Dense Wavelength Division Multiplexing Scheme and Regenerators Spacing for Ultra Large Area Fibers

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Abstract: This study has been undertaken to investigate the distance between the regenerators in case of Ultra Large Area Fiber (ULAF) for dense wavelength division multiplexing scheme. In case of ULAF the separation between regenerators should be increased due to decrease in nonlinear losses in comparison of Standard Single Mode Fiber (SSMF) in C-Band (1.53µm-1.57µm).

Key Words**:** Figure of Merit, Spacing, Regenerator, Non-Linearity's

Index Terms**: Ultra Large Area Fiber (ULAF, Standard Single Mode Fiber (SSMF), Stimulated Raman Scattering (SRS), Amplified Spontaneous Emissions (ASE), Spectral Efficiency (SE), Erbium Doper Fiber Amplifier (EDFA), Signal to Noise Ratio (SNR), Optical Signal to Noise Ratio (OSNR).**

1.1. INTRODUCTION

In recent time communication plays a vital role in our life. Our world is shrinking by means of communication, our demand and requirement every day is increasing for high speed communication. For communication system, generally measure of system performance is product of bit rate (B) and distance (L) between repeaters (BL) for point to point links [1]. The system performance may be increased several times if optical waves are used as carrier waves and nearly ~1(Tb/s)-km for third generation optical communication systems operating at 1.55 µm nearly, as the product of bit rate and distance (BL) depends on wave length, as the fiber losses and dispersion depends on refractive index of fiber on wavelength [1] - [2], [6]. So, we switched to optical communication to meet out our requirements for high speed communication. Now we have to guide light wave in a medium like electrons are guided in copper wire. Optical fibers were designed to meet out the requirement of channels [3]. An optical fiber was developed that is commonly used for optical communication that is standard single mode fiber (SSMF). It has low dispersion losses in comparison of multimode fiber [4]. When optical power is incident on optical fiber cross section area that will be very high power per unit cross section area of the undertaken optical fiber [1]. This very high power per unit cross section area in fiber will generate nonlinear losses in the optical fiber [5]. Hence signal will get attenuated due to nonlinear losses. So for telecommunication signal amplifiers will be used for the amplification of the signal. But at one stage amplified signal will have low SNR value and we have to regenerate the signal again. So we will use the signal generator after a certain distance in the optical communication. Such devices are called regenerator.

Such placing of regenerators will increase the cost of communication infrastructure. The development of ultra large area fibers, whose diameters ranges from 40-100 µm with the development of technology give us new channels for communications, whereas the diameter of SSMF fiber is nearly 8-9 µm. These ultra large area fibers when used for communications then effective incident power per unit cross section area of the fiber will reduce due to large cross section area of the optical fiber [5]. This will result into low nonlinear losses of the subjected optical fiber [5].

1.2. OPTICAL FIBER WAVELENGTH BAND AND OPTICAL TRANSMISSION WINDOWS

Silica based glass optical fibers can transmit 250nm to 2000nm wavelengths. But long distance optical transmission is limited to specific wavelength ranges due to the optical fiber transmission losses. We have heard about the O-bands, S-bands, C -bands etc. These optical bands are nothing but are the transmission wavelength ranges of optical fibers. The band are as given below [7]:

Serial No.	Name of Band	Wavelength Range	Losses per Kilometer
1	O – Band -Original Band	1260nm – 1360nm	0.33dB/km
2	E – Band -Extended Band	1360nm – 1460nm	0.19dB/km
3	S – Band -Short Wavelength Band	1460nm – 1530nm	0.22dB/km
4	C – Band –Conventional Band	1530nm – 1565nm	0.20dB/km
5	L – Band –Long Band	1565nm – 1625nm	0.23dB/km
6	U – Band -Ultra-Long Band	1625nm – 1675nm	0.28dB/km

Optical fibers are made of silica glass. When light travels through silica glass fibers, it gets attenuated due to material absorption, scattering, waveguide attenuation and leaky modes [1]-[4], [6]. It is important for the glass to become pure for low loss transmission. Shorter wavelengths such as 250nm get more attenuated due to the absorption and Rayleigh scattering. Whereas on the other hand higher wavelengths like above 1700nm also get attenuated due to infrared resonant absorption bands within the material [8].

