The Energy Efficiency of EDFA and Raman Fiber Amplifier

Peng Wang

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supervised by
Dr. Kerry Hinton
Dr. Peter Farrell
Dr. Bipin Sankar Gopalakrishna Pillai

Abstract

Optical fibre links using optical amplifiers in combination with advanced modulation formats and Forward Error Correction (FEC) are promising technologies to increase transmission distance as well as the capacity of communication systems. The rapidly increasing energy consumption of telecommunication networks is driving network designers to consider how to minimize energy consumption of optical fibre links by choosing the right combination of optical amplifier, advanced modulation format and error correction technology.

This thesis involves development of a model for calculating the lower limit of power consumption of EDFAs when designing an optical fibre link. We compare the energy efficiency of Distributed Raman Fiber Amplifiers (DRFA) and Erbium-Doped Fiber Amplifiers (EDFA) used in long-haul transmission systems. This comparison accounts for the interaction between optical link power, signal quality (as measured by the Bit Error Rate (BER)), and the use of FEC. We show that deploying DRFAs in some scenarios may be more energy efficient than EDFAs, despite their intrinsic requirement for higher pump powers.

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Chapter 1

Introduction

1.1 Significance of Using Energy Efficient Optical Amplifiers

The energy consumption of the Internet is becoming an issue that may constrain the Internet′s continued growth and the future economic and social benefits. Direct electricity use of the Internet is responsible for 2.3% of world total energy consumption [3] in developed countries, which costs $7 billion per year in 2011 [4]. Meanwhile the IP traffic is increasing by 23% per year [5]. The energy consumption of Internet is growing between 7% and 10% per year [6, 7] while the growth in the production of world electrical power was increasing by 3.7% in 2010 [8] and is forecast to have an annual growth of 2.2% in 2040 [4]. These trends have stimulated significant efforts in the ICT sector to improve the energy efficiency of telecommunications networks. Independent of environmental issues, good engineering principles require systems to be well-designed and energy efficient to minimise operational costs over the life of the system.

The energy consumption of various parts of optical networks has been studied by many researchers [9–12]. Few such studies have included the energy consumption of optical amplifiers, such as Erbium-Doped Fiber Amplifiers (EDFAs), because amplifiers consume much less energy than the IP switches and routers used to route packets from source to destination. However, a recent study by GreenTouch [13] predicted that the power consumption of routers will substantially reduce by 2020, resulting in the power consumption of EDFAs becoming a significant part in the power consumption of optical network by 2020 due to router bypass technology and increased popularity of long-haul transmission.

In addition, the rapid growth in bandwidth requirements of optical systems has brought about an increasing interest in distributed Raman fibre amplifiers (DRFAs) which can provide better signal quality (i.e. higher Optical Signal to Noise Ratio (OSNR)) than traditional EDFAs. This improvement in signal quality enables the use of modulation formats of larger constellation size requiring a higher OSNR [14]. Another important advantage of DRFAs in Wavelength-Division Multiplexing systems is that the system designer can select the frequencies (and bandwidth) over which gain is provided by selecting appropriate pump laser diode frequencies and powers. Further a DRFA does not require the introduction of a specialised gain medium, providing easy upgradability of existing fibre links. Recent developments in diode lasers have also resulted in reliable, high output power, low noise Raman pumps [2,15]. Because DRFA consumes much more power than EDFA, if DRFA is employed to upgrade current EDFA assisted links, the power consumption of optical amplifiers will be more significant. Thus energy efficiency of optical amplifiers is likely to become increasingly important.

When comparing the energy efficiency of EDFAs and DRFAs, the power consumption of Forward Error Correction (FEC) should be included. This is due to the fact that at the end of the link, the amount of amplification provided determines the OSNR. The OSNR and in turn the SNR determine the error correction technique that is required to attain the target Bit Error Rate (BER). Thus amplification and error correction are closely inter-connected, and need to be dealt with simultaneously from an energy consumption perspective. FEC is an effective technology to reduce BER in high-speed, long-haul optical transmission systems [16, 17]. Recent progress in FEC has enabled a pre-FEC BER of 10^{-2} to be corrected to a BER smaller than 10^{-13} [16, 17]. For a given OSNR and baud rate, the use of modulation formats with larger constellation size leads to a higher BER, and the ability to reduce the BER to acceptable levels allows use of advanced modulation formats to increase data rate without increasing optical signal bandwidth [14, 18]. The power consumption of FEC depends on the algorithm used for error correction, hardware implementation of the algorithm and amount of redundancy introduced by error correction. The algorithm required is a function of pre- and post-FEC BER, which in turn is dependent on received OSNR. Algorithms that are able to correct larger pre-FEC BER consume more power. Therefore, the higher the received signal OSNR is, the weaker the error correction required and this leads to less power consumed by FEC [17]. Therefore an energy efficient fibre link balances the energy consumption of the optical amplifier and FEC.

1.2 Overview of Thesis Objectives

The goal of this thesis is to develop models to compare the power consumption and energy efficiency of optical amplifiers by considering the interaction between amplifier, modulation format and error correction. We will also study the impact of modulation formats on maximum link length and the power consumption of the link. The modulation formats to be considered are Intensity Modulation with Direct Detection (IMDD), Quadrature Phase-Shift Keying (QPSK), Dual-Polarization Quadrature phase-shift keying (DP-QPSK), and Dual-Polarization 16 Quadrature Amplitude Modulation (DP-16QAM).

Chapter 2 provides literature survey covering components involved in this thesis. Chapter 3 presents the power consumption model for the optical amplifier and the simulation setup of optical fibre links. Chapter 4 discusses the results. Chapter 5 gives a summary of this thesis, and lists suggestions for possible future work.

Chapter 2

Literature Survey

2.1 Overview of Optical Fibre Link

Optical amplifiers in an optical fibre link are used to compensate signal attenuation caused by optical fibre, optical device and splice loss [19]. The optical amplifier gains should be sufficient to satisfy signal level requirements and maintain an acceptable BER. The model of optical link shown in figure 2.1 contains three parts:

- The first part is a signal transmitter that lauches the optical signal into the fibre. A power amplifier is usually integrated in the transmitter to increase signal transmission power P_{sig}. The power consumption of power amplifier is considered separately from the other amplifiers as its gain requirement is different from the in-line amplifiers. A FEC encoder is included in the transmitter.

- The second part is a chain of in-line optical amplifiers. It consists of spans of optical fibre that cause signal losses L_1, L_2......L_{n} and in-line optical amplifiers which provide gains G_1, G_2......G_{n}. The optical fibre is passive and does not consume energy. The last amplifier is a preamplifier. This amplifier is often treated as part of receiver. We will treat it the same as the other in-line amplifiers.

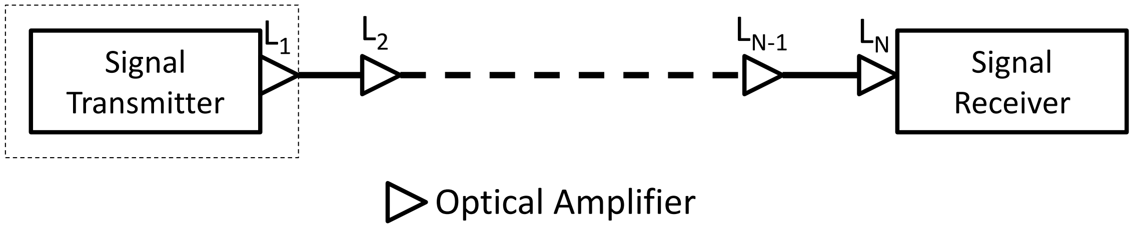

Figure 2.1: Structure of optical fibre link. The first amplifier is power amplifier that is coupled with signal transmitter, and the last amplifier is pre-amplifier that is immediately before the signal receiver. The second and second last amplifiers, together with dashed line indicate the fibre link and chain of in-line amplifiers.

- The last part is the optical receiver, demodulator and devices to convert optical signal into electrical data. This part contains a FEC decoder to correct errors.

In this thesis we assume the link does not include any electronic regeneraters, therefore the optical amplifiers are the only active components in fibre link and the power consumption of fibre link is the power consumption of optical amplifiers. Existing studies have considered power consumption and signal quality of optical amplifiers [2, 15, 19]. However, all of these studies consider power consumption and signal quality separately without considering the trade-off between power consumption and signal quality.

In order to consider the impact of signal quality on energy consumption, we include the power consumption of FEC that is embedded in transmitter and receiver. FEC is now generally used in optical transmission systems to improve signal quality [17,20] therefore it is appropriate to include FEC when discussing signal quality. The power consumption of FEC is also directly related to signal quality. We thus investigate the combined energy consumption of optical amplification and error correction. We also study if the additional power consumption of DRFA, beyond that of an EDFA, will provide a net gain in energy efficiency due to the increase in signal quality. Therefore we define the power consumption P_{link} and energy efficiency E_{link} of the optical fibre link as:

$$P_{\text{link}} = P_{\text{pa}} + n_{\text{span}} P_{\text{A}} + P_{\text{FEC}} + P_{\text{Tx}} + P_{\text{Rx}} \tag{2.1}$$

$$E_{\text{link}} = \frac{P_{\text{link}}}{R_{\text{I}}} \tag{2.2}$$

where P_{pa} (Watts) is the power consumption of power amplifier, n_{span} is the number of spans of the link, P_A (Watts) is power consumption of in-line optical amplifier and preamplifier, P_{FEC} (Watts) is power consumption of FEC, P_{Tx} (Watts) is power consumption of signal transmitter, P_{Rx} (Watts) is power consumption of signal receiver and R_{I} is total information rate. The power consumption of power amplifier is considered separately because it is designed to provide high signal transmission power to extend the transmission distance rather than to compensate fibre loss hence its gain is different from the other amplifiers [21]. We consider pre-amplifier of receiver as part of amplifier chain thus the gain of pre-amplifier equals the loss of fibre span before it. The information rate is a function of baud rate and modulation format. Advanced modulation formats increase the information rate without increasing bandwidth but they have stricter requirement of signal quality [14]. We include their effect on power consumption of fibre link.

Our optical fibre link consists of optical amplifiers to maintain signal power. At the end of link in the receiver, FEC will correct errors to provide an acceptable BER so that information is transferred successfully. The modulation format is chosen so that required information rate can be achieved. The power consumption and energy efficiency of optical fibre links that employ the two amplifier technologies will be compared to decide which amplifier is more energy efficient (in terms of energy per bit of the overall system) for a give scenario.

2.2 Forward Error Correction (FEC)

Error correction coding is an essential part of modern fibre optic communication systems, particularly for long-haul, high data rate systems with high spectral efficiencies [17,20,22].

These systems are evolving rapidly. The current commercial systems apply DP-QPSK to construct 100G channels, while 400G and 1T channels employing DP-16QAM are being tested [23, 23, 24]. The network capacity is doubled every 12-18 months [20, 22]. FEC is considered as a cost-effective solution to recover signal quality over long-haul high data rate optical links. In fact, FEC has been successfully implemented in a variety of commercial optical systems [20].

In typical FEC, data is encoded with additional bits by implementing a block of code words with data to build error-correcting codes [21]. The additional bits inserted into the data stream allow the signal decoder to detect errors that may occur due to signal degradation as it propagates along the link. The maximum number of error bits that can be corrected is determined by the algorithm of FEC. The ratio between the additional bits and information bits is called code rate. For example, if an FEC has a code rate of 7%, it produces 7 additional bits for every 100 information bits. Different types of FEC employ different algorithms and are requiring different code rate. FEC algorithms can be classified as either hard-decision decoding or soft-decision decoding.

2.2.1 Hard-decision FEC

The FEC decoder usually operates within the demodulator. If the output of demodulator is quantized and the demodulator makes "hard-decisions", the error-correcting decoder is performing hard-decision decoding [21]. Hard-decision decoding sets the value of a received bit to be a '1' or '0' by comparing the voltage of the received bit with a single pre-set voltage threshold. If a received bit voltage is greater than the threshold, the bit is considered to be definitely '1' regardless of how close the bit is to the threshold and if it is less, the bit is considered to be definitely '0'. Hard-decision decoding uses the additional FEC bits inserted into the data stream to determine if the decision is correct.

Hard-decision decoding has low code rate, good performance and moderate complexity. The International Telecommunication Union (ITU-T) has recommended Reed-Solomon (255, 239) (RS (255, 239)) code for optical fiber submarine cable systems [22], which are typically long-haul high data rate optical links, because performance of RS (255, 239) coding is well understood and analytical models exist that can quantify its coding gain at all BERs. RS (255, 239) accepts signals of pre-FEC BER of 10^{-4} and generates signals that have BER smaller than 10^{-13}. The code length is $255 \times 8 = 2040$ bits, of which $239 \times 8 = 1912$ bits are information bits. This means the redundancy of RS (255, 239) is 7% [17].

Experimental measurements show that decoder of RS (255, 239) consumes 360 mW at 43 Gbps bit rate, 160 nm CMOS with a voltage supply of 1.5 V [16]. We will later compare systems that adopt different FEC, therefore we will scale the decoder of RS (255, 239) [25] to 107 Gbps bit rate (corresponding to an information rate of 100 Gbps), 40 nm CMOS and 0.8 V supply:

$$P_{\mathrm{RS}} = 360\ mW \times 2 \times \frac{107\ Gbps}{43\ Gbps} \times \frac{40\ nm}{160\ nm} \times \frac{0.8\ V^2}{1.5\ V^2} \approx 130\ mW \qquad (2.3)$$

The factor 2 accounts for energy consumption of the encoder which is approximately equal to decoder energy consumption at a pre-FEC BER of 10^{-4} [17]. At 100 Gbps the energy consumption per information bit of RS (255, 239) is:

$$E_{\text{RS}} = 130\ mW/100\ Gbps = 1.3\ pJ/bit \tag{2.4}$$

2.2.2 Soft-decision FEC

As the demand for higher data rates continues, the industry is implementing 100G and 400G channels with the same channel bandwidth (i.e. 50 GHz) [20]. In these circumstances, soft-decision decoding is considered a cost-effective solution. The performance gain provided by soft-decision FEC enables an increase in transmission link length, a reduction of signal transmission power and enables the use of higher order modulation formats such as DP-16QAM.

In contrast to hard-decision decoding, soft-decision decoding uses additional bits to decide not only if the received information is '1' or '0', but also provides a measure of the reliability of the obtained information [21]. Table 2.1 gives an example of how soft-decision FEC determines the value and reliability of received data. The first one bit of received data is an information bit which tells the determined value of the bit, while the last two bits are confidence bits which indicate how reliable the determined value is. A soft-decision decoder typically performs better in the presence of noise than its hard-decision counterpart. However, soft-decision FEC requires more redundancies as it requires confidence bits.

Table 2.1: Example of codes and decisions in soft-decision FEC

Code	Decision
000	definitely 0
001	probably 0
010	maybe 0
011	guess 0
100	guess 1
101	maybe 1
110	probably 1
111	definitely 1

For soft-decision FEC, we will consider Quasi-Cyclic Low Density Parity Check codes with a code length of 24576 bits of which 20482 bits carry information [17]. This code is written as LDPC (24576, 20482) and is suitable as long as pre-FEC BER is better than 10^{-2} in order to generate a post-FEC BER less than 10^{-13}. The encoder and decoder of LDPC (24576, 20482) consume approximately 122 pJ/bit at a pre-FEC BER of 10^{-2} correspond to 40 nm CMOS, 100 Gbps information rate and 0.8 V voltage supply [17]. When the signal pre-FEC BER reduces from 10^{-2} to 10^{-3}, the average number of required decoder iterations reduces from 4 to 2. Hence the energy consumption is halved.

Table 2.2 describes energy consumption per bit and BER requirement of these FEC options for 40 nm CMOS, 100 Gbps information rate and 0.8 V voltage supply. We denote LDPC (24576, 20482) with 2 average iterations as LDPC sc. 1 and LDPC (24576, 20482) with 4 average iterations as LDPC sc. 2.

Table 2.2: Power consumption and BER values of FEC

FEC	pre-FEC BER	Energy per bit (pJ/bit)
RS (255, 239)	10^{-4}	1.3
LDPC sc. 1	10^{-3}	61
LDPC sc. 2	10^{-2}	122

2.3 Optical Amplifier

An optical amplifier is a device that provides signal gain in the optical domain. Compared to traditional signal repeaters, optical amplifiers do not perform photon-to-electron-to-photon signal conversion, therefore the conversion delay and energy consumption required for these conversions are eliminated [19, 26]. Optical amplifiers can provide simultaneous gain across multiple wavelength channels in optical fiber link. They have found widespread use in diverse applications ranging from ultra-long links to short links in access networks.

2.3.1 Erbium Doped Fibre Amplifier (EDFA)

EDFA is considered to be an extremely pump efficient, high-gain and low noise amplifier [19]. It requires only tens of milliwatts of power at its most efficient pump wavelength of 980 nm, and can exhibit gain up to 50 dB virtually independent of signal polarization state. The noise figure of EDFA is very close to quantum limit with a very low insertion loss. Its gain dynamics are slow, thus minimizing crosstalk which is a non-linear effect suffered by other optical amplifiers [19].

