Limitations on Light-Wave Communications Imposed by Attenuation and Dispersion in Optical Fibers

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Abstract— **Single mode optical fibers have already been one of the major transmission media for long distance telecommunication, with very low losses and high bandwidth. In optical fiber communication systems used single mode fiber, fiber attenuation and chromatic dispersion are two fundamental limitations. Attenuation limits the maximum distance, while dispersion limits the information capacity of the fiber. In the present paper, a computer simulation has been made for single mode optical fiber systems to study the limitations on light wave communications by attenuation and dispersion in this mode of optical fibers used for long distances. It is found that there are linear effects of chromatic dispersion and attenuation increase with increasing the distance along the fiber optic length.**

***Index Terms*— Fiber Optic Communication, Fiber Attenuation, Fiber Dispersion.**

I. Introduction

Optical fiber transmission is used from a short distance below one meter up to transoceanic distances in undersea cable. Single-mode fibers are now established as prime transmission medium for communications. A single-mode optical fiber is an optical fiber that carries a single ray (Mode) of light transmission. A mode is the path the laser light travels down the fiber. For single-mode optical fiber, the fiber has a small core diameter which only allows one mode. With only one mode, the signal is free of distortion and therefore the fiber optic medium has extremely long reach; as such, single-mode fiber is used for high speed signal transmission over long distances. The goal of communication channel in optical fiber networks is the lowest possible loss simultaneously with the highest possible bandwidth [Salah (2011)]. Advantages of fiber optic as a medium of transmission are many from unlimited bandwidth, immunity from both radio frequency interference and electromagnetic interference to excellent attenuation properties, when compared with other transmission media like coaxial cable [Thyagaraian (2007)]. Attenuation is the loss of optical power as light travels along the fiber. This loss in fiber depends on the wavelength of the light propagating within it [Agrwal (2001) &Agrwal (2002)]. Attenuation is caused by absorption, scattering, and bending losses. These losses increase with the distance through the fiber optic [Gowar (1984) &Saeid (2009)]. Another system impairment called dispersion, which is the spreading out of light pulses in time which also degrades the original transmitted signal and may cause errors as well. Light from a typical optical source will contain a finite spectrum. The different wavelength components in this spectrum will propagate at different speeds along the fiber eventually causing the pulse to spread. When the pulses spread to the degree where they 'collide' it causes detection problems at the receiver resulting in errors in transmission.

Fiber losses and dispersion in single mode optical fiber are two fundamental limitations in optical communication system design [Saeid (2007)]. There are three main bandwidths (windows) of interest in the attenuation spectrum of fiber the first window is at 800-900 nm, here there is a good source of cheap silicon based sources and detectors. The second window is at 1260-1360 nm, here there is low fiber attenuation coupled with zero material dispersion. The third window of interest is at 1430-1580 nm where fiber has its attenuation minimum. In a 1310 nm wavelength, standard single mode fibers have minimum chromatic dispersion but higher loss. A 1550 nm wavelength is suitable for high bit-rate, long-haul transmission owing to high capacity and low transmission loss of the fiber [Mohammed (2004)]. Typically the telecommunications industry use wavelengths in the third window which coincides with the gain bandwidth of fiber amplifiers.

II. Optical Communication System

The typical optical communication system consists of a transmitter, optical source, transmission media, a detector and a receiver. The fiber optic link system is similar in concept to any type of communication system [Hainberger (2004) & Michael (2006)]. The transmission medium consists one of an optical fiber cable type and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier [Singh (2007)].

There are many variables enter into system design, such as operating wavelength, coupling losses, splice and connecter loss, fiber attenuation and dispersion. Many of these variables are interrelated, for example, fiber attenuation and dispersion depend on operating wavelength as well as the fiber type. Also there are additional variables involves in optical link design, such as power budget, rise time budget, and the transmission distance which is equal to optical fiber length. Figure (1) shows an optical fiber communication system.

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III. Attenuation and Dispersion:

The type of pulses that used in the simulation is Gaussian pulse, [Pearce (1999)]. The pulse envelope in time t at the spatial position z, propagating from transmitting to the receiving end of an optical fiber communication system is A(z,t). This pulse is described by the non-linear Schrodinger equation given in [Saeid (2013)] as:

$$\frac{\partial A}{\partial z} + \frac{\beta_1 \partial A}{\partial t} + \frac{i}{2}\frac{\beta_2 \partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\Delta\beta A \quad (1)$$

where: A is the pulse envelope, β1 is the first order dispersion, [Saeid (2008)]. β2 is the second order dispersion parameter causes pulse broadening due to chromatic dispersion. α is the attenuation coefficient of the fiber.
The term with Δβ includes the effect of fiber loss and nonlinearity. It is evaluated in [Agrwal (2001)] and given as:

$$\Delta\beta = \gamma |A|^2 \quad (2)$$

where γ is the non-linear parameter of the fiber. i is a complex vector notation.
In obtaining Eq. (1) the pulse amplitude A is assumed to be normalized such that |A|^2represents the optical power. This equation describes propagation of picosecond optical pulse in single-mode fibers. It is often referred to as the nonlinear Schrodinger (NLS) equation because it can be reduced to that form under certain conditions. It includes the effects of fiber losses through α, of chromatic dispersion through β1 and β2, and of fiber nonlinearity through γ.
The pulse envelope moves at the group velocity $vg \equiv 1/\beta_1$ while the effects of group-velocity dispersion (GVD) are governed by β2. The GVD parameter β2 can be positive or negative depending on whether the wavelength λ is below or above the zero-dispersion wavelength $\lambda_D$of the fiber.