The attenuation of a common glass which we use for windows is in the order of 1000dB/km [7]. It was in the 1960s scientists started to remove the impurities from the glass to make it useful for light transmission. Scientists were successful to develop low water peak fiber by eliminating OH ions from the silica material.

The U band or Ultra long band is used for system monitoring and maintenance. The C – Band 1550nm region is used for DWDM [9] transmission.

1.3. DENSE WAVELENGTH DIVISION MULTIPLEXING (DWDM)

Dense Wavelength division multiplexing (DWDM) [9] is an approach by which we can use the huge optoelectronic bandwidth [10]. Multiple different DWDM channels from different end users may be multiplexed on the same fiber. Thus multiple DWDM channels may be allowed to coexist on a single fiber. In this way one can use the huge fiber bandwidth. The use of huge bandwidth is subject to the corresponding challenges which are the design and development of appropriate network architectures, protocols and algorithms. DWDM devices are easier to implement as all the components in the DWDM devices need to operate at electronic speed only [9] - [11]. DWDM networks have matured considerably over the last decade and the next generation of the internet is using DWDM based optical backbones.

A DWDM systems use a multiplexer at the transmitter to join the signals together and a de-multiplexer at the receiver to split them separately. Using the accurate kind of fiber it is possible to have a device that can perform the both functions simultaneously. De-multiplexer must provide the wavelength selectivity of the receiver in the DWDM system as optical receivers are wide band devices in contrast to laser sources. The capacity of a given link can be expanded by simply upgrading the multiplexers and de-multiplexers at each end. So that it capable technique to expand the capacity of the optical network without laying more fibers and thus we may expand the basic 10 Gbit/s fiber system to a theoretical fiber system of total capacity of over 1.6 Tbit/s for placing of 160 channels with 25 GHz spacing over a single fiber link. Most of the DWDM systems operate on single mode fiber optical cables which have a core diameter of 9 µm.

DWDM systems use the same C-band around 1550 nm but with denser channel spacing. Channel spacing vary, for example in a typical system, it would use 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing. For advanced technologies, we are capable for placing of 160 channels with 25 GHz spacing sometimes this scheme is called as ultra-dense WDM). New amplification options with Raman amplifiers, enable the extension of the usable wavelengths to the L-band, more or less doubling these numbers.

1.4. EDFA Amplifier

Erbium-doped Fiber Amplifier (EDFA) invented in 1987. It is the most commonly deployed optical amplifier in the DWDM system that uses the Erbium-doped fiber as optical amplification medium to enhance the signals level. This amplifier enables instantaneous amplification for the signals with multiple wavelengths, basically within two bands. One is the Conventional or C-band which is approximately from 1530 nm to 1565 nm and the other band is the Long or L-band which is approximately from 1565 nm to 1625 nm [12]-[16]. It has also two commonly used pumping bands first is 980 nm and other is 1480 nm [1]. The 980nm band has a higher absorption cross-section usually used in low-noise application, while 1480nm band has a lower but broader absorption cross-section that is generally used for higher power amplifiers [1], [17]-[19].

When the EDFA amplifier works, it offers a pump laser with 980 nm or 1480 nm. As the input signals and the pump laser pass through the coupler then they will be multiplexed over the Erbium doped fiber. Over the interaction with the doping ions, the signal amplification will be achieved finally. This EDFA improves the efficiency for optical signal amplification highly [16]. The EDFA is a milestone in the history of fiber optics, which can directly amplify signals with multiple wavelengths through one fiber, instead of optical-electrical-optical (O/E/O) signal amplification.

EDFA amplifiers are available in the low-loss 1530 nm to 1565 nm wavelength window of telecommunication fibers with variety of gains and with performance of ideal noise nearly [20]. These amplifiers amplify the optical signals without distortion or crosstalk between frequencies/wavelengths. These amplifiers are made from fiber using splicing naturally of telecommunication fibers, furthermore these are insensitive to polarization impacts [21].