EDFA employs the effect of simulated emission to amplify incoming signals [19]. Figure 2.2 displays a general architecture of an EFDA. In an EDFA, source pumps supply optical power to a gain medium which is connected to the signal carrying optical fibre by fibre couplers. Pump power in the gain medium will generate a population inversion that provide signal gain via the process of stimulated emission when signal photons enter gain medium. The gain medium in an EDFA is produced by doping the silica fiber core with Erbium. Optical isolators are usually deployed in links with EDFAs to remove back scattered optical power which can disturb previous amplifiers and become a source of

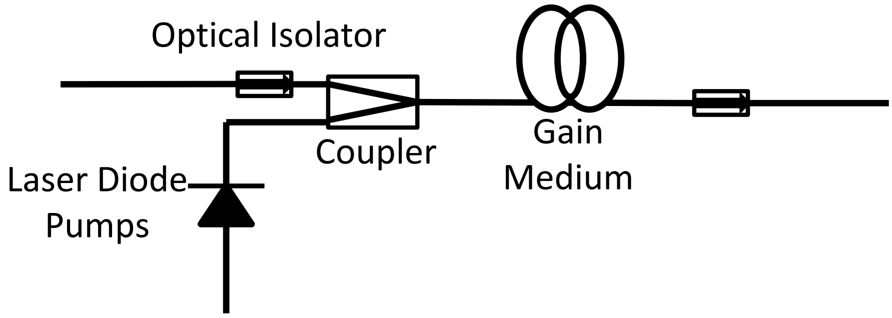

Figure 2.2: EDFA architecture

noise. In order to support signal wavelengths ranging from 1530 nm and 1565 nm (C band), pump wavelengths are usually 1480 nm and 980 nm. Many commercial EDFAs have built-in variable optical attenuator (VOA) [27] (VOA is not shown in Figure 2.2). VOA is used in most pre-amplifiers to regulate output power and provide gain flatness control.

An EDFA can be pumped co-directionally, counter-directionally or dual-directionally. In a co-directional pumped EDFA, pump light is injected from the same direction as the signal flow. Figure 2.2 is a co-directionally pumped EDFA. If the pump power is injected in the opposite direction to the signal flow, it is known as counter-directional pumping. Co-directional pumping gives better noise performance while counter-directional pumping allows higher gain [19]. If both pumping are employed, it is called dual-directional pumping. Additional pumps are usually employed in an actual EDFA for redundancy because pumps are more reliable when they operate at low power [19].

The gain of an amplifier is defined as the ratio of output signal power $P_{\text{sig,out}}$ to input signal power $P_{\text{sig,in}}$:

$$G = \frac{P_{\text{sig,out}}}{P_{\text{sig,in}}} \tag{2.5}$$

In a typical attenuation compensated optical fibre link, the gain of amplifier will be set equal to the loss of fibre span immediately before the amplifier. That is:

$$G = \exp\left(-\alpha_{\text{s}} L_{\text{span}}\right) \tag{2.6}$$

where α_{s} is the fibre attenuation coefficient at the signal wavelength. L_{span} is the length of the fibre span between amplifiers. As discussed above, we consider a long-haul transmission link that employs multiple optical amplifiers in series (Figure 2.1). Because fibre attenuation is compensated by the gain of the optical amplifiers, the amplifier output signal power is the same as signal transmission power $P_{\text{sig,out}} = P_{\text{Tx}}$.

Today EDFAs provide flat gain over broad bandwidth (C + low L bands: 1530-1610 nm) at low energy consumption [19, 28]. The gain medium is about 100 metres for a gain up to 50 dB. Industry is also testing other rare-earth dopants to make doped optical amplifiers at alternative wavelengths [19]. Other optical amplifiers, especially Distributed Raman amplifiers that utilize a completely different mechanisms are becoming popular [19].

2.3.2 Noise in EDFA Assisted Link

Amplified spontaneous emission (ASE) is the dominant noise that limits signal quality in EDFA assisted link [21]. It originates from the spontaneous recombination of electrons and holes in the amplifier medium. This random recombination occurs over the full bandwidth of EDFA (i.e. 1530-1565 nm for C-band, 1565-1610 nm for L-band). Therefore noise photons give a broadband background noise. When noise photons travel along the amplifier with the optical signal, they are amplified as well. The power of ASE $P_{\mathrm{ASE,E}}$ generated by individual EDFA is modeled as [19]:

$$P_{\mathrm{ASE,E}} = hf n_{\mathrm{sp,E}} \left(G - 1\right) B_{\mathrm{o}} \tag{2.7}$$

where $n_{\mathrm{sp,E}}$ is population inversion factor, h is Planck's constant, f is channel frequency, and B_{o} is bandwidth for OSNR measurement. ASE noise comes from population inversion which is the prerequisite for gain in an EDFA, thus ASE is an unavoidable noise in EDFA assisted link.

When ASE is received by optical receiver, it will generate ASE-signal beat noise and ASE-ASE beat noise in electrical domain. Advanced optical receiver such as Balanced Coherent Detector is able to remove ASE-ASE beat noise. Although thermal noise and shot noise also degrade signal quality in electrical domain. In a long-haul transmission link where multiple optical amplifiers are used, ASE-signal beat noise is the dominant noise [21] and we will neglect the other noises in electrical domain.

Another important penalty in long-haul optical fibre link is Non-Linear Interference (NLI) [29, 30]. NLI is caused by the Kerr effect when light propagates in silicon. This effect is caused by intensity-dependent variations in the refractive index. The common Kerr effects are self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). SPM and XPM affect the phase of signals and distort information encoded in phase (e.g. Phase-shift keying). FWM provides signal gain in some channels while depletes signal power from others. Thus they generate NLI. The effect of NLI can be modeled as an additive Gaussian noise in an uncompensated optical fibre link [31]. An analytical expression, which has been experimentally validated [32], for noise power P_{NLI} has been developed for EDFA assisted links:

$$P_{\mathrm{NLI}} = \left(\frac{2}{3}\right)^3 N_{\mathrm{span}} \gamma^2 L_{\mathrm{eff}} P_{\mathrm{sig}}^3 \frac{\log\left(\pi^2 |\beta_2| L_{\mathrm{eff}} N_{\mathrm{channel}}^2 R_{\mathrm{b}}^2\right)}{\pi |\beta_2| R_{\mathrm{b}}^3} B_{\mathrm{o}} \tag{2.8}$$

where γ is fibre nonlinear coefficient, R_{b} is baud rate, $L_{\mathrm{eff}} = \left(1 - \exp\left(-2\alpha_{\mathrm{s}} L_{\mathrm{span}}\right)\right) / (2\alpha_{\mathrm{s}})$ is effective fibre span length, α_{s} is fibre attenuation coefficient at signal wavelength and β_2 is second derivative of propagation constant. All other parameters are defined previously. This relationship indicates an increase in signal transmission power leads to an increase of NLI. Thus high signal transmission power does not always generate a high OSNR.

Simulation results indicate the highest OSNR occurs when $P_{\text{NLI}} = 1/2P_{\text{ASE}}$. The signal transmission power which results in $P_{\text{NLI}} = 1/2P_{\text{ASE}}$ is called optimized signal transmission power. If the optical link requires high OSNR, we can consider using the optimized signal transmission power to attain the required OSNR. On the other hand, at low signal transmission power, the effect of NLI is negligible compared to ASE [29]. Therefore if the OSNR requirement is not so strict, it is possible to use a low signal transmission power at which NLI is negligible in order to minimize signal transmission power.

2.3.3 Power Consumption and Efficiency of EDFA

There are many existing models for considering the optimization of EDFA from different aspects. For example, they discuss how to optimize signal gain in a small signal scenario, how to reduce pump power consumption while maintaining signal quality, how to choose the appropriate fibre type to improve signal quality, how to use pumps efficiently at specific wavelengths , etc [19, 26, 33]. In this work we are considering the lower limit of power consumption of EDFAs in an optical fibre link, therefore we will construct a model for this purpose.

Desurvire's model

The most widely used model of EDFA is Desurvire [19] which suggests the minimum power consumption of EDFA P_{EDFA} is the power required to be injected into gain medium in order to amplify incoming signal:

$$P_{\text{EDFA}} = \frac{P_{\text{sig,out}} - P_{\text{sig,in}}}{\text{PCE}} \tag{2.9}$$

where PCE is Power Conversion Efficiency. The output signal power $P_{\text{sig,out}}$ is much higher than the input signal power $P_{\text{sig,in}}$ because gain of amplifier is usually much greater than 1 and $P_{\text{sig,in}} = P_{\text{sig,out}}/\text{G}$:

$$P_{\text{EDFA}} \approx \frac{P_{\text{sig,out}}}{\text{PCE}} \tag{2.10}$$

Desurvire suggests the theoretical maximum PCE is the ratio of the signal/pump photon energies, or $\text{PCE}_{\text{max}} = \lambda_{\text{p}}/\lambda_{\text{s}}$. Then if 980 nm pumps are used to amplify C-band channels that have centre wavelength of 1550 nm, $\text{PCE}_{\text{max}} \approx 63\%$, while if 1480 nm pumps are used, $\text{PCE}_{\text{max}} \approx 95\%$. The value of PCE suggests the wavelength of pump should be as close as the wavelength of signal to make the amplifier energy efficient [19].

Desurvire model considers wavelength conversion efficiency only and it does not include many necessary factors that affect lower limit of amplifier power consumption. For example, it does not consider inefficiency of pump laser diode which is not perfect in converting electrical power into optical power, power consumed by cooling and management, inefficiencies in the technologies, etc. In addition, Desurvire does not consider the minimum signal power requirement when using EDFAs in a long-haul optical fibre link. The accumulation of noise degrades signal quality thus there is a minimum signal transmission power requirement in order to maintain a given signal quality (i.e. BER).

Further, Desurevire does not consider optical amplifiers and FEC together, when both of them are used to improve signal quality. The use of FEC has a strong impact on optical amplifiers, and vice versa.

Tucker's model

Another widely used power consumption model of EDFA is Tucker's model [10] which considers EDFA assisted optical fibre links in a transmission system composed of multiple hops (i.e. includes signal regenerators) in which photon-to-electron-to-photon conversion of signal occurs. Tucker considered how ASE impacts the minimum signal transmission power required to maintain signal quality (measured by Signal-to-noise ratio (SNR)) and calculated the energy consumption per bit for the EDFAs in an optical fibre link composed of multiple spans:

$$E_{\mathrm{EDFA,min}} = \frac{\mathrm{SNR_{bit}} N_{\mathrm{span}}^2 (1/G - 1)(1 - G) n_{\mathrm{sp,E}} hf}{\eta} \tag{2.11}$$

where $\mathrm{SNR_{bit}}$ is SNR per bit and $\eta = P_{\mathrm{sig}}/P_{\mathrm{EDFA}}$ is the overall power efficiency of EDFA. The part $N_{\mathrm{span}}^2(1/G - 1)(1 - G)n_{\mathrm{sp,E}}hf$ calculates the energy of total ASE of optical fibre link that reaches optical receiver. Tucker estimated the value of $\eta \approx 1\%$ by comparing results from (2.11) and energy consumption of commercialized EDFA. However, he did not undertake an analysis of the factors that determine of the value of η.

In order to estimate a theoretical lower limit for amplifier power consumption, a theoretical maximum value of η is required. In this thesis we consider future networks with ultra-long-haul links consisting of multiple spans without regenerators. In addition, we consider the interaction between optical amplifier and FEC. Neither Desurvire nor Tucker include these features.

2.3.4 Distributed Raman Fibre Amplifiers (DRFA)

DRFAs are often regarded as next generation amplifiers that can increase reach and capacity of long-haul optical transmission systems [2,15]. They reduce linear and nonlinear penalties of fibre systems, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and longer optical fibre link length. DRFA is based on Stimulated Raman Scattering (SRS). As with the EDFA, we focus on the lower limit for the power consumption and so will not consider the energy consumed by the monitoring and control circuits.

Raman gain arises from Raman scattering, during which a pump photon ($\mathrm{f_P}$) excites a molecule up to a virtual level (non-resonant state), and then the molecule quickly decays to a lower energy level emitting a signal photon of lower frequency ($\mathrm{f_S}$) (Figure 2.3) [1]. Because the emitted photon is downshifted in frequency or upshifted in wavelength, the light incident on a medium is converted to a lower frequency. DRFAs are implemented by injecting a high power pump optical field to the link fibre [1]. The power consumption of pump laser diodes in a DRFA link is primarily determined by fibre span attenuation and amplifier gain. Signal and ASE power has a less effect on power consumption of DRFA than that of EDFA [1,15]. The Raman gain spectrum in fused silica fibers is illustrated in

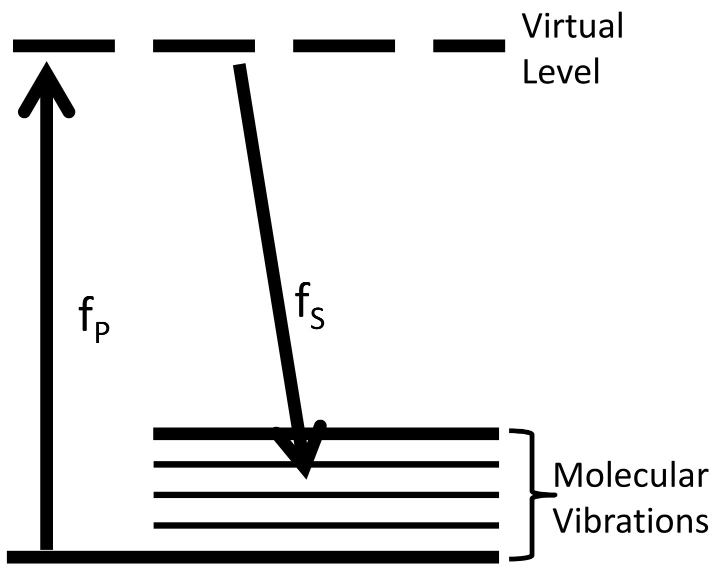

Figure 2.3: Schematic of the quantum mechanical process taking place during Raman scattering. The figure is taken from [1].

Figure 2.4. The gain bandwidth is over 40 THz, with the dominant peak near 13.2 THz (which is equivalent to 100 nm) offset from the pump wavelength when signal channels are in C-band [34]. Thus pumps of DRFA are placed near 1450 nm for efficient pumping in the 1550 nm channels. Figure 2.4 indicates the fiber type significantly influences the Raman gain. Dispersion compensation fibre (DCF) has a Raman gain almost ten times larger than that of single mode fibre (SMF). However, DCF has much higher fibre attenuation and NLI. We will focus on SMF because we are considering uncompensated optical fibre link in which NLI is compensated electronically.

Raman amplifiers have several advantages over EDFA. Raman gain can be created in all types of fibre at any wavelength for which a pump is available, which provides a cost-effective means of upgrading existing optical fibre links. Raman gain bandwidth can be extended by using multiple pump wavelengths. For example, multiple pumps can be used to provide flat gain over the entire C+L bands (1530-1625 nm) while L-band EDFA can only provide gain up to 1610 nm [15, 21, 28].

Raman amplifiers have some fundamental disadvantages as well. Raman amplifiers have relatively poor pumping efficiency compared to EDFAs. It is believed that Raman amplifiers consume 10 times more power than EDFAs. The high pump power requirement of Raman amplifiers also leads to gain saturation even at low signal gain. Most Raman amplifiers are designed to provide gains less than 30 dB. Raman amplifiers do not require special gain medium, but Raman amplifiers require a much longer gain fiber than an EDFA. Gain medium of DRFA is typically 20-30 km. The distributed property of Raman amplifiers enables the signal OSNR to be maintained at higher level than an EDFA, however, because the signal power is maintained at high level, more NLI is generated

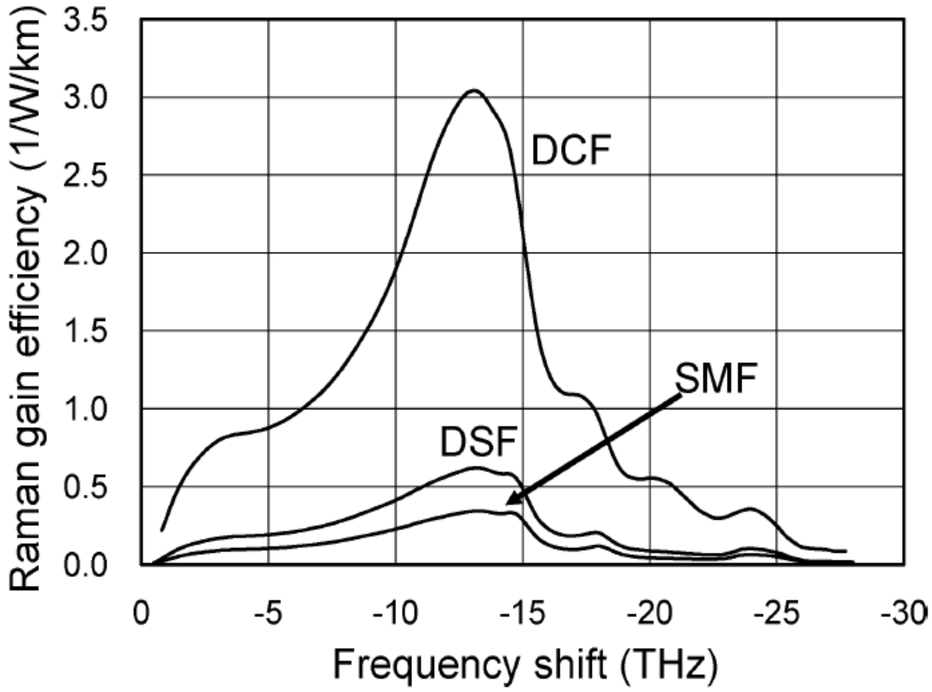

Figure 2.4: Raman gain vs. pump-signal frequency shift for standard single mode fiber (SMF), dispersion shifted fiber (DSF) and dispersion compensating fiber (DCF). The figure is taken from [2].

