently by PON in both upstream as well as downstream directions for N=128. This analysis for mobile backhaul analog RoF arm showed that it can independently support a maximum of 30 km fiber length. Since this is an integrated architecture based on optical fiber sharing scheme, maximum length that can be allowed for the whole architecture is 20 km.

Delay analysis done in interest of meeting requirements for 5G show that a maximum of 0.26 ms end to end delay is possible in mobile backhaul which is less than 1 ms (5G requirement) and hence meets the requirement.

Rise time budget analysis of PON show that for the given architecture, fiber lengths up to 35 km meet the rise time budget for both US as well as DS.

It can be thus be concluded here that for the above ODN sharing scheme, maximum reach possible is 20 km.

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