1.5. QAM MODULATION SCHEME

It is feasible to combine ASK, FSK and PSK. Benefit of combining different modulation methods is to increase the number of symbols available. Increasing the number of available symbols is a standard way to increase the bit rate. Because increasing the number of symbols, increases the number of bits per symbol. If we combine ASK and PSK, it will create Quadrature amplitude modulation (QAM) [22]-[23].

QAM is based on the application of ASK and PSK on two sinusoidal waves of the same frequency but with a phase difference of 90°. Sinusoidal waves with 90° phase difference are said to be in a quadrature phase association. One of these waves is termed as I wave, or in-phase wave or sine wave and the other wave as the Q wave, or quadrature wave or cosine wave (Figure 1.3.1).

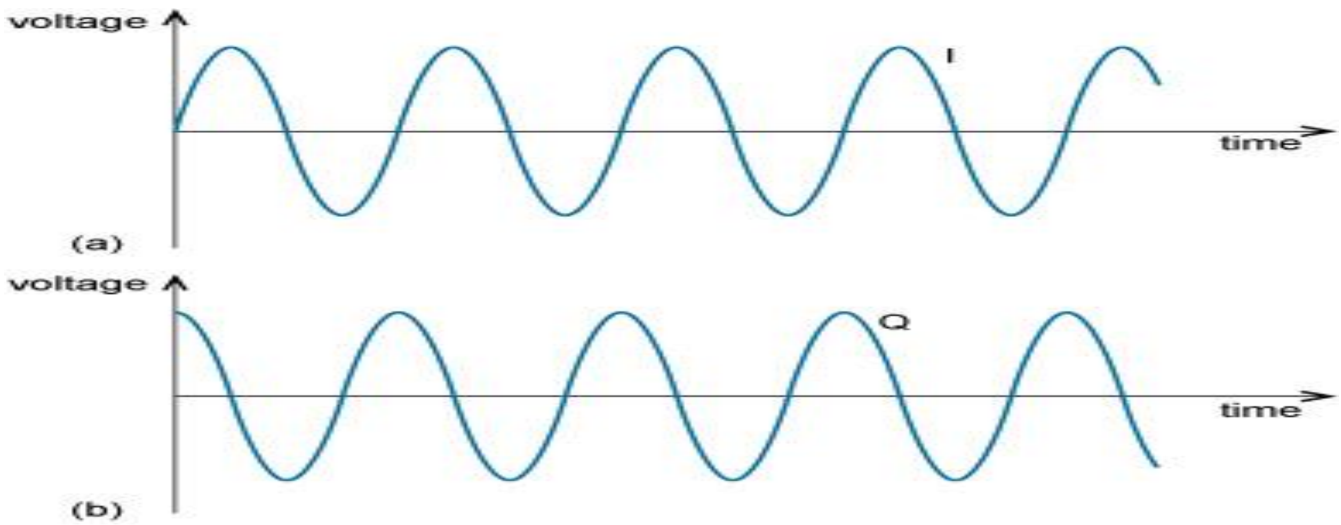

Figure 1.3.1 (a) I (in-phase or sine) wave (b) Q (quadrature or cosine) wave

It may be recognized that I wave in Figure 1.3.2 as a sine function and the Q wave as a cosine function. These functions are orthogonal to each other. If these two signals are orthogonal to each other then, when they are transmitted simultaneously, one can be recovered completely at the receiver without any interference from the other. I and Q waves remain orthogonal if either or both of the wave are inverted.

The set of symbols in QAM can be conveniently represented on a signal constellation diagram (Figure 2.2). The plot of I and Q amplitudes with I on the horizontal axis and Q on the vertical axis. Each dot in Figure 2.2 is a symbol as it represents a unique combination of amplitude and phase of I and Q waves. So, in each symbol period, only one of the 'dots' is transmitted. As there are 16 symbols, this version of QAM is called 16-QAM.