[2, 15, 21].

2.3.5 Noise in DRFA Assisted Link

The most significant noise source in DRFA is spontaneous Raman scattering which is amplified by stimulated Raman scattering to generate ASE [1, 15]. The noise mechanism of ASE of DRFA is similar to the ASE that affects the performance of EDFA except that, in the DRFA case, it depends on the phonon population in the vibrational state instead of population inversion ratio [1]. In DRFA assisted links, ASE is generated and amplified in the fibre bi-directionally. The backward propagating ASE affects OSNR only when it is double backscattered. This effect on OSNR is negligible. Also the backward propagating ASE has negligible impact on power consumption of DRFA [1]. Therefore we will not consider backward ASE.

Another important source of noise in DRFA is Double Rayleigh Back Scattering (DBS). DBS may also be referred as multiple-path interference. Rayleigh Back Scattering (RBS) occurs in all fibers. Although most of the RBS escapes through the cladding, a part of RBS can couple into the core mode. In a DRFA, when a portion of coupled RBS is backscattered again and travels with signal, it will pass through the distributed amplifier twice. Therefore it can experience significant gain and appear as a noise at the receiver [1]. An optical isolator is usually placed at the middle of a span to stop the build up of back scattering in order to reduce the rate of growth of DBS.

DRFA suffers NLI as well, especially at locations where pump power is injected. The high optical field strength at the site of injection leads to high NLI. The main NLIs involved are pump-pump four wave mixing (FWM), pump-signal FWM, polarization dependent gain (PDG), noise transfer from pumps to signals or transfer of relative intensity noise (RIN), and pump-mediated signal crosstalk (XGM) [15].

NLI in a well designed DRFA assisted link is negligible [15]. The wavelengths that are affected by FWM are determined by a combination of fibre type and channel wavelengths [15]. In a DRFA assisted fibre link composed of standard SMF, FWM does not affect C and L bands. Polarization-multiplexing can be used to reduce PDG significantly. RIN is no longer an important issue in current systems as low noise pumps are available for DRFA [15, 35]. Finally XGM is much smaller than ASE when signal transmission power is smaller than -8 dBm [1]. Therefore, if a DRFA assisted fibre link is composed of standard SMF and the signal transmission power is less than -8 dBm, the NLI will be negligible. When signal transmission power is greater than -8 dBm, we can not neglect NLI in DRFA assisted links. Due to time constraints, in this work we have not constructed a simulator that includes NLI for DRFA assisted links. Therefore we will not consider signal transmission powers greater than -8dBm in DRFA assisted links.

2.3.6 Power Consumption and Efficiency of DRFA

Numerical Model of DRFA

The steady state behavior of DRFA can be described by a set of ordinary differential equations [1]. The simplest DRFA consists one co-pump and one counter-pump with pump power P_p^+ and P_p^- respectively at each end of the span. Two ordinary differential equations are used [1] to describe the behavior of signal and pump power in the fibre:

$$\frac{dP_{\mathrm{Tx}}}{dz} = -\alpha_{\mathrm{s}} P_{\mathrm{Tx}} + g_{\mathrm{R}}\left(\lambda_{\mathrm{s}} - \lambda_{\mathrm{p,R}}\right)\left(P_{\mathrm{p}}^{+} + P_{\mathrm{p}}^{-}\right) P_{\mathrm{Tx}} \tag{2.12}$$

$$\pm\frac{dP_{\mathrm{p}}^{\pm}}{dz} = -\,\alpha_{\mathrm{p,R}} P_{\mathrm{p}}^{\pm} - \left(\frac{\lambda_{\mathrm{s}}}{\lambda_{\mathrm{p,R}}}\right) g_{\mathrm{R}}\left(\lambda_{\mathrm{s}} - \lambda_{\mathrm{p,R}}\right) P_{\mathrm{Tx}} P_{\mathrm{p}}^{\pm} \tag{2.13}$$

where α_{s} is fibre loss coefficient at the signal wavelength, $\alpha_{\mathrm{p,R}}$ is fibre loss coefficient at the pump wavelength, $g_{\mathrm{R}}\left(\lambda_{\mathrm{s}} - \lambda_{\mathrm{p,R}}\right)$ is the Raman gain coefficient which is a function of wavelength separation $(\lambda_{\mathrm{s}} - \lambda_{\mathrm{p,R}})$ between the pump and signal wavelength, The value of $g_{\mathrm{R}}\left(\lambda_{\mathrm{s}} - \lambda_{\mathrm{p,R}}\right)$ can be found from Figure 2.4 or [1,15,36], and P_{Tx} is signal power in the DRFA. These differential equations do not have an analytical solution. A small signal solution does exist but we are considering multiple channels which violates the small signal assumption. Therefore we use a numerical solution of (2.12) and (2.13).

Raman gain comes from the transfer of power from an optical pump laser generating light at a shorter wavelength than the signal. The Raman gain depends primarily on wavelength separation between pump and signal, $(\lambda_s - \lambda_p)$, rather than absolute wavelengths. Therefore the gain profile of DRFA is determined by the pump wavelengths and the interaction between the gain profiles arising from each of the pumps. It should also be noted that Raman gain is polarization dependent [15]. Pump and signal should be co-polarized to maximize gain. For broadband DRFAs, the pump power needs to be provided by multiple pumps at different wavelengths to provide gain flatness [1, 15, 36] (pump wavelengths are denoted by the set $\{\lambda_{\mathrm{p,R,mult}}\}$). A large number of ordinary differential equations, one at each pump and signal wavelength, will be required to describe a multi-pump Raman amplifier. In addition, pump-pump interaction will make this system of differential equations quite complicated because it must model the impact of pump power of shorter pump wavelengths provide pump power of longer pump wavelengths in the optical fibre due to Raman scattering between pumps. In a broadband DRFA (2.13) is replaced by:

$$\begin{aligned} \pm\frac{dP_{\mathrm{p}}^{\pm}(\lambda_1)}{dz} &= -\alpha_{\mathrm{p,R}}P_{\mathrm{p}}^{\pm}(\lambda_1) \\ &+ \sum_{\lambda_1>\lambda_2} g_{\mathrm{R}}(\lambda_1-\lambda_2)\,P_{\mathrm{p}}^{\pm}(\lambda_1)P_{\mathrm{p}}^{\pm}(\lambda_2) \\ &- \sum_{\lambda_1<\lambda_2}\left(\frac{\lambda_2}{\lambda_1}\right) g_{\mathrm{R}}(\lambda_2-\lambda_1)\,P_{\mathrm{p}}^{\pm}(\lambda_1)P_{\mathrm{p}}^{\pm}(\lambda_2) \\ &- \sum_{\lambda_{\mathrm{s}}}\left(\frac{\lambda_{\mathrm{s}}}{\lambda_1}\right) g_{\mathrm{R}}(\lambda_{\mathrm{s}}-\lambda_1)\,P_{\mathrm{Tx}}(\lambda_{\mathrm{s}})P_{p}^{\pm}(\lambda_1) \end{aligned} \tag{2.14}$$

where λ_1 refers to the pump wavelength that is under consideration and $\lambda_1, \lambda_2 \in \{\lambda_{\mathrm{p,R,mult}}\}$. The summation over all pump and signal wavelengths is required since every pump interacts with all other pump and signal wavelengths, and optical power is converted from shorter wavelength to longer wavelengths. The term $\alpha_{\mathrm{p,R}}P_{\mathrm{p}}^{\pm}(\lambda_1)$ refers to the power attenuation due to fibre loss. The term $\sum_{\lambda_1>\lambda_2} g_{\mathrm{R}}(\lambda_1-\lambda_2)\,P_{\mathrm{p}}^{\pm}(\lambda_1)P_{\mathrm{p}}^{\pm}(\lambda_2)$ refers to pump power converted from pump power of shorter wavelengths while the term $\sum_{\lambda_1<\lambda_2}\left(\frac{\lambda_2}{\lambda_1}\right) g_{\mathrm{R}}(\lambda_2-\lambda_1)\,P_{\mathrm{p}}^{\pm}(\lambda_1)P_{\mathrm{p}}^{\pm}(\lambda_2)$ refers to pump power converted to longer wavelengths. Power conversion represented by these terms does not involve power loss but they are an important part of gain flatness. The term $\sum_{\lambda_{\mathrm{s}}}\left(\frac{\lambda_{\mathrm{s}}}{\lambda_1}\right) g_{\mathrm{R}}(\lambda_{\mathrm{s}}-\lambda_1)\,P_{\mathrm{Tx}}(\lambda_{\mathrm{s}})P_{p}^{\pm}(\lambda_1)$ refers to pump power converted to signal wavelengths and represents the signal amplification process.

The noise power of forward ASE noise $P_{\mathrm{ASE,R}}$, back scattering P_{BS} and DBS P_{DBS} can be modeled by:

$$\begin{aligned} \frac{dP_{\mathrm{ASE,R}}}{dz} =& -\alpha_s P_{\mathrm{ASE,R}} + g_{\mathrm{R}}(\lambda_{\mathrm{s}}-\lambda_{\mathrm{p,R}})\left(P_{\mathrm{p}}^{+}+P_{\mathrm{p}}^{-}\right)P_{\mathrm{ASE,R}} \\ &+ hfn_{\mathrm{sp,R}}g_{\mathrm{R}}(\lambda_{\mathrm{s}}-\lambda_{\mathrm{p,R}})\left(P_{\mathrm{p}}^{+}+P_{\mathrm{p}}^{-}\right)B_{\mathrm{o}} \end{aligned} \tag{2.15}$$

$$\begin{aligned} -\frac{dP_{\mathrm{BS}}}{dz} =& -\alpha_{\mathrm{s}}P_{\mathrm{BS}} + \frac{\lambda_{\mathrm{s}}}{\lambda_{\mathrm{p,R}}}g_{\mathrm{R}}(\lambda_{\mathrm{s}}-\lambda_{\mathrm{p,R}})\left(P_{\mathrm{p}}^{+}+P_{\mathrm{p}}^{-}\right)P_{\mathrm{BS}} \\ &+ f_{\mathrm{R}}\left(P_{\mathrm{Tx}}-P_{\mathrm{DBS}}\right) \end{aligned} \tag{2.16}$$

$$\begin{aligned} \frac{dP_{\mathrm{DBS}}}{dz} =& -\alpha_{\mathrm{s}}P_{\mathrm{DBS}} + \frac{\lambda_{\mathrm{s}}}{\lambda_{\mathrm{p,R}}}g_{\mathrm{R}}(\lambda_{\mathrm{s}}-\lambda_{\mathrm{p,R}})\left(P_{\mathrm{p}}^{+}+P_{\mathrm{p}}^{-}\right)P_{\mathrm{DBS}} \\ &+ f_{\mathrm{R}}P_{\mathrm{BS}} \end{aligned} \tag{2.17}$$

where $n_{\mathrm{sp,R}} = (1-\exp(-h \mid f-\mu \mid)/k_{\mathrm{B}}T)^{-1}$, T is temperature, k_{B} is Boltzmann constant, f and μ are frequencies of signal and pump respectively, and f_{R} is the fraction of DBS that travels with the signal [1].

In order to reduce the build up of back scattering, optical isolators are usually placed in the middle of DRFA spans to filter out the back scattering. Therefore when simulating (2.16), the value of P_{BS} at the middle of spans is zero.

In order to determine the pump power required and signal quality in broadband DRFA, the numerical model of DRFA is constructed from (2.12), (2.14), (2.15), (2.16) and (2.17) at all pump and signal frequencies. These ordinary differential equations are solved numerically to obtain pump power, ASE noise power and DBS noise power. Power consumption of DRFA is a function of the sum of power of all pumps in the fibre span.

Small signal approximation

When the signal power is small, an analytical approxmation [1, 15]of pump power consumption P_p can be derived from (2.13) and (2.12):

$$P_{\mathrm{p}} = \frac{\ln G + \alpha_{\mathrm{s}} L}{g_{\mathrm{R}} \left(\lambda_{\mathrm{s}} - \lambda_{\mathrm{p,R}}\right) L_{\mathrm{eff,R}}} \tag{2.18}$$

where $L_{\mathrm{eff,R}} = \left(1 - \exp\left(-\alpha_p L\right)\right) / \alpha_p$ is the effective length of Raman gain fibre. However this approximation is only valid when signal transmission power is very small (i.e. $P_{\mathrm{Tx}} << \alpha_p / g_R$). The assumption of small signal is violated in a high-speed broadband fibre link which has multiple channels and high signal power per channel. However, the value of P_p from (2.18) is a good indicator for numerical solutions.

Extremum Seeking Control (ESC) model

Existing numerical models primarily focus on the control aspect in order to achieve gain flatness over a large bandwidth rather than power consumption or energy efficiency of DRFA [37–39]. The algorithms in these models are developed to determine the wavelengths and optical power requirement of pumps in a DRFA to provide flat gain. Among these numerical models, we will consider the ESC model developed in [36].

[36] applies the general extremum seeking framwork to regulate signal power in cascaded DRFA by solving finite difference-based partial differential equations. The simulation results have shown that 2 co-pumps and 2-counter pumps are sufficient to provide flat gain over C-band (1530-1565 nm). These results indicates we can place 2 co-pumps at 1438 nm and 1465 nm and 2 counter-pumps at 1425 nm and 1456 nm to achieve gain flatness overall C-band so that the differences in output signal power among signal channels are less than 0.2 dBm.

2.3.7 Comparison of EDFA and DRFA

Long before the invention of EDFA, DRFA was investigated for use in optical communications starting early in the 1970s [15]. Raman gain requires large pump power placed at appropriate wavelengths. In the early 1990s, as EDFA was so successful in optical fibre link design and deployment that research on Raman amplifier subsided until late 1990s [15]. As discussed earlier, EDFA is a low-cost, high-gain and low-noise amplifier, and it has been implemented in commercial and industrial systems. However, bandwidth demand is growing dramatically and long-haul transmission is a key technology for transporting this traffic across the network. Thus together with recent breakthrough in high-output, low-noise pumps, interest in DRFA has resurged.

It is widely accepted that EDFA consumes less power while DRFA gives better signal quality and wider bandwidth [35]. Table 2.3 lists the common differences between EDFA and DRFA that affect power consumption. There are a few other differences that are not directly related to power consumption: (i) the gain transience with burst traffic of DRFA is negligible compared to EDFA. (ii) pumps of DRFA are less reliable, more hazardous, more noisy and more expensive. (iii) DRFA is a cheap option to upgrade existing optical fibre links as it does not require special gain medium.

Table 2.3: Comparison of EDFA and DRFA assisted fibre link. Typical values are listed in the table.

	EDFA	DRFA
Channel wavelengths	C band: 1530-1565 nm L band: 1565-1610 nm	arbitrary any wavelength (providing a pump is available)
Pump power consumption	10 mW or higher	up to 1000 mW
Pump wavelength	980 nm, 1480 nm	13 THz upshifted from channel frequency or 100 nm downshifted from channel wavelength
Output signal power	-20 dBm to 3 dBm	usually up to -10 dBm
Gain	up to 50 dB	usually no more than 25 dB
Gain medium	require special doped fibre as gain medium	most fibre
Length of gain fibre	80-200 m	20-30 km
Noise	higher	lower
Noise type	ASE	ASE, DBS
NLI	Not negligible if signal output power is high	negligible if DRFA is well-designed
Model type (in this thesis)	analytical	Numerical

2.4 Signal Quality Measurement and Modulation Format

The optical signal-to-noise ratio (OSNR) is an indicator of signal quality in an optical fibre link and can be used to predict the BER [14]. It is the ratio between signal power

P_{sig} and noise power P_{noise} in a given measurement bandwidth:

$$\text{OSNR} = \frac{P_{\text{sig}}}{P_{\text{noise}}} \tag{2.19}$$

In a long-haul broadband EDFA assisted optical fibre link the OSNR is limited by ASE and NLI as discussed previously. At low signal power, system performance is limited by ASE noise power reaching receiver within channel bandwidth $P_{\text{ASE,E}}$, while at high signal power, system performance is limited by P_{NLI}, the equivalent Gaussian noise power of NLI [30]. OSNR of EDFA assisted optical link can be calculated by [30]:

$$\text{OSNR}_{\text{E}} = \frac{P_{\text{sig}}}{P_{\text{ASE,E}} + P_{\text{NLI}}} \tag{2.20}$$

In a DRFA assisted optical fibre link, we can neglect NLI because signal transmission power is usually -10 dBm or smaller. Therefore the OSNR is mainly limited by linear noises, which are ASE and DBS. Thus OSNR of DRFA assisted link is calculated by [1]:

$$\text{OSNR}_{\text{R}} = \frac{P_{\text{sig}}}{P_{\text{ASE,R}} + P_{\text{DBS}}} \tag{2.21}$$

BER is the ratio of error bits to total bits over an extended duration of time $T >> T_{\text{bit}}$ where T_{bit} is the data bit period [14]. Its value is mainly impacted by transmission channel noise, interference, distortion, .etc. We can calculate BER from received OSNR. Because information is encoded and decoded differently when using different modulation formats, the relationship between OSNR and resulting BER depends upon the modulation format. Table 2.4 lists the relationships for a range of modulation formats. IMDD is a mature format that has been widely used over many years. QPSK is the most popular modulation format nowadays and many commercial optical communication networks employ QPSK. Many systems using QPSK have been upgraded to DP-QPSK to increase information rate by employing polarization. DP-16QAM is believed to be the modulation format of next generation networks.

Figure 2.5 displays the relationship between OSNR per bit and BER for different modulation formats. It can be seen that the higher order modulation formats have a higher BER for a given OSNR. For example, when soft-decision FEC is implemented, the optical fibre link can tolerate a BER up to 10^{-2} before error correction. At this BER, if IMDD is used, OSNR needs to be 7 dB, while if DP-16QAM is used, OSNR needs to be 19 dB. As a result of this OSNR difference, a transmission system using IMDD can have a extra 12 dB power margin compared to a system using DP-16QAM. This power margin can enable a smaller signal transmission power hence less power consumption of optical amplifiers, or it can be used to extend link length. In other words, advanced modulation format is more energy consuming. However, advanced modulation formats are needed if we want to increase data rate without increasing bandwidth. Thus the choice of modulation format is multifaceted.

It should be noted that OSNR of an optical fibre link suffers penalties from connector loss, ageing loss, etc. We will allocate a 2 dB OSNR penalty to account for these factors. Also advanced modulation formats such as DP-16QAM suffers an additional OSNR penalty related to high crosstalk and inter-symbol interference when channel bandwidth is limited [29,30]. International Telecommunication Union (ITU) wavelength grid divides C-band into fixed 50 GHz spectrum slots [40]. At this channel bandwidth, this penalty is about 2 dB for DP-QPSK and DP-16QAM at about 30 Gbaud baud rate [29].

Apart from OSNR, we will use two more methods to measure signal quality. They are the Q factor and Eye Closure Penalty (ECP) [41,42]. They are defined as:

$$\mathrm{Q} = \frac{\Delta P_{\mathrm{r}}}{\Delta \sigma_{\mathrm{r}}} = \frac{P_{1,\mathrm{r}} - P_{0,\mathrm{r}}}{\sigma_{1,\mathrm{r}} + \sigma_{0,\mathrm{r}}} \tag{2.22}$$

$$\mathrm{ECP} = \frac{\Delta P_{\mathrm{t}} - \Delta \sigma_{\mathrm{t}}}{\Delta P_{\mathrm{r}} - \Delta \sigma_{\mathrm{r}}} \tag{2.23}$$

where $\Delta P_{\mathrm{X}} = P_{1,\mathrm{X}} - P_{0,\mathrm{X}}$ represents difference between the average signal levels for a received "1" and received "0" at the receiver, and $\Delta\sigma = \sigma_{1,\mathrm{X}} + \sigma_{0,\mathrm{X}}$ represents noise which reduces the difference between the signal levels for a received "1" and received "0" with $P_{1,\mathrm{X}}$, $P_{0,\mathrm{X}}$, $\sigma_{1,\mathrm{X}}$ and $\sigma_{0,\mathrm{X}}$ the mean and standard deviation of power of symbol '1' and '0' respectively at the signal receiver located at the transmit node (X=T) and receiver node (X=R). At the transmitter side, we can assume the signal noise is negligible hence $\Delta P_{\mathrm{t}} >> \Delta\sigma_{\mathrm{t}}$, and we assume the transmission system fully compensates for signal loss so that received signal power equals launched signal power $\Delta P = \Delta P_{\mathrm{t}} = \Delta P_{\mathrm{r}}$:

$$\mathrm{ECP} = \frac{\Delta P}{\Delta P - \sigma_{1,\mathrm{R}} - \sigma_{0,\mathrm{R}}} \tag{2.24}$$

Table 2.4: The relationship between OSNR and resulting BER

Modulation Format	Relationship
IMDD	$\mathrm{BER} \approx \frac{1}{2}\mathrm{erfc}\left(\sqrt{\mathrm{OSNR}\frac{2B_o}{R_b}}\right)$
QPSK	$\mathrm{BER} \approx \frac{1}{2}\mathrm{erfc}\left(\sqrt{\mathrm{OSNR}\frac{B_o}{R_b}}\right)$
DP-QPSK	$\mathrm{BER} \approx \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\mathrm{OSNR}}{2}\frac{B_o}{R_b}}\right)$
DP-16QAM	$\mathrm{BER} \approx \frac{3}{8}\mathrm{erfc}\left(\sqrt{\frac{\mathrm{OSNR}}{10}\frac{B_o}{R_b}}\right)$

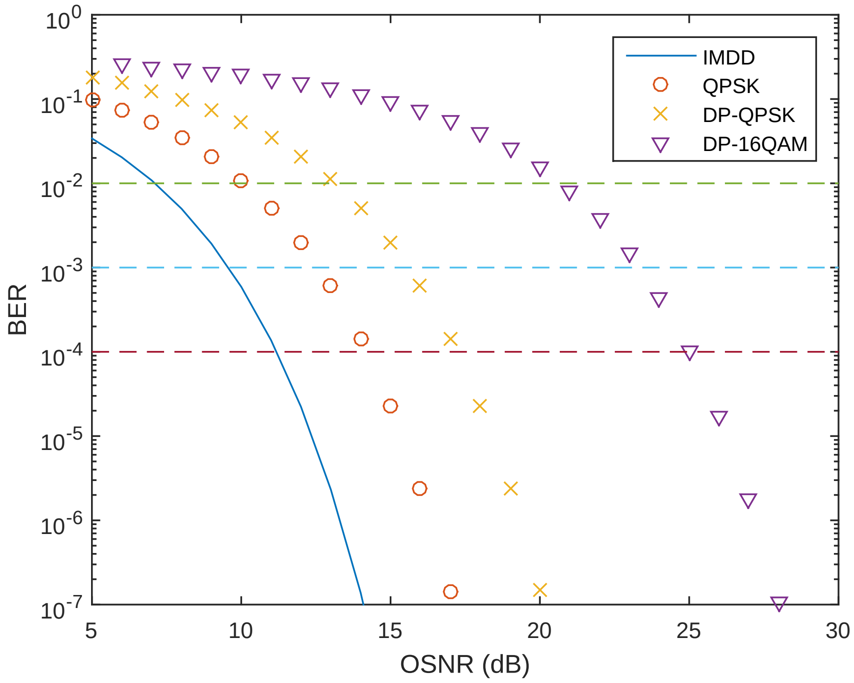

Figure 2.5: OSNR vs. BER for different modulation formats. The horizontal dashed lines correspond to the pre-FEC BER limits of the three FEC schemes (Table 2.2).

Chapter 3

Power Consumption of Optical Amplifier

3.1 Power Consumption of EDFA

3.1.1 EDFA Power Consumption Model

In order to estimate the theoretical lower limit of EDFA power consumption, we need to find the theoretical limit of the power consumption of the laser diode pump used in optical amplifier because laser diode pumps are the active part of optical amplifiers. In optical fibre links, EDFA laser diode pumps operate in steady state and so their behaviour is described by the steady state equations [19]:

$$0 = \frac{qi}{eV} - G_{\mathrm{N}}(N - N_{\mathrm{t}})S - \frac{N}{\tau} \tag{3.1}$$

$$0 = (\Gamma G_{\mathrm{N}}(N - N_{\mathrm{t}}) - \Gamma_0)\, S + \frac{\gamma N}{\tau} \tag{3.2}$$

where q is the laser injection quantum efficiency, i is the drive current, e is electronic charge, V the active region volume, G_{N} the differential gain ($\delta G/\delta N$), N is the conduction band electron density in the active region, N_{t} is the threshold electron density, S is the photon density in the active region, τ is the electron spontaneous lifetime, Γ is confinement factor, Γ_0 is the cavity loss, γ is the spontaneous emission factor. The relationship between photon density S and output power is [43]:

$$P_{\mathrm{LD,out}} = S\frac{hfcA}{n}\,(1 - R_1) \tag{3.3}$$

Where A is the active region cross-sectional area of the laser diode, R_1 is the end-facet reflectivity of the diode, n is the refractive index of the active region and c the speed of light. By solving these three equations at the lasing threshold (A detailed derivation is given in [43]), we can obtain an equation of electrical power consumption of laser diode pump:

$$P_{\mathrm{elec}} = \frac{P_{\mathrm{p}}}{\eta_{\mathrm{PCE}}} + P_{\mathrm{t}} \tag{3.4}$$

$$\eta_{\text{PCE}} = \frac{2q_e\lambda_p\Gamma(1-R_1)}{\lambda_s \ln\left(\frac{1}{R_1R_2}\right)} \tag{3.5}$$

where P_{elec} is electrical power consumption of laser diode pump, P_p is the minimum pump laser output optical power required to provide the target EDFA signal gain, P_t is the input electrical power required to provide threshold current in a laser diode pump, and R_1 and R_2 are end-facet reflectivity of the pump lasers. By applying typical values of laser diode pump [19], $\eta_{\text{PCE}} \approx 0.4$ for 980 nm pumps used by EDFAs, and $\eta_{\text{PCE}} \approx 0.6$ for pumps of about 1450 nm used by DRFAs. The value of η_{PCE} for pumps of commercialized EDFAs is typically only 0.01 because of the additional power consumption of monitoring and control circuits in the EDFA. However, as we are focusing on the lower limit of power consumption, we will not consider the energy consumed by the monitoring and control circuits.

The optical power emitted by an EDFA consists of two components: The output signal power and the ASE generated by the EDFA. The EDFA also has an input optical power corresponding to the input optical signal. Therefore the total optical power emanating from an EDFA is given by:

$$P_{\text{p,EDFA}} = N_{\text{ch}}\left(P_{\text{sig,out}} - P_{\text{sig,in}}\right) + P_{\text{ASE}} \tag{3.6}$$

Where N_{ch} is the number of signal channels propagating through the EDFA. In a chain of amplifiers, the input power $P_{\text{sig,in}}$ is composed of signal power plus accumulated ASE power produced by previous amplifiers in the link. Both the signal and accumulated ASE are subject to fibre loss. We assume the gain G of each EDFA is the same as fibre attenuation of fibre span immediately before it because we are fully compensating fibre losses to maintain signal transmission power ($P_{\text{sig,out}} = P_{\text{Tx}}$). The ASE generation can be described by (2.7). Thus the minimum optical power emanating of m-th EDFA in a chain of amplifiers is:

$$P_{\text{p,EDFA,m}} = \frac{N_{\text{ch}}}{G}(G-1)\left(P_{\text{Tx}} + (m-1)hfn_{\text{sp}}(G-1)B_o\right) + 2hfn_{\text{sp}}(G-1)\Delta f \tag{3.7}$$

where Δf is the whole gain bandwidth of EDFA. This is because ASE is generated over the whole gain bandwidth not just the optical signal bandwidth B_o. The G in the denominator of (3.7) represents the fibre loss of the link immediately preceding the EDFA because we have set the EDFA gain equal to the fibre loss. A factor of 2 is used because ASE is generated bi-directionally. Usually the gain, G, is much larger than 1, thus:

$$P_{\text{p,EDFA,m}} = N_{\text{ch}}P_{\text{Tx}} + N_{\text{ch}}(m-1)hfn_{sp}GB_o + 2hfn_{sp}G\Delta f \tag{3.8}$$

The total optical power consumption of a fibre link composed of N_{span} equally spaced EDFAs is:

$$\begin{aligned} P_{\text{opt,EDFA,link}} &\approx \sum_{m=1}^{N_{\text{span}}} P_{\text{p,EDFA,m}} \\ &= N_{\text{span}}N_{\text{ch}}P_{\text{Tx}} + \frac{(N_{\text{span}}-1)N_{\text{span}}}{2}N_{\text{ch}}hfn_{\text{sp}}GB_o + 2N_{\text{span}}hfn_{\text{sp}}G\Delta f \\ &= N_{\text{span}}\left(N_{\text{ch}}P_{\text{Tx}} + hfn_{\text{sp}}GB_o\left(\frac{N_{\text{span}}-1}{2}N_{\text{ch}} + 2\frac{\Delta f}{B_o}\right)\right) \end{aligned} \tag{3.9}$$

By combining (3.4), (3.5) and (3.9), we can obtain the total electrical power consumption $P_{\mathrm{EDFA,link}}$ of all EDFAs in an optical fibre link:

$$P_{\mathrm{EDFA,link}} = N_{\mathrm{span}}\left(N_{\mathrm{ch}}P_{\mathrm{Tx}} + hfn_{\mathrm{sp}}GB_{\mathrm{o}}\left(\frac{N_{\mathrm{span}}-1}{2}N_{\mathrm{ch}} + 2\frac{\Delta f}{B_{\mathrm{o}}}\right)\right)\frac{\lambda_{\mathrm{s}}\ln\left(\frac{1}{R_1R_2}\right)}{2q_{\mathrm{e}}\lambda_{\mathrm{p}}\Gamma\left(1-R_1\right)} + N_{\mathrm{span}}N_{\mathrm{pump}}P_{\mathrm{t}} \tag{3.10}$$

Where N_{pump} is the number of pumps per amplifier. (3.10) indicates that for a given link design, signal transmission power P_{Tx} determines lower limit of EDFAs' power consumption. Under these circumstances in order to minimize power consumption of EDFAs, we therefore need to minimize signal transmission power. Thus we want to examine the relationship between OSNR and signal transmission power. From (2.20), this relationship is:

$$\mathrm{OSNR} = \frac{P_{\mathrm{Tx}}}{P_{\mathrm{ASE}} + P_{\mathrm{NLI}}} \tag{3.11}$$

where P_{ASE} and P_{NLI} can be calculated from (2.7) and (2.8) respectively. Figure 3.1 is plotted from (3.11) to display the relationship between signal power and OSNR. The results plotted in Figure 3.1 are for a span length of 100 km. The value of parameters used are listed in appendix. It shows for this optical link configuration, when signal transmission power is less than -4 dBm, the NLI is negligible and OSNR is limited by ASE. Figure 3.1 also shows that for this link configuration, the highest OSNR occurs at a signal transmission power of -1 dBm. Although Figure 3.1 is plotted for a link of 1000 km, the results about signal transmission power and OSNR can be applied in links of other link lengths as long as span length is 100 km [32]. Therefore for a fibre link composed of 100 km spans, if we are targeting the best signal quality or maximum link length, we should use a signal transmission power of -1 dBm.