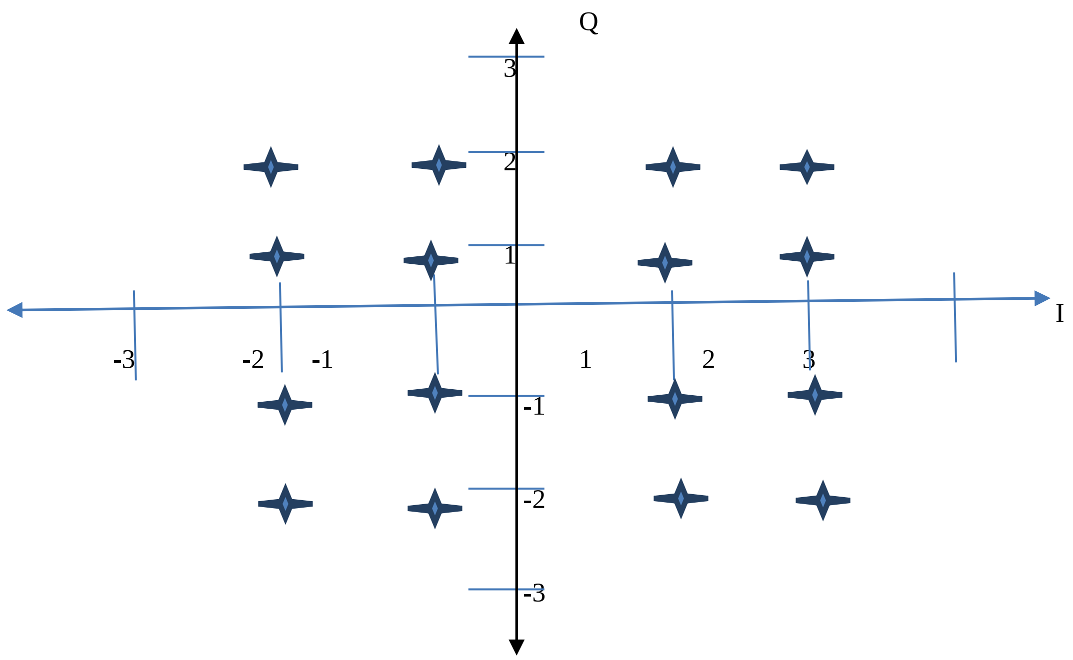

Figure 1.3.2 Constellation diagram for 16-QAM.

To understand what each dot in the diagram represents, take the top left one. This represents a symbol where the Q wave is at an amplitude of 2 and I wave is at an amplitude of –2. The minus sign means that I wave is inverted (or phase shifted by 180°) relative to Q wave in Figure 2.2.

As the number of symbols increases, more data bits can be transmitted per symbol. For example if we use 64-QAM, is a QAM scheme with 64 symbols, and 256-QAM is a scheme with 256 symbols. 256-QAM conveys 8 bits per symbol (as $256 = 2^8$). As a constellation point is away from the origin, the more power is required in the signal for the scheme. It could be necessary to keep the maximum signal power constant whether we are using 16-QAM or 256-QAM. This would mean packing the points closer together in 256-QAM than in 16-QAM. However, if the points are closer to each other then adjacent symbols will be more likely to be misinterpreted at the receiver as a neighbouring symbol. The effects of noise is to add a degree of uncertainty about which symbol has arrived and which not at the receiver.

1.6. OPTICAL FIBER NON LINERITIES

When the optical intensity increases inside the optical fibres, then the refractive index of the fiber changes. The propagation characteristics of a wave becomes a function of optical power. Unlike, linear fiber optics where the propagation constant is a function of fiber and the wavelength only. Here the propagation constant becomes a function of optical power also in addition to the other parameters. Inside a single mode optical fiber, an optical power of few tens of milli Watt (mW) can make the medium as a non-linear medium. As the optical fiber becomes a non-linear, the pulse propagation gets significantly modified and some new frequencies get generated inside the optical fiber.

The spectrum of the output signal is not same as of the input signal. As the large optical power is required to observe the non-linearity in the bulk of a medium generally, whereas optical non-linearity can be easily seen inside an optical fiber with very low optical power of few tens of mW. Efficiency of non-linear effect is proportional to the optical intensity i.e. Optical Power per unit area and the interaction length. We can avoid non-linearity in the system by keeping low optical power levels of input. By understanding the non-linear signal propagation with in channel, we can create intelligent use of it for increasing the transmission capability of the optical fiber.