In the situation where the NLI is negligible relative to the ASE (such as the link configuration used for Figure 3.1 with $P_{\mathrm{Tx}} <$ -4 dBm), we can ignore the NLI and the signal transmission power required for a target OSNR will be determined by ASE power alone, giving:

$$\mathrm{OSNR} = \frac{P_{\mathrm{Tx}}}{N_{\mathrm{span}}n_{\mathrm{sp}}hf(G-1)B_{\mathrm{o}}} \tag{3.12}$$

Substitute P_{Tx} to (3.10):

$$P_{\mathrm{EDFA,link}} = N_{\mathrm{span}}hfn_{\mathrm{sp}}GB_{\mathrm{o}}\left(N_{\mathrm{ch}}N_{\mathrm{span}}\mathrm{OSNR} + \frac{N_{\mathrm{span}}-1}{2}N_{\mathrm{ch}} + 2\frac{\Delta f}{B_{\mathrm{o}}}\right)\frac{\lambda_{\mathrm{s}}\ln\left(\frac{1}{R_1R_2}\right)}{2q_{\mathrm{e}}\lambda_{\mathrm{p}}\Gamma\left(1-R_1\right)} + N_{\mathrm{span}}N_{\mathrm{pump}}P_{\mathrm{t}} \tag{3.13}$$

Equation (3.13) indicates the lower limit of power consumption of EDFAs is determined by configuration and OSNR requirement of optical fibre link. Note that in deriving (3.13) the noise power (P_{ASE}) is independent of signal power giving a result that enables

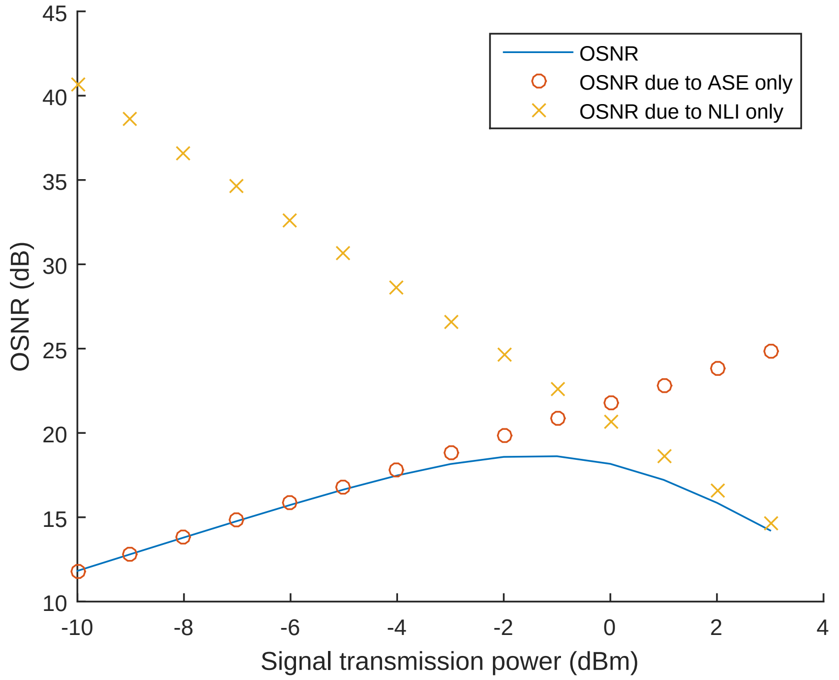

Figure 3.1: Signal transmission power vs. OSNR for 100 km span length and parameter values listed in the appendix. The link length is 1000 km.

the EDFA link power to be expressed in terms of the required OSNR. In contrast, for an optical link in which both the ASE and NLI contributions to noise must be considered, we use (2.7) and (2.8) in (3.11). In this case, because the NLI noise power is dependent upon the cube of the signal power, outcome is a cubic equation in the transmit power, P_{Tx}:

$$\begin{aligned}&\left(\left(\frac{2}{3}\right)^3 N_{\text{span}}\gamma^2 L_{\text{eff}}\frac{\log\left(\pi^2|\beta_2|L_{\text{eff}}N_{\text{channel}}^2R_{\text{b}}^2\right)}{\pi|\beta_2|R_{\text{b}}^3}B_{\text{o}}\text{OSNR}\right)P_{\text{Tx}}^3\\&-P_{\text{Tx}}\\&+N_{\text{span}}hfn_{\text{sp}}(G-1)B_{\text{o}}\text{OSNR}\\&=0\end{aligned} \tag{3.14}$$

Apply the standard root equation of cubic function, the positive real root of this equation is the minimum signal transmission power which will achieve required OSNR in the presence of NLI. If such a positive real root does not exist, it means no signal transmission power can satisfy required OSNR and the link length can not be achieved. We note that in the limit of small P_{Tx}, (3.14) reduces to (3.12) which corresponds to the regime $P_{\text{NLI}} << P_{\text{ASE}}$. For the link parameters listed in the Appendix and span length of 100 km, the regime $P_{\text{NLI}} << P_{\text{ASE}}$ requires $P_{\text{Tx}} \leq -4$ dBm.

The required OSNR for links using different FEC and modulation format can be calculated using the data in Table 2.2 and the equations in Table 2.4. The resulting required OSNR values are listed in Table 3.3. Using these values in (3.14), we can determine the minimum signal transmission power as a function of total link length

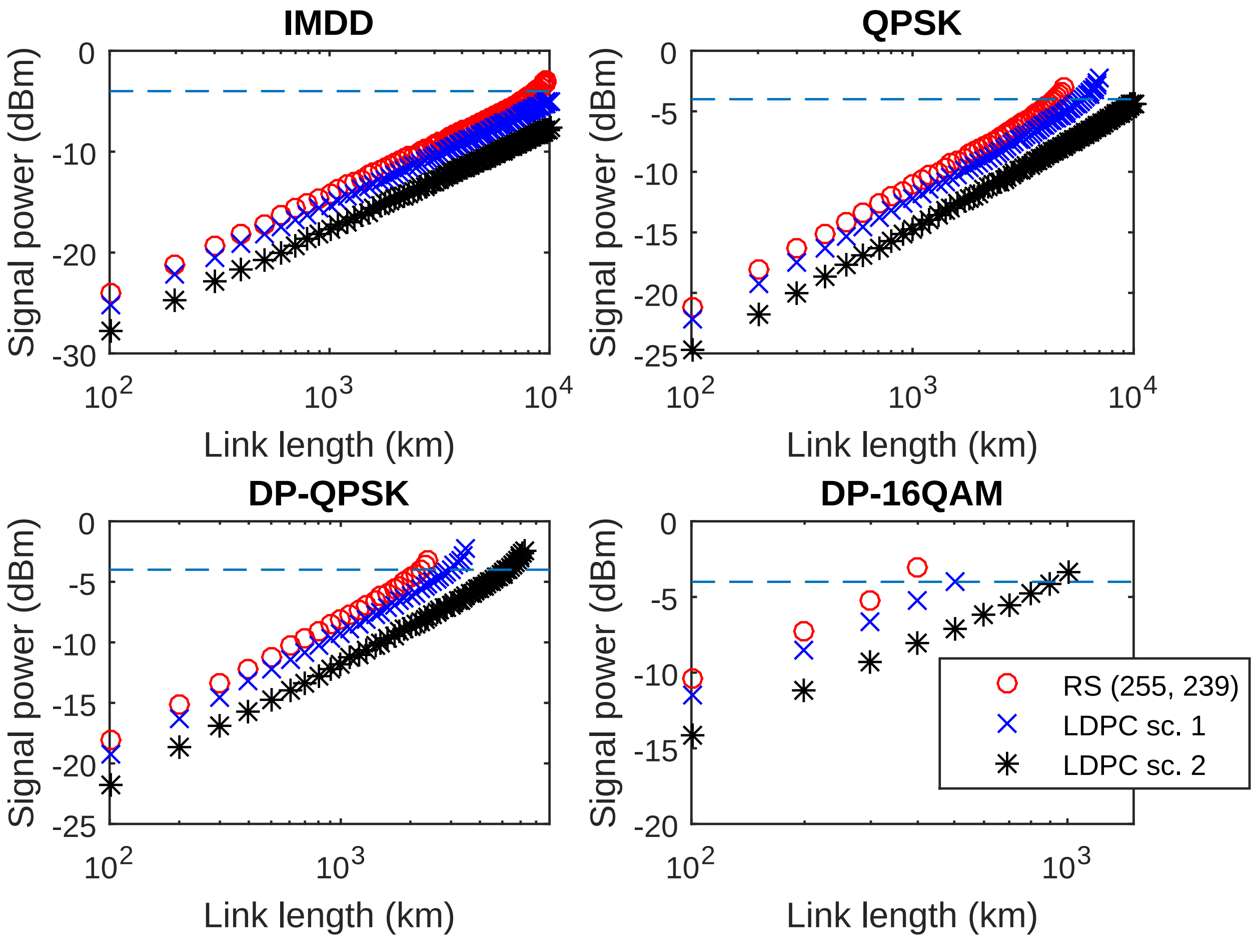

Figure 3.2: Link length (km) vs. Signal transmission power (dBm) for links using different modulation format and FEC. The dashed lines indicate signal power of -4 dBm.

using multiple 100 km spans. The results are presented in Figure 3.2. When the NLI is negligible relative to the ASE, we can use (3.13) to calculate EDFAs' power consumption in an optical fibre link.

Table 3.1 lists the threshold link length and maximum link length. For distances less than the threshold link length, the signal transmission power is less than -4 dBm, hence $P_{\mathrm{NLI}} << P_{\mathrm{ASE}}$ and (3.13) is used to calculate EDFAs' power consumption. Between threshold link length and maximum link length, P_{NLI} cannot be ignored relative to P_{ASE} and (3.10) is used to calculate EDFAs' power consumption. When the link length is larger than maximum link length, we cannot achieve required OSNR to maintain the target Pre-FEC BER (10^{-2}) and the transmission link is considered to be non-compliant with the BER requirements. Because the trans-pacific distance is 12000 km, we will not consider optical links longer than 12000 km.

Table 3.1: Threshold link length and maximum link length for links using different modulation format and FEC. Threshold link length is the maximum link length that can be achieved using -4 dBm signal transmission power. Maximum link length is achieved using -1 dBm signal transmission power. The unit of link length is km.

Modulation format	Link Length	RS (255, 239)	LDPC sc. 1	LDPC sc. 2
IMDD	Threshold	8700	11700	> 12000
	Maximum	9700	> 12000	> 12000
QPSK	Threshold	4400	5900	10500
	Maximum	4800	7000	> 12000
DP-QPSK	Threshold	2200	2900	5200
	Maximum	2400	3500	6200
DP-16QAM	Threshold	300	500	900
	Maximum	400	500	1000

3.1.2 Q Factor Based EDFA Power Consumption Model

Apart from OSNR, the Q factor Q is also a commonly used parameter to measure signal quality. In [43] an equivalent model to (3.10) was derived to calculate lower limit power consumption of EDFAs in a fibre link by using Q factor:

$$\begin{aligned} P_{\mathrm{EDFA,link}} =& N_{\mathrm{span}} N_{\mathrm{pump}} P_{\mathrm{t}} + N_{\mathrm{span}} \frac{n_{\mathrm{sp}} hf \left(G-1\right) B_{\mathrm{o}} \lambda_{\mathrm{s}} \ln\left(\frac{1}{R_1 R_2}\right)}{2 q_{\mathrm{e}} \Gamma \lambda_{\mathrm{p}} \left(1-R_1\right)} \times \\ & \left(\frac{N_{\mathrm{ch}} Q^2 \chi^2}{\left(Q - \left(Q-1\right) \prod_{\mathrm{p}} \mathrm{ECP}_{\mathrm{p}}\right)^2} + \frac{\left(N_{\mathrm{span}}+1\right) \Delta f}{B_{\mathrm{o}}} \right) \end{aligned} \tag{3.15}$$

where χ is degradation factor on signal quality due to modulation format and it is defined below, $\prod_{\mathrm{p}} \mathrm{ECP}_{\mathrm{P}}$ is eye closure penalty due to degradation factors other than ASE. We will focus on the ECP due to ASE and we will not consider degradation factors other than ASE in this model, thus we set $\prod_{\mathrm{p}} \mathrm{ECP} = 1$. The assumption $\prod_{\mathrm{p}} \mathrm{ECP} = 1$

indicates NLI is negligible and thus (3.15) can be used only when $P_{\text{NLI}} << P_{\text{ASE}}$. As discussed in Chapter 2.4, the ECP due to ASE is:

$$\text{ECP}_{\text{ASE}} = \frac{\Delta P}{\Delta P - \sigma_{1,\text{R}} - \sigma_{0,\text{R}}} \tag{3.16}$$

where $\sigma_{1,\text{R}}$ and $\sigma_{0,\text{R}}$ are standard deviation of ASE noise power of symbol '1' and '0' respectively. We now calculate an expression for ECP_{ASE} for several common modulation formats.

IMDD

For IMDD system, the power of symbol '1' is much greater than the power of symbol '0': $P_1 >> P_0$, thus $\Delta P \approx P_1$. Also the ECP is dominated by ASE power beating with the optical field on the receiver of the received symbols '1' [19]. The beating noise will give:

$$\sigma_{1,\text{R}} = \sqrt{4P_{\text{ASE}}P_1} \tag{3.17}$$

$$\sigma_{0,\text{R}} = \sqrt{4P_{\text{ASE}}P_0} \tag{3.18}$$

Thus we have:

$$\text{ECP}_{\text{ASE}} = \frac{\Delta P}{\Delta P - \sigma_{1,\text{R}} - \sigma_{0,\text{R}}} \approx \frac{P_1}{P_1 - \sqrt{4P_{\text{ASE}}P_1}(1+\sqrt{r})} = \frac{1}{1 - \chi \text{OSNR}^{-1/2}} \tag{3.19}$$

where $r = P_0/P_1$ is extinction ratio, and $\text{OSNR} = \frac{P_1}{P_{\text{ASE}}}$ because $P_0 \approx 0$ for IMDD. The χ factor refers to degradation on OSNR thus $\chi = 2/\left(1 - r^{1/2}\right)$. Also in the limit $P_0 \approx 0$ we get $r \approx 0$, $\chi \approx 2$.

QPSK

For QPSK system, we consider the use of a balanced coherent detector. Because information is encoded in phase by two orthogonal carriers (I and Q in Figure 3.3), all symbols will have the same power. Thus $P_1 = P_0 = P_{\text{Tx}}$. A local oscillator of power P_{LO} is beating with the signal power at the receiver for coherent detection thus in electrical domain the received signal is $P_1 = P_0 = \sqrt{2P_{\text{LO}}P_{\text{Tx}}}$ [18]. The receiver is designed to generate its output data stream from the beat component of the optical field incident on the detector. The resulting difference between symbol power in electrical domain is $\Delta P = 2\sqrt{2P_{\text{LO}}P_{\text{Tx}}}$. ASE is beating with signal and local oscillator power. Because $P_{\text{LO}} >> P_{\text{Tx}}$, we neglect beating noise between ASE and signal. Thus $\sigma_{1,\text{r}} = \sigma_{0,\text{r}} = \sqrt{4P_{\text{LO}}P_{\text{ASE}}}$. Therefore the ECP due to ASE in QPSK is:

$$\begin{aligned} \text{ECP}_{\text{ASE}} &= \frac{\Delta P}{\Delta P - \sigma_{1,\text{R}} - \sigma_{0,\text{R}}} \\ &= \frac{2\sqrt{2P_{\text{LO}}P_{\text{Tx}}}}{2\sqrt{2P_{\text{LO}}P_{\text{Tx}}} - 2\sqrt{4P_{\text{LO}}P_{\text{ASE}}}} \\ &= \frac{1}{1 - \chi \text{OSNR}^{-1/2}} \end{aligned} \tag{3.20}$$

where $\text{OSNR} = \frac{P_{\text{Tx}}}{P_{\text{ASE}}}$ and $\chi = \sqrt{2}$ for QPSK. For dual polarization modulation format DP-QPSK, $\chi = \sqrt{2}$ because transmitting across two polarizations does not affect symbol power or standard deviation of noise [14].

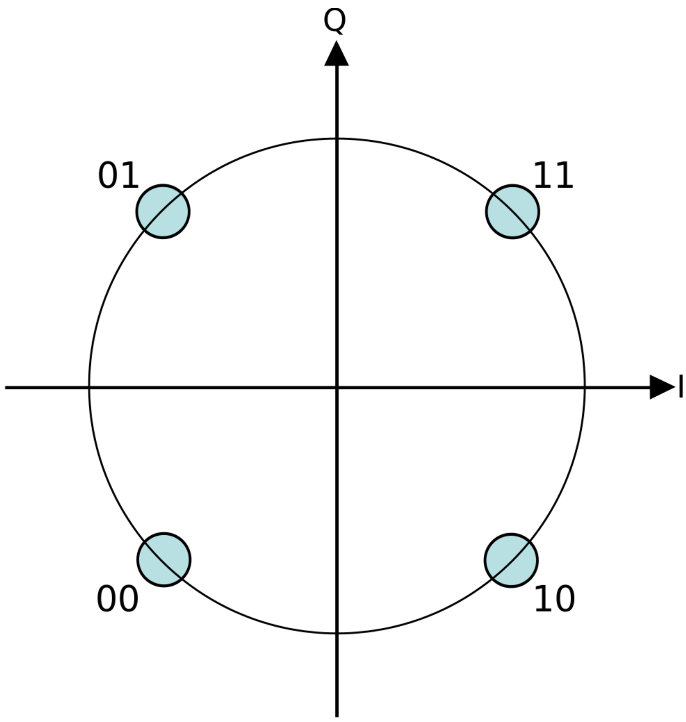

Figure 3.3: Constellation oF QPSK

16-QAM

16-QAM also employs two orthogonal carriers (I and Q in Figure 3.4). The signal transmission power is the average power of all symbols:

$$\frac{P_{0000} + P_{0001} + P_{0010} + ... + P_{1111}}{16} = P_{\text{Tx}} \tag{3.21}$$

If we consider only one carrier, the power of single carrier is half of signal transmission power [14]:

$$\frac{P_{00} + P_{01} + P_{10} + P_{11}}{4} = \frac{P_{\text{Tx}}}{2} \tag{3.22}$$

From the symmetry of symbols in constellation ($P_{00} = P_{10}$ and $P_{01} = P_{11}$) we have:

$$P_{10} + P_{11} = P_{\text{Tx}} \tag{3.23}$$

The constellation represents electric fields and power is proportional to square of electric field:

$$P_{10} : P_{11} = 9 : 1 \tag{3.24}$$

Combine (3.23), (3.26), we can find out:

$$P_{10} = \frac{9}{10} P_{\text{Tx}} \tag{3.25}$$

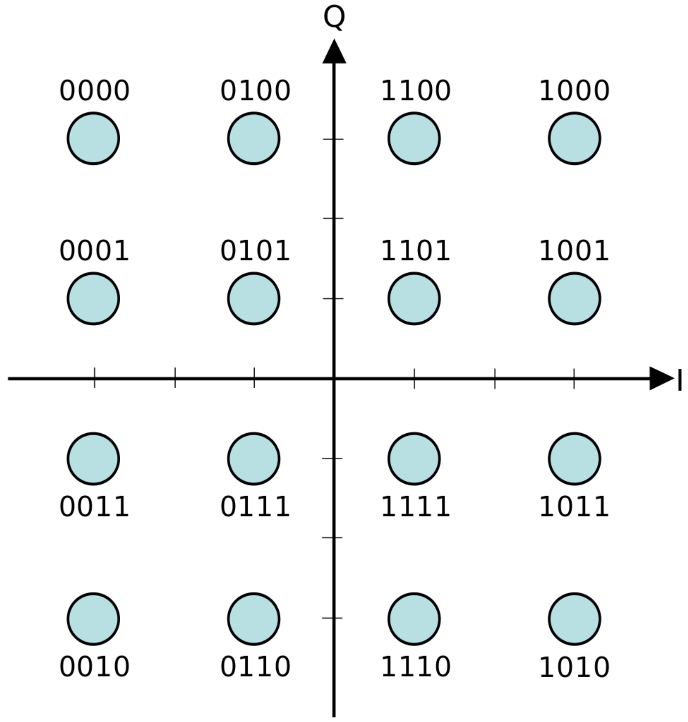

Figure 3.4: Constellation of 16-QAM

$$P_{11} = \frac{1}{10} P_{\mathrm{Tx}} \tag{3.26}$$

In 16-QAM system which employs coherent detection with local oscillator, the received symbols in electrical domain come from the beating between received optical power and local oscillator power, thus $P_{10} = \sqrt{2P_{\mathrm{LO}} \times \frac{9}{10} P_{\mathrm{Tx}}}$ and $P_{11} = \sqrt{2P_{\mathrm{LO}} \times \frac{1}{10} P_{\mathrm{Tx}}}$. Therefore the difference between decision points is:

$$\Delta P = P_{10} - P_{11} = 2\sqrt{\frac{1}{5} P_{\mathrm{LO}} P_{\mathrm{Tx}}} \tag{3.27}$$

The beat noise gives the same standard deviation of signal symbols as QPSK $\sigma_{1,\mathrm{r}} = \sigma_{0,\mathrm{r}} = \sqrt{4P_{\mathrm{LO}} P_{\mathrm{ASE}}}$ [14]. Therefore for 16-QAM, ECP can be calculated as:

$$\begin{aligned} \mathrm{ECP}_{\mathrm{ASE}} &= \frac{\Delta P}{\Delta P - \sigma_{1,\mathrm{R}} - \sigma_{0,\mathrm{R}}} \\ &= \frac{2\sqrt{\frac{1}{5} P_{\mathrm{LO}} P_{\mathrm{sig}}}}{2\sqrt{\frac{1}{5} P_{\mathrm{LO}} P_{\mathrm{sig}}} - 2\sqrt{4P_{\mathrm{LO}} P_{\mathrm{ASE}}}} \\ &= \frac{1}{1 - \chi \mathrm{OSNR}^{-1/2}} \end{aligned} \tag{3.28}$$

where $\mathrm{OSNR} = \frac{P_{\mathrm{Tx}}}{P_{\mathrm{ASE}}}$ and $\chi = \sqrt{20}$ for 16-QAM.

3.1.3 Simulation and Results of EDFA Model

We consider a high speed long distance optical fibre link. In this work, we use IMDD, QPSK, DP-QPSK and DP-16QAM as modulation formats across the complete C-band which has bandwidth of 4 THz [14]. The frequency grid (bandwidth per channel) defined by ITU Recommendation supports a variety of channel bandwidth ranging from 12.5 GHz to 100 GHz and wider (integer multiples of 100 GHz) [44]. Based on our information rate requirement, we use 80 channels spaced by 50 GHz. The information rate per channel is 25 Gbps, 50 Gbps, 100 Gbps and 200 Gbps for links using IMDD, QPSK, DP-QPSK and DP-16QAM respectively. And the total information rate R_{I} is 2 Tb/s, 4 Tb/s, 8 Tb/s and 16 Tb/s for links using IMDD, QPSK, DP-QPSK and DP-16QAM respectively. Note that the baud rate R_{b} would be 26.67 Gbaud when RS (255, 239) (with 7% redundancy) is used and 30 Gbaud when LDPC (24576, 20482) (with 20% redundancy) is used.

We can use information about signal transmission power (Figure 3.2) and EDFA power consumption model ((3.10), (3.13) or (3.15)) to calculate the power consumption of EDFAs in an optical fibre link $P_{\mathrm{EDFA,link}}$. For span length 100 km, if required signal transmission power is less than -4 dBm, (3.13) or (3.15) can be used, while if required signal transmission power is greater than -4 dBm, (3.10) will be used. The energy consumption of EDFAs per bit in an optical fibre link is:

$$E_{\mathrm{EDFA}} = \frac{P_{\mathrm{EDFA,link}}}{R_{\mathrm{I}}} \tag{3.29}$$

The information rate is different for different modulation formats as discussed above and also listed in appendix. Figure 3.5 is calculated from (3.29) and it shows the relationship between link length and energy consumption per bit for optical link with EDFAs spaced at 100 km span.

Figure 3.5 shows that EDFAs in links using higher order modulation formats consume less energy per bit than those using lower order modulation formats, however, links using higher order modulation have a shorter transmission distance. For example, with RS (255, 239) used for error correction, a link employing QPSK can reach a maximum transmission distance of 6600 km while another link employing DP-16QAM can only reach 500 km. However, a 500 km link employing QPSK consumes 0.16 pJ/bit while another 500 km link employing DP-16QAM consumes only 0.070 pJ/bit. This is because advanced modulation formats provide higher data rate at the same baud rate, resulting in a smaller energy consumption per bit, however, they have a more stringent requirement on signal quality leading to a shorter transmission distance. Also in Figure 3.5, we can see immediately before the link length reaches maximum transmission length, the gradient of the energy consumption per bit curve increases. This change in gradient can be explained by (3.14). When signal transmission power is less than -4 dBm, ASE is the only noise that degrades signal quality while when signal transmission power is larger than -4 dBm, NLI begins to degrade signal quality as well. As a result more signal transmission power is required to maintain signal quality and energy consumption of EDFAs increases faster.

When we compare the effect of error correction technologies, Figure 3.5, 3.6 and 3.7 show a general trend that optical amplifiers consume less energy per bit when stronger error correction is applied. This is due to the fact that stronger error correction implies OSNR can be lower to obtain a particular post-FEC BER. A lower OSNR requires less signal transmission power which leads to less power consumption of EDFAs. For example,

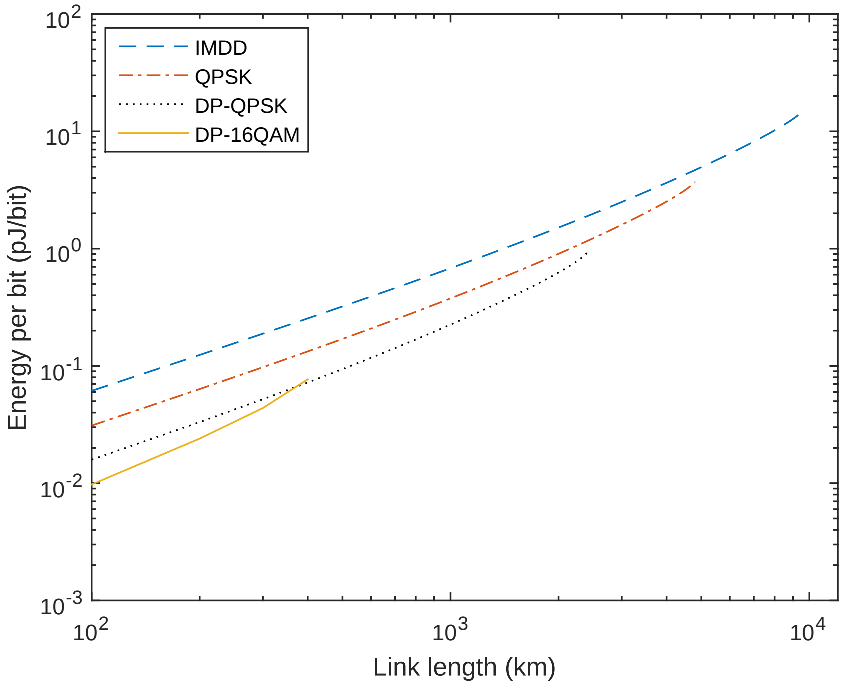

Figure 3.5: Energy consumption per bit of EDFAs vs. optical link length. Pre-FEC BER is 10^{-4} and hence RS (255, 239) is used for error correction.

the EDFAs in a 400 km link using QPSK with pre-FEC BER 10^{-2} consume 0.126 pJ/bit while the EDFAs in another 400 km link using DP-16QAM with pre-FEC BER 10^{-2} consume 0.045 pJ/bit.

Another commonly used method to measure energy consumption is energy consumption per bit per kilometer as defined by:

$$E_{\mathrm{d,EDFA}} = \frac{P_{\mathrm{EDFA,link}}}{R_{\mathrm{I}} \times L_{\mathrm{max}}} \tag{3.30}$$

Table 3.2: Energy consumption per bit per kilometer of EDFA assisted links using different modulation formats and error correction technologies at maximum transmission distance.

Modulation format	FEC	Energy consumption per bit per kilometer (fJ/(bit×km))
IMDD	RS (255, 239)	1.62
	LDPC sc. 1	1.41
	LDPC sc. 2	1.03

QPSK	RS (255, 239)	0.77
	LDPC sc. 1	0.88
	LDPC sc. 2	0.80
DP-QPSK	RS (255, 239)	0.38
	LDPC sc. 1	0.43
	LDPC sc. 2	0.43
DP-16QAM	RS (255, 239)	0.19
	LDPC sc. 1	0.17
	LDPC sc. 2	0.18

where $L_{\max}$ is the maximum transmission distance (The values of $L_{\max}$ is listed in Table 3.1). Table 3.2 lists the results calculated from (3.30). By comparing the power consumption of EDFAs of links using different modulation formats, we can see EDFAs in links using advanced modulation formats consume less energy per bit per kilometer despite the fact they have much shorter transmission link length. Therefore we should use advanced modulation formats such as DP-16QAM whenever possible to reduce energy consumption of the EDFAs in the link. In addition the results in Table 3.2 indicate the choice of FEC affects energy consumption per bit per kilometer of EDFA amplified links. This effect is more significant for lower order modulation formats.

3.2 Power Consumption of DRFA

In a DRFA, optical power is injected into the link to transform the optical fibre into a gain medium that amplifies incoming signal. We shall adopt as a link design principle that the minimum power required is the power needed to equally amplify all channels (gain-flatness). We apply the results from the ESC model [36] to numerically solve the characteristic equations of a DRFA given by (2.12), (2.14), (2.15), (2.16) and (2.17), to calculate the power required to make flat gain over signal bandwidth (entire C-band). Our results show we need 2 co-pumps at 1442 nm and 1470 nm and 2 counter-pumps 1421 nm and 1449 nm to achieve gain flatness over entire C-band (The wavelengths are not exactly the same as [36] because our link configuration is slightly different).

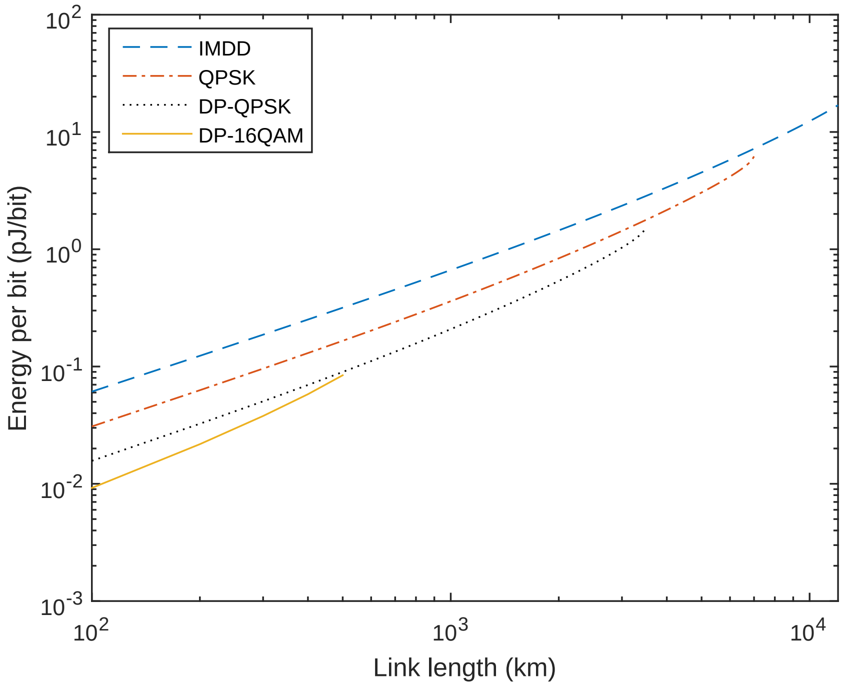

Figure 3.6: Energy consumption per bit of EDFAs vs. optical link length. Pre-FEC BER is 10^{-3} and hence LDPC sc. 1 is used for error correction.

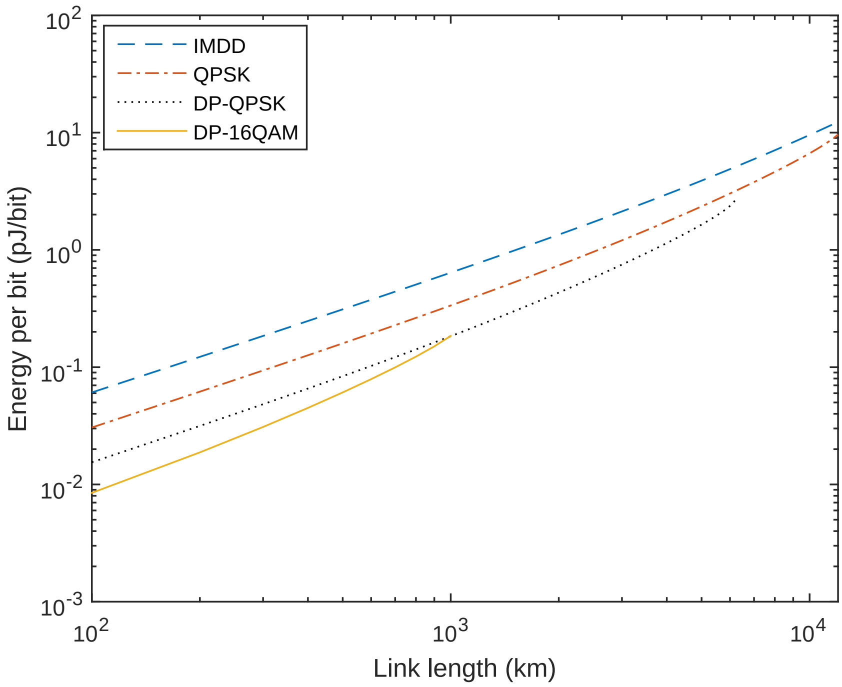

Figure 3.7: Energy consumption per bit of EDFAs vs. optical link length. Pre-FEC BER is 10^{-2} and hence LDPC sc. 2 is used for error correction.

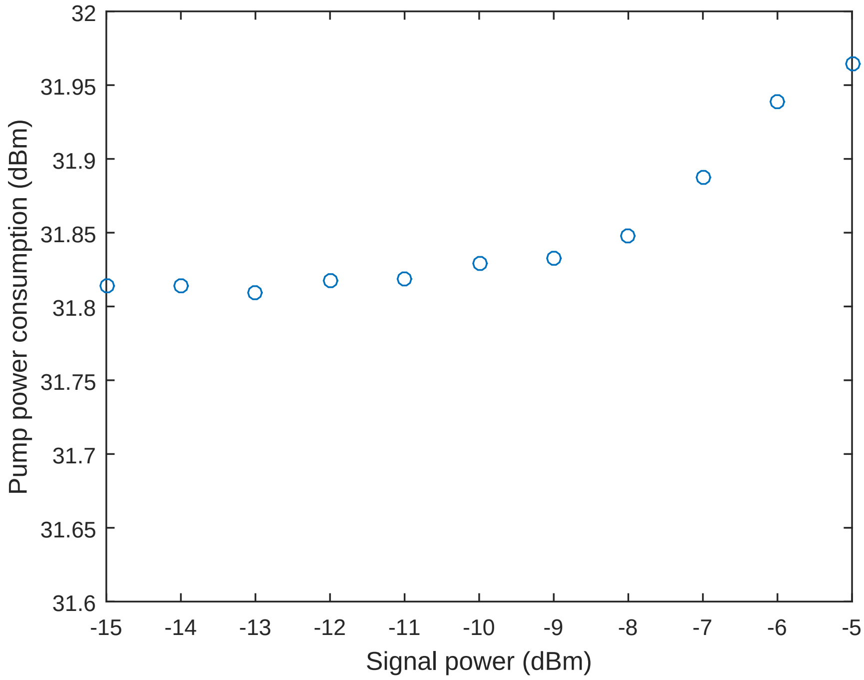

Figure 3.8: Signal transmission power vs. pump power consumption. When signal power is below -8 dBm, pump power consumption changes little with signal transmission power.