Further if we consider the non-linearity's of a fiber at different wavelengths, the fiber shows less attenuations at .850 µm, 1.310 µm and 1.550 µm keeping in view of the hint in reference [24]. So that for fiber optic communication system, we took the work for the improvement of regenerator spacing. One of the feasible strategy in this approach is to reduce the Amplified Spontaneous Emissions (ASE) and whereas increment in the optical signal to noise ratio (OSNR) [25]. In a Laser Source for optical communication the excess ASE is an unwanted parameter [26]. We are considering all the above parameters for calculating the spacing of the regenerators.

2. FIGURE OF MERIT (FOM)

For a large capacity long haul digital coherent transmission through a dispersion uncompensated link yields great benefits, such as high spectral efficiency with optimal modulation of the signal and low nonlinearity of the transmission link [27]. An important benefit is that NLI can be predicted by the GN model theory [28]. Increase in OSNR and transmission distance can be predicted by figure of merit (FOM) theory [29] - [32] of the optical fiber.

An uncompensated DWDM transmission link has been taken that have multiple spans composed of a transmission fiber and an EDFA without distributed Raman amplification. That is designed for the calculation of regenerator spacing in a transmission systems. Each span have certain losses, which are Non Linear losses (NLI), fiber losses and splice losses at both ends of the transmission fiber.

Further, it is supposed that these will be compensated by the amplifier gain closely. As per the GN model theory [28] the NLI is treated as an additive noise. Optical signal to noise ratio (OSNR) is generalized as [27] -

$$OSNR = P_{ch} / (P_{ASE} + P_{NLI}) \quad [27]$$

Where, $P_{ASE} =$ Power of Amplifier ASE
$P_{NLI} =$ Power of Amplifier NLI

3. METHODOLOGIES

The methodology used here to accomplish the above said objectives involves the following steps.

The steps are as:-

1) Analysis of the theoretical formulation
2) Application of theoretical formulation on ULAF

The first step involves the study of existing literature available and data analysis of the collected data. The second step involves the application of theoretical formulation on ULAF data to find out results for improving their properties in future.

4. ESTIMATION OF FIGURE OF MERIT (FOM) FOR ULAF

As per the specification of Tera Wave® ULL Single-Mode Optical Fiber designed for terrestrial optical networks. That have large area of 125 µm2, which is ultralow loss ITU-T G.654.B and ITU-T G.654.E fiber [33]. This fiber has optimized for long haul transmission in the C- and L-bands (1530 nm – 1625 nm) at 100 Gb/s and 400 Gb/s [33]. The core of this fiber is with an effective area of 49% larger than G.652.D single-mode fiber to reduce nonlinear effects [33]. The parameters of the considered fiber are as [33]:-

Serial Number		Product Specifications [33]	Tera Wave® ULL Single-Mode Optical Fiber [33]
1		Physical Characteristics	---------
	A	Clad Diameter	125.0 ± 0.7 μm
	B	Core/Clad Concentricity Error (Offset)	≤ 0.8 μm
	C	Coating Diameter (Natural)	240 - 250 μm
	D	Coating-Clad Concentricity Error (Offset)	≤ 12 μm
	E	Standard Reel Lengths	Up to 50.4 km (31.3 miles)
	F	Optical Characteristics	---------
2		Attenuation Maximum at 1550 nm	≤ 0.17 dB/km, typical 0.168 dB/km
	A	Range (1525 – 1575 nm) at Reference λ 1550 nm value of α	0.03
	B	Chromatic Dispersion at 1550 nm	≤ 22 ps/nm-km
	C	Chromatic Dispersion Slope at 1550 nm	< 0.070 ps/nm 2 -km
	D	Group Refractive Index at 1550 nm	1.465
	E	Mode Field Diameter	12.4 ± 0.5 μm
	F	Effective Area at 1550 nm	Typical: 125 μm2

As per the theory of FOM [27], [29] - [32], equation numbers 6 and 7 of reference [27] are applied for the OSNR and FOM. A channel length of 100Km of ULAF has been considered for the transmission with fiber effective core area A_{eff} (125 μm^2). The theory of FOM was applied on the data

For the link with following parameters a fiber-independent fitting parameter *C*2 of 38.4 dB [27], and the splice loss estimated from the actual span loss. The additional a fiber independent fitting parameter *C*1 is −6.6 dBm/ch [27] and an NLI mitigation coefficient k_{NLC} is 0.6 [31]. The link assumed with pure silica core fibers with constant n_2 = 22 μm^2/GW and *D* = 21 ps/nm/km [27].