We first simulate the characteristic equations to observe the relationship between signal transmission power and pump power consumption. Figure 3.8 displays the relationship between signal transmission power, P_{Tx}, and pump power consumed to maintain signal power (so that $P_{\text{Sig}} = P_{\text{Tx}}$ at the beginning of each span) and gain-flatness. The result shows when signal power is less than or equal to -8 dBm, pump power consumption of DRFA is relatively independent of signal power and accumulated noise indicating the pump process is unsaturated. This result is consistent with [1]. Therefore when we are operating DRFAs in this regime in a long-haul optical fibre link, the total power consumption of all DRFAs in the link will be the sum of the power consumption of each of the DRFAs in the link. Therefore:

$$P_{\text{DRFA,link}} = N_{\text{span}} P_{\text{DRFA}} \tag{3.31}$$

where $P_{\text{DRFA,link}}$ is the total power consumption of all the DRFAs in the link and P_{DRFA} is the sum of power consumption of all four pumps used by DRFA in a span. For 100 km span, in order to provide flat gain for the whole C-band, the two co-pumps and two counter-pumps require 262.1 mW, 648.2 mW, 580.6 mW and 28.2 mW respectively, and $P_{\text{DRFA}} = 1512$ mW. Putting these values of pump power into characteristic equations of DRFA (Chapter 2.3.6), we can find that the noise generated in one span is $P_{\text{ASE,span}} = 2.53 \times 10^{-8}$ mW and $P_{\text{DBS,span}} = 1.90 \times 10^{-8}$ mW if signal transmission power is -8 dBm. The noise power of DBR will be less significant if a smaller signal transmission power is used because a smaller signal transmission gives smaller backscattering power and thus a smaller double backscattering power. The link is designed using identical spans with the DRFAs fully compensating the fibre loss of the previous span, therefore the noise is generated equally in each span: $P_{\text{ASE}} = P_{\text{ASE,span}} \times N_{\text{span}}$ and $P_{\text{DBS}} = P_{\text{DBS,span}} \times N_{\text{span}}$. The link length is $L_{\text{link}} = N_{\text{span}} L_{\text{span}}$. Therefore by rearranging (2.21), we can obtain:

$$L_{\text{Link}} = \frac{P_{\text{sig}}}{(P_{\text{ASE,span}} + P_{\text{DBS,span}})\text{OSNR}} L_{\text{span}} \tag{3.32}$$

Table 3.3: Minimum OSNR (dB) requirement for links using different modulation format and FEC. The results are obtained from Table 2.2 and 2.4. A 2 dB OSNR penalty is given to IMDD and QPSK and a 4 dB OSNR penalty is given to DP-QPSk and DP-16QAM for reasons discussed in Chapter 2.4.

	RS (255, 239)	LDPC sc. 1	LDPC sc. 2
IMDD	10.7	9.6	7.1
QPSK	13.7	12.6	10.1
DP-QPSK	16.7	15.6	13.1
DP-16QAM	24.5	23.3	20.7

By using Table 3.3 of minimum OSNR requirement, we can calculate the maximum transmission distance of DRFA assisted links. The resulting maximum transmission distances are listed in Table 3.4.

Table 3.4: Maximum link length (km) of DRFA assisted links using different combination of modulation format and FEC.

	RS (255, 239)	LDPC sc. 1	LDPC sc. 2
IMDD	> 12000	> 12000	> 12000
QPSK	9600	> 12000	> 12000
DP-QPSK	4800	6200	10900
DP-16QAM	800	1000	1900

Table 3.5: Energy consumption per bit per kilometer of DRFAs in links using different modulation formats. The energy consumption per bit per kilometer of DRFAs is independent of the choice of FEC because signal transmission power has negligible effect on power consumption of DRFAs.

Modulation format	Energy per bit per kilometer (fJ/(bit×km))
IMDD	15.12
QPSK	7.56
DP-QPSK	3.78
DP-16QAM	1.89

The energy consumption of DRFAs per bit in an optical fibre link is:

$$E_{\mathrm{DRFA}} = \frac{P_{\mathrm{DRFA,link}}}{R_{\mathrm{I}}} = \frac{N_{\mathrm{span}} P_{\mathrm{DRFA}}}{R_{\mathrm{I}}} \tag{3.33}$$

Figure 3.9 is plotted using (3.33). The energy consumption per bit of DRFAs is a linear function of the number of spans or link length. Because the energy consumption per bit of DRFAs is not related to OSNR, it is not related to the type of FEC used. At the same link length, links using more advanced modulation format consume less energy per bit. For example, the DRFAs in a link of 500 km using IMDD consume 7.56 pJ/bit. If the link uses QPSK, DRFAs will consume 3.78 pJ/bit, if the link uses DP-QPSK, DRFAs will consume 1.89 pJ/bit, and if the link uses DP-16QAM, DRFAs will consume 0.945 pJ/bit. The value of energy consumption per bit of DRFAs across different modulation formats is in proportion to the number of bits per symbol for these modulation formats. This is because R_{I} in (3.33) is determined by the bits per symbol ratio.

Because the energy consumption per bit of DRFAs is linearly proportional to link length, the energy per bit per kilometer is independent of the total link length. That is:

$$E_{\mathrm{d,DRFA}} = \frac{P_{\mathrm{DRFA,link}}}{R_{\mathrm{I}} \times L_{\mathrm{max}}} = \frac{N_{\mathrm{span}} P_{\mathrm{DRFA}}}{R_{\mathrm{I}} \times L_{\mathrm{max}}} = \frac{P_{\mathrm{DRFA}}}{R_{\mathrm{I}} \times L_{\mathrm{span}}} \tag{3.34}$$

The result of (3.34) is listed in Table 3.5. It shows the energy consumption per bit per kilometer across modulation formats is inversely proportional to the number of bits per symbol.

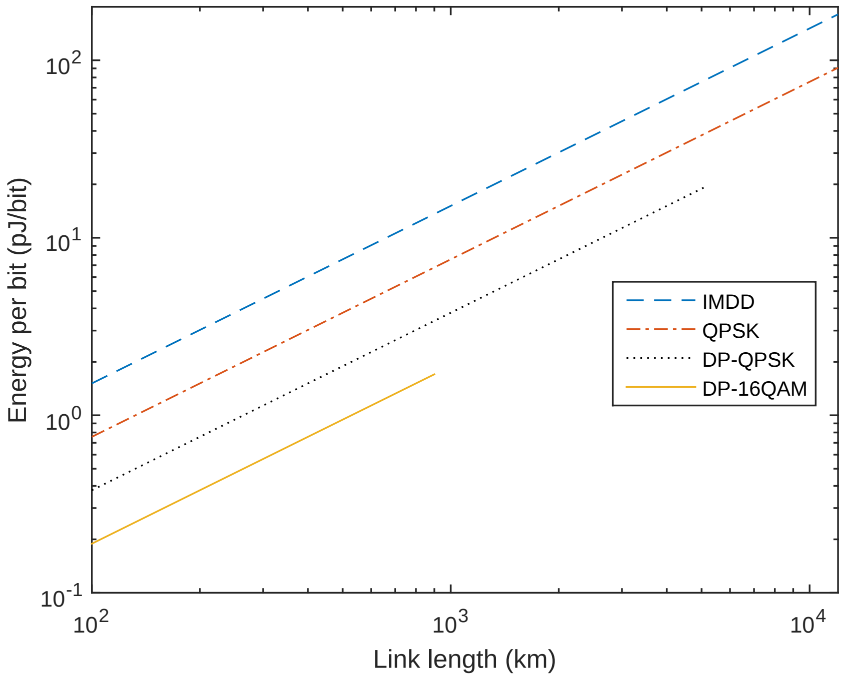

Figure 3.9: Energy consumption per bit of DRFAs vs. optical link length. LDPC sc. 2 is used to correct error.

3.3 Comparison of Energy Efficiency of EDFA and DRFA

One difference in energy efficiency of EDFA and DRFA is wavelength conversion efficiency $\frac{\lambda_p}{\lambda_s}$ which is an important factor in η_{PCE} in (3.4). EDFA pumps are usually located at 980 nm or 1480 nm while DRFA pumps are usually placed at the range of 1420 nm to 1510 nm depending on signal bandwidths. As DRFA pumps are usually placed at longer wavelengths, they will have a better wavelength conversion efficiency.

However, a better wavelength conversion efficiency does not result in better energy efficiency for DRFA. The power consumption of optical amplifiers can be calculated by solving analytical EDFA model based on (3.10), and numerical DRFA model based on (3.5), (2.12), (2.14) (2.15), (2.16) and (2.17). We found that the amplifier electrical power consumption per span corresponding to 100 km span length is about 0.22 W per span for EDFA assisted links and 2.3 W per span for DRFA assisted links. Therefore, EDFA is more energy efficient than DRFA although DRFA has a better wavelength conversion efficiency.

Comparing maximum transmission distance of EDFA assisted links and DRFA assisted links (Table 3.1 and Table 3.4), we can see DRFA assisted links can attain a much longer transmission distance. For example, a EDFA assisted link using DP-16QAM and LDPC sc. 2 can reach only 1000 km while a DRFA assisted link using the same modulation format and FEC can reach 1900 km. However, comparing Table 3.2 and Table 3.5, we can see DRFAs consume almost 10 times more energy per bit per kilometer than EDFAs. These comparisons show EDFA is a more energy efficient optical amplifier while

DRFA provides longer transmission distance and better signal quality.

Comparing the energy efficiency per bit per kilometer (3.30) and (3.34), we can see the energy consumption per bit per kilometer of EDFAs increases when the link length is increasing but energy consumption per bit per kilometer of DRFAs is independent of link length when signal transmission power is below the NLI threshold.

It should be noted that energy consumed by cooling, monitoring systems and other control circuits is not considered in our model. There are two reasons why they are not included. The first reason is that one purpose of the thesis is to find the energy consumption of amplifiers at the limiting cases (where we consider the fundamental limits due to the physics of atoms and photons so that the energy efficiency is maximized). This approach has been frequently adopted to estimate the energy efficiency limits in telecommunications systems and technologies [10, 11, 45].

By understanding what is happening at the limiting case, we can have an indication about energy consumption of amplifiers regardless of the method of implementation. Therefore we are not considering the "overheads" that may occur in the various implementations such as monitoring and management equipment. The second reason is because the energy consumption of the "overheads" is different for different implementation methods, and even for the same implementation methods, as the technologies are changing so fast, a result with "overheads" will not hold for too long. By focusing on just the amplification aspect, we can get a definite answer that holds for all time. It is not easy to experimentally validate our result because no practical optical system is built without monitoring and management. However, our results at limiting cases are consistant with other people's theoretical results [10]. Comparing our results with energy consumption of commerciallized EDFAs, monitoring and management systems consume more than 95% of total energy [46]. In all commercial optical transmission systems, most of the power is consumed by the monitoring and management systems. Therefore our values do not reflect current practice. This is a problem common to many other works done in network equipment [11, 45, 47, 48]. However, as the power consumption of "overheads" is reducing rapidly over the years, our values for the limiting cases will become more and more relevant.

Chapter 4

Combining Power Consumption of Optical Amplifier and FEC

4.1 Maximum Link Length Scenario

From the results in previous chapter, EDFA consumes less energy than DRFA. However, this does not account for the benefit of better signal quality provided by DRFA at the receiver. In an optical fibre link, the better the signal quality, the less energy intensive error correction technique can be used. We combine the use of optical amplifiers and FEC to examine if the improvement in signal quality provided by DRFA can in fact improve the overall energy efficient optical fibre link. The combined energy consumption per bit per kilometer of optical amplifier and FEC E_{tot} is:

$$E_{\text{tot}} = \frac{P_{\text{amplifier,link}}}{R_{\text{I}} \times L_{\text{link}}} + \frac{E_{\text{p,FEC}}}{L_{\text{link}}} \tag{4.1}$$

where $P_{\text{amplifier,link}}$ is the power consumed by the link and $P_{\text{amplifier,link}} = P_{\text{EDFA,link}}$ for EDFA link given by (3.10), (3.13) or (3.15), and $P_{\text{amplifier,link}} = P_{\text{DRFA,link}}$ for DRFA link given by (3.31). $L_{\text{link}} = L_{\text{span}} N_{\text{span}}$ is total link length, and $E_{\text{p,FEC}}$ is the energy consumption per bit of the FEC. Value of $E_{\text{p,FEC}}$ is give in Table 2.2.

Figure 4.1 shows the energy per information bit per kilometer consumed by optical amplifier and FEC for six combinations of optical amplifier and FEC at the maximum possible link length for each combination, using DP-QPSK and span length of 100 km.

From Figure 4.1 as well as Table 4.1, we can see that for a given value of pre-FEC BER, energy consumption per information bit per kilometer for amplification is approximately half for DP-16QAM compared to that for DP-QPSK (0.13 fJ/(bit×km) vs. 0.27 fJ/(bit×km) when EDFAs spaced at 100 km are used for amplification.) This is because total information rate for DP-16QAM is double the value for DP-QPSK across the C-band transmission bandwidth of 4 THz. Note that maximum transmission distance for DP-QPSK is higher than that for DP-16QAM for a given value of pre-FEC BER.

Compared to EDFAs (and ignoring the power consumption of FEC), the DRFAs are less energy efficient (0.27 fJ/(bit×km) vs. 2.9 fJ/(bit×km) as seen in Table 4.1). Comparing scenarios ER and DR shown in Figure 4.1, we see that RS (255, 239) (FEC) consumes more energy per bit per kilometer when using EDFA compared to using DRFA (0.52 fJ/(bit×km) vs. 0.27 fJ/(bit×km)). However, DRFA consumes much higher energy

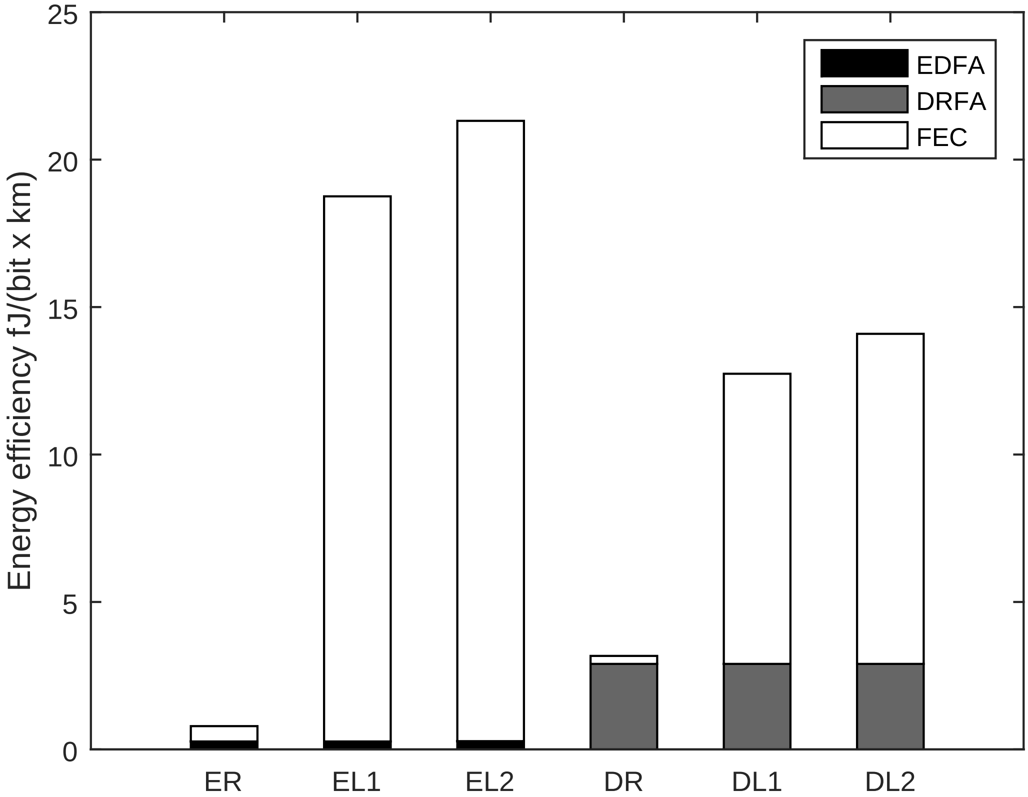

Figure 4.1: Energy consumptions per information bit per kilometer (fJ/(bit×km)) by EDFAs, DRFAs and FEC are indicated by sections of the plot shaded as shown in the legend. The modulation format is DP-QPSK and span length is 100 km. The scenarios are: ER) EDFA assisted link with pre-FEC BER 10^{-4} and requiring RS (255, 239) for error correction. EL1) EDFA assisted link with pre-FEC BER 10^{-3} and requiring LDPC sc. 1 for error correction (as defined in Table 2.2). EL2) EDFA assisted link with pre-FEC BER 10^{-2} and requiring LDPC sc. 2 for error correction. DR) DRFA assisted link with pre-FEC BER 10^{-4} and requiring RS (255, 239) for error correction. DL1) DRFA assisted link with pre-FEC BER 10^{-3} and requiring LDPC sc. 1 for error correction. DL2) DRFA assisted link with pre-FEC BER 10^{-2} and requiring LDPC sc. 2 for error correction. The post-FEC BER is 10^{-13} in all scenarios under consideration. These scenarios are also described in Table 4.1.