5. RESULTS AND DISCUSSION

Based on theory of FOM [27], [29] - [32], equation numbers 6 and 7 of reference [27] are applied for the OSNR and FOM for the said link and we get the following result.

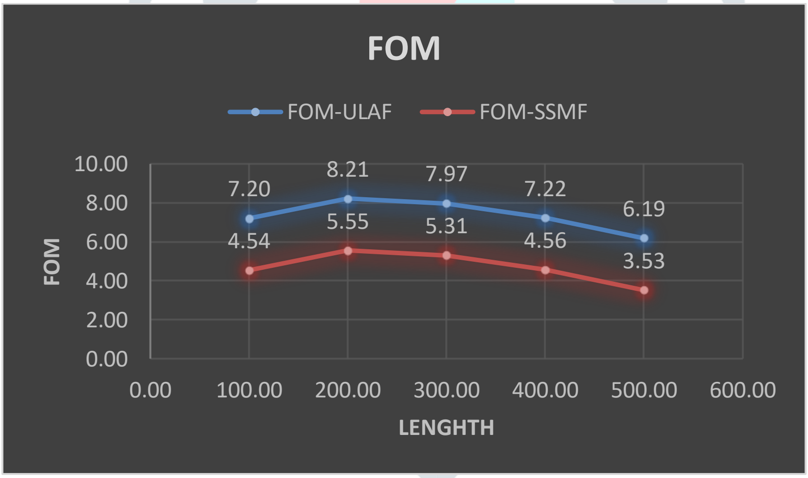

Figure 5(a) trend lines for the FOM of ULAF and SSMF for the link over length of 500Km.

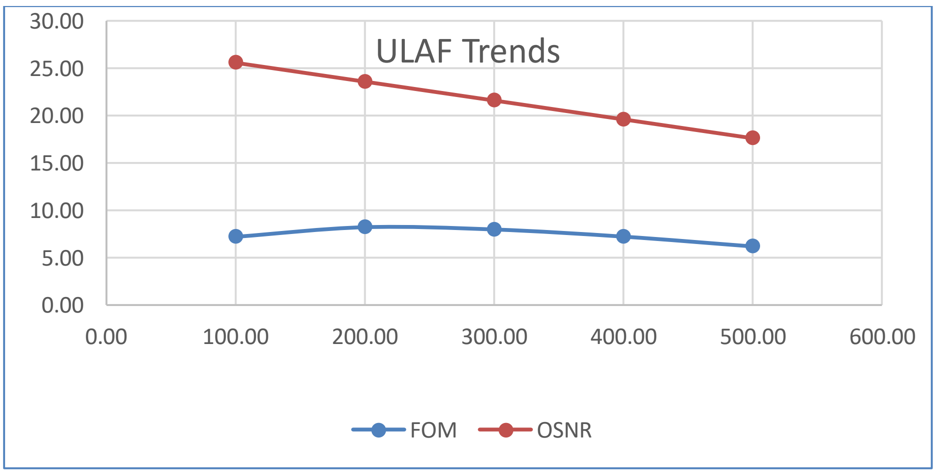

Figure 5(b) trend lines for the FOM and OSNR of ULAF for the link over length of 500Km.

6. CONCLUSION

An approach has been explored to enhance the capacity of an optical fiber system network by advancement in the optical fiber. Further by this advancement an improvement in the OSNR and FOM for the ULAF, so that signal will travel for longer distance with adequate value of OSNR in ULAF in comparison of SSMF. Hence the distance of placing of amplifiers will increase as well as the signal will have better OSNR value in comparison of SSMF, so it will travel longer distance in ULAF in compare of SSMF. So the spacing between the regenerators will be enhanced.

As we have considered the fiber nonlinearity and its exchange with the input power. Increase in spacing between the regenerators depends upon the optical fiber nonlinearities. Further DWDM revolution gave the improvements to increase the limit. Thus by increasing the spacing between the regenerators will results in to decrease the cost for the optical fiber communication networks.

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