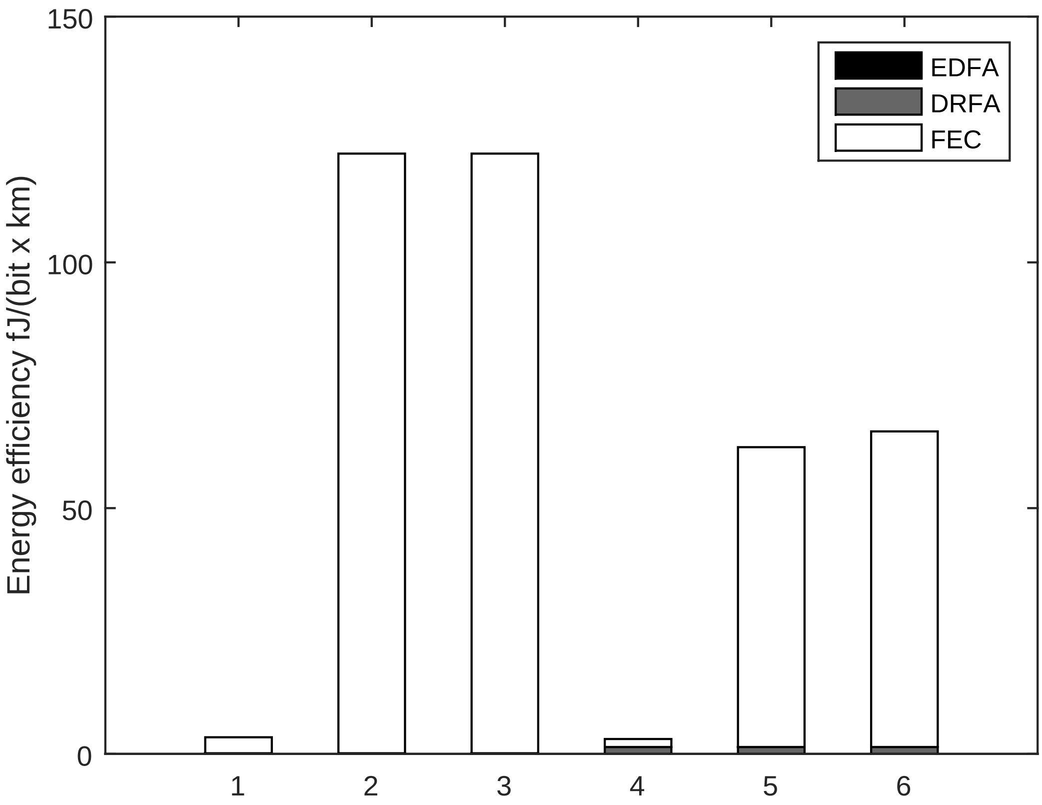

Figure 4.2: Energy consumptions per information bit per kilometer (fJ/(bit$\times$km)) by EDFAs, DRFAs and FEC are indicated by sections of the plot shaded as shown in the legend. The modulation format is DP-16QAM and span length is 100 km. The scenarios are the same as Figure 4.1.

per bit (2.9 fJ/(bit×km)) per kilometer than RS (255, 239). Thus using EDFAs with RS (255, 239) is more energy efficient than DRFAs with RS (225, 239) in these scenarios.

Table 4.1: Energy per bit per kilometer and maximum reach of EDFA and DRFA assisted links. The span length is 100 km.

Amplifier	FEC	Maximum reach	Energy consumption per bit per kilometer for amplification fJ/(bit×km)	Energy consumption per bit per kilometer for error correction fJ/(bit×km)
DP-QPSK				
EDFA	RS (255, 239)	2500	0.27	0.52
	LDPC sc. 1	3300	0.27	18.5
	LDPC sc. 2	5800	0.28	21
DRFA	RS (255, 239)	4800	2.9	0.27
	LDPC sc. 1	6200	2.9	9.8
	LDPC sc. 2	10900	2.9	11.2
DP-16QAM				
EDFA	RS (255, 239)	400	0.13	3.3
	LDPC sc. 1	500	0.13	122
	LDPC sc. 2	1000	0.13	122
DRFA	RS (255, 239)	800	1.5	1.6
	LDPC sc. 1	1000	1.5	61
	LDPC sc. 2	1900	1.5	64.2

In contrast, when the energy consumption per bit per kilometer for error correction dominates the total value of energy consumption, total energy per bit per kilometer for EDFA assisted links can be higher than that for DRFA assisted links. This happens when soft-decision decoding based on LDPC (24576, 20482) is used in scenarios EL1 and DL1 (18.3 fJ/(bit×km) vs. 12.8 fJ/(bit×km)) in Figure 4.1. This is also the case for scenarios EL2 and DL2 (21.2 fJ/(bit×km) vs 13.9 fJ/(bit×km)) in the same figure. Therefore in links using DP-QPSK that require soft decision LDPC (24576, 20482), using DRFAs will be more energy efficient than EDFAs. The same trend can be observed in links using DP-16QAM (Table 4.1 and Figure 4.2). When transmission links are employing LDPC (24576, 20482), DRFA assisted links consume less energy per bit per kilometer than EDFA assisted links.

These results show that despite the apparent energy advantage of EDFAs over the DRFAs, in long-haul optical fibre links that employ LDPC (24576, 20482), DRFAs are more energy efficient (in Joules/bit/km) for both DP-QPSK and DP-16QAM.

Optical fibre links using IMDD or QPSK can achieve a much longer transmission distance because these modulation formats have lower requirement on signal quality. But similar results are observed. For links using IMDD, if the transmission distance is less than 9700 km, it is more energy efficient to employ EDFA, but if the transmission distance is more than 9700 km, it is more energy efficient to employ DRFA. This is because the EDFA assisted link requires LDPC while a DRFA assisted link only requires RS. For optical fibre links using QPSK, this threshold distance is 4800 km.

4.2 Fixed Link Length Scenario

We now consider some scenarios where total link length is kept constant. From Table 4.1, for a transmission link of 1000 km using DP-16QAM with 100 km span length DRFA assisted link can employ LDPC sc. 1 because BER is 10^{-3} while EDFA assisted link has to use LDPC sc. 2 because BER is 10^{-2}. As a result, DRFA assisted link will consume 1.5 fJ/(bit $\times$ km) $\times$ 1000 km + 61 pJ/bit = 62.5 pJ/bit while EDFA assisted link will consume 122 pJ/bit. Therefore for this scenario it is more energy efficient for the link to use DRFAs than EDFAs. Similarly for a transmission link of 4000 km using DP-QPSK with 100 km span length, EDFA assisted link will consume more than 62.1 pJ/bit (as it requires larger number of error correction iterations than LDPC sc. 1) whereas DRFA assisted link will consume less than 12.9 pJ/bit (as it requires error correction that is weaker than RS(255,239)).

We see from Table 4.1 that soft-decision FEC consumes much more energy per bit per kilometer than amplifiers for the link designs under consideration. If using DRFAs in an optical link provides an OSNR which enables the use of low power FEC, then deploying DRFAs will provide a more energy efficient link than EDFAs. Therefore DRFAs can be a more energy efficient solution than EDFAs in terms of energy consumption per information bit per kilometer.

The optical fibre link connecting Sydney and Melbourne is about 1200 km [49]. We can design a 1200 km link using 12 identical spans spaced by 100 km with combinations of modulation format, optical amplifiers and FEC to see which combination provides the most energy efficient link. Because the link length is relatively short, we will not consider IMDD or QPSK but focus on DP-QPSK and DP-16QAM which provide higher data rates. The data of maximum link lengths in Table 3.1 and 3.4 indicate the following combinations are possible: 1) DP-QPSK, EDFA and RS (255, 239), 2) DP-QPSK, EDFA and LDPC sc. 1, 3) DP-QPSK, EDFA and LDPC sc. 2, 4) DP-QPSK, DRFA and RS (255, 239), 5) DP-QPSK, DRFA and LDPC sc. 1, 6) DP-QPSK, DRFA and LDPC sc. 2, 7) DP-16QAM, DRFA and LDPC sc. 2. From our discussion above, the energy consumption of LDPC is so high that if RS (255, 239) is available, we should not consider

LDPC. Thus we will not consider 2), 3), 5) and 6). Table 4.2 shows energy consumption of optical amplifier and FEC for 1), 4) and 7). For 4) and 7), because LDPC is used, we use highest possible signal transmission power to improve pre-FEC BER so that energy consumption of LDPC could be minimized to achieve overall reduction in energy consumption. For 1), we will not use highest signal transmission power, because when RS (255, 239) is used, increasing signal transmission power does not always lead to overall reduction in energy consumption. We can see at this link length, the most energy efficient combination to construct optical fibre link is to use DP-QPSK, EDFA and RS (255, 239). However, if we require a link capacity greater than 8 Tb/s, the only choice is to use the combination of DP-16QAM, DRFA and LDPC sc. 2, which consumes much more energy per bit than the EDFA based design.

Table 4.2: Energy consumption of optical amplifiers and FEC for 1200 km links using combinations of modulation format, optical amplifier and FEC.

	DP-QPSK EDFA RS (255, 239)	DP-QPSK DRFA RS (255, 239)	DP-16QAM DRFA LDPC sc. 2
Data rate (Tb/s)	8	8	16
Signal transmission power (dBm)	-7.3	-8.0	-8.0
Pre-FEC BER	10^{-4}	$< 10^{-4}$	$10^{-3} \sim 10^{-2}$
Power consumption of optical amplifier (W)	2.27	18.1	18.1
Energy consumption of FEC (pJ/bit)	1.3	< 1.3	< 122
Total energy consumption per bit (pJ/bit)	1.58	< 3.56	< 123
Total energy consumption per bit per kilometer (fJ/(bit×km))	1.32	< 2.97	< 103

The optical fibre link connecting Perth and Adelaide is about 2900 km [50]. We can design this 2900 km link using 29 identical 100 km spans using combinations of modulation format, optical amplifiers and FEC to see which combination provides the most energy efficient link. Using the same procedures as above, we can obtain Table 4.3. At this distance, the most advanced modulation format we can use is DP-QPSK which gives 8 Tb/s link capacity. From Table 4.3, we can see a DRFA assisted link is much more energy efficient than an EDFA assisted link because the implementation of DRFA enables the use of a less energy intensive FEC. This is consistent with the concept we obtained above.

Table 4.3: Energy consumption of optical amplifiers and FEC for 2900 km links using combinations of modulation format, optical amplifier and FEC.

	DP-QPSK EDFA LDPC sc. 1	DP-QPSK DRFA RS (255, 239)
Data rate (Tb/s)	8	8
Signal transmission power (dBm)	-1	-8
Pre-FEC BER	$10^{-3} \sim 10^{-4}$	$< 10^{-4}$
Power consumption of optical amplifier (W)	6.11	43.8
Energy consumption of FEC (pJ/bit)	< 61	< 1.3
Total energy consumption per bit (pJ/bit)	< 61.8	< 6.78
Total energy consumption per bit per kilometer (fJ/(bit×km))	< 21.3	< 2.34

Chapter 5

Conclusion

5.1 Conclusion

In this thesis, we have compared the energy efficiency of EDFAs and DRFAs for long-haul, high-capacity coherent optical links by including the energy consumption of the FEC required to secure an acceptable link BER performance. The following goals have been met:

- Studied the existing power consumption model of EDFA and DRFA. Studied energy consumption of some commonly used FEC. Investigated the method to construct optical amplifier assisted fibre link to maintain signal quality.
- Developed a power consumption model of EDFA by considering theoretical lower limit of electrical-to-optical power conversion, ASE generation across the entire gain profile and minimum power requirement to maintain signal quality. Calculated power consumption of DRFA based on numerical modeling of the DRFA characteristic equations and demonstrated that energy per bit for amplification is higher for DRFA than EDFA.
- Compared power consumption and energy efficiency of EDFA and DRFA for optical fibre links using different modulation formats and FEC. We showed that DRFA can be more energy efficient than EDFA in certain scenarios by reducing energy consumption of FEC.

For a system with a span length of 100 km, error-correction codes available as described in Table 2.2, modulation formats as DP-QPSK or DP-16QAM and other parameters as specified in this thesis, the following is a rough guide for maximizing the energy efficiency of long haul, amplified optical links: When transmission distance is below 400 km, use a combination of DP-16QAM and EDFA, along with RS(255,239) for error correction. When transmission distance is greater than 400 km but less than 2500 km, the combination of DP-QPSK and EDFA, along with error correction using RS(255,239) is optimal. Between 2500 km and 4800 km, use DP-QPSK and Raman amplification with error-correction using RS(255,239) for maximum energy efficiency. Beyond 4800 km, use DP-QPSK and Raman amplification as well as soft-decision decoding based on LDPC(24576,20482).

5.2 Future Work

The numerical modeling in this thesis is based on C-band. Today optical amplifier technologies can cover both C and L Bands. The additional L-band provides a wider system operational bandwidth and more channels to enable a higher total system link data rate than is available with the C Band only. One extension of the work in this thesis will be to cover amplifiers technologies that include both C- and L-bands. For DRFA model, we will need to adjust pump wavelength/power and possibly add more pumps at higher wavelengths to achieve flat gain profiles over both bands.

Another potential for future work will be to extend the model to include NLI in DRFA assisted links. We can consider the use of higher signal transmission power (greater than -8 dBm) if power of NLI is included in the link simulation. This will require the construction of a numerical model for NLI in DRFA assisted links.

The amplifier power model presented in this thesis does not include power consumption of monitoring and management. Future work could include the power consumption in future modelling if the management and monitoring does not totally dominate the power consumption of amplifier.

The amplifier assisted optical fibre links modelled in this thesis are composed of spans of equal lengths. Future work could simulate links constructed by spans of unequal length to investigate energy efficiency of more real world scenarios. Future work could also simulate links composed of combinations of different fibre, such as DCF interspersed with SMF or alternating positive and negative dispersion fibre. Including these factors will be more representative of real fibre links. Furthermore other FEC codes such as concatenated codes or turbo codes could be considered.

Appendix A

Parameters

The parameters used in this paper are listed in Table A.1.

Table A.1: Parameters and Values

Quantity	Symbol	Value	Unit
Pump wavelength (EDFA)	$\lambda_{p,E}$	980	nm
Pump wavelength (DRFA)	$\lambda_{\mathrm{p,R,mult}}$	1421	nm
		1442	
		1449	
		1470	
Signal wavelength	λ_s	1530-1565	nm
Pump frequency (DRFA)	μ	1421 nm : 211	THz
		1442 nm : 208	THz
		1449 nm : 207	THz
		1470 nm : 204	THz
Signal frequency	f	approx 194 across C-Band	THz
Current injection efficiency	q_e	0.9	
Planck's constant	h	6.63×10^{-34}	Js
Bandwidth for OSNR measurement	B_o	12.5	GHz
Fibre attenuation coefficient at signal wavelength	α_s	0.220	dB/km
Fibre attenuation coefficient (Raman pump)	α_{p_R}	1421 nm : 0.281	dB/km
		1442 nm : 0.270	dB/km
		1449 nm : 0.267	dB/km
		1470 nm : 0.256	dB/km
Optical link length	L		km
Number of spans in link	N_{span}		
Number of channels	N_{channel}	80	
Number of pumps per amplifier	N_{pump}	4	
Confinement factor	Γ	0.7	
End facet reflectivity	R_1	0.3	

End facet reflectivity	R_2	0.9	
EDFA gain bandwidth	Δf_G	4.37×10^{12}	Hz
Population inversion ratio	$n_{sp,E}$	1.3	
Drive power of the laser at threshold current	P_t	0.015	W
Fibre nonlinear coefficient	γ	1.3	$\mathrm{km}^{-1}\mathrm{W}^{-1}$
Second derivative of propagation constant	β_2	2.17×10^{-23}	s^2/km
Baud rate	R_b	RS (255, 239): 26.67 LDPC (24576, 20482): 30	Gb/s
Total information rate	R_I	IMDD: 2 QPSK: 4 DP-QPSK: 8 DP-16QAM: 16	Tb/s
boltzmann constant	k_B	1.38×10^{-23}	$\mathrm{m}^2\mathrm{kg}/(\mathrm{s}^2\mathrm{K})$
Temperature	T	300	K
Capture ratio of Rayleigh scattering light	f_R	10^{-4}	km^{-1}

Appendix B

Publications

- P. Wang, K. Hinton, P. Farrell, and B. Pilai, "On EDFA and Raman Fiber Amplifier Energy Efficiency", the 11th IEEE Conference on Green Computing and Communications, 2015.
- K. Hinton, P. Wang, P. Farrell, and B. Pilai, "Power consumption of Erbium Doped Fibre Amplified links," in Big Data and Cloud Computing (BdCloud), 2014 IEEE Fourth International Conference on. IEEE, 2014, pp. 662-668.

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