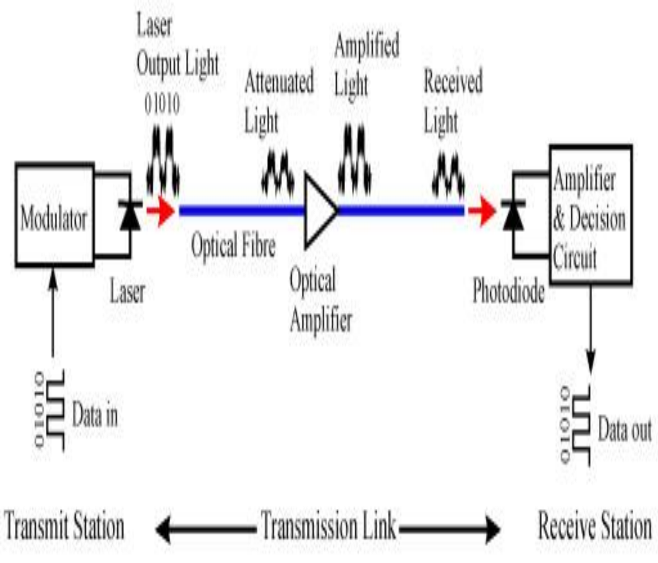

Figure (1): Optical fiber communication system.

In the anomalous-dispersion regime ($\lambda > \lambda_D$), β2 is negative, and the fiber can support optical solutions. In standard silica fibers, β2 ~50 ps^2/km in the visible region but becomes close to - 20 ps^2/km near wavelengths ~ 1.5 μm, the change in sign occurring in the vicinity of 1.3 μm.

The solution of equation (1) is obtainable using split-step Fourier method [Min (2003)]. Considering the effect of attenuation and dispersion, which are added in every step, that the pulse position is at zero center-frequency, the solution yields to:

$$A(L,\omega) = A(0,\omega) exp\left\{\left(\frac{i\beta_2 \omega^2 - \sigma}{2}\right) L\right\} \quad (3)$$

It is clear that the signal amplitude decreases as it is propagated along the line, while the dispersion makes the signal to be broadened. The attenuation per unit length is given as [Saeid (2012)]:

$$Attenuation\ (\alpha_{dB}) = \frac{10}{L} log_{10}\left(\frac{P_t}{P_r}\right) \quad (4)$$

The attenuation is measured in dB/km, L is the fiber length expressed in kilometers, P_t is the transmitted power and P_r is the received power. Attenuation is caused by absorption, scattering, and bending losses [Gowar (1984)]. Each mechanism of loss is influenced by fiber material properties and fiber structure. However, loss is also present at fiber connections. So attenuation increases with the distance through the fiber optic.
β_2 is called the group velocity dispersion, the time delay between different spectral components separated by a certain frequency interval is determined from the dispersion (β_2). The propagation distance after which a Gaussian pulse is broadened is termed the dispersion length and given by [Agrwal (2001)].

$$\beta_2 = \frac{-\lambda^2}{2\pi c} D \quad (5)$$

$$L_D = \frac{-t_o^2}{|\beta_2|} \quad (6)$$

where D is the dispersion coefficient, t_o is the pulse full-width at half-maximum amplitude. The input is represented by a Gaussian pulse and it is defined as [Saeid (2008)].

$$A(t) = A_0 exp\left[-\left(\frac{t - t_o}{2\sigma^2}\right)^2\right] \quad (7)$$

with full width at half amplitude:

$$\tau = \sqrt{ln2}\,\tau_e = 0.833\tau_e \quad (8)$$

and with root-mean-square pulse width:

The Gaussian pulse is used because the optical sources have a distribution of power with wavelength that is approximately Gaussian distribution in form [Saeid (2008)].

IV. Simulation:

In general, a simulation is a computer model of a part of a real-world system, [Rossi (1997) & Zheng (1998)]. In the present paper the simulation is a computer model of a single mode optical fiber link system, includes attenuation function, dispersion function, and propagation function. The method of propagation is divided the path length of signal propagation in steps to add the effective of attenuation, and dispersion in every step. This method called split-step Fourier, [Min (2003) &Sinkin (2003)], shown in Figure (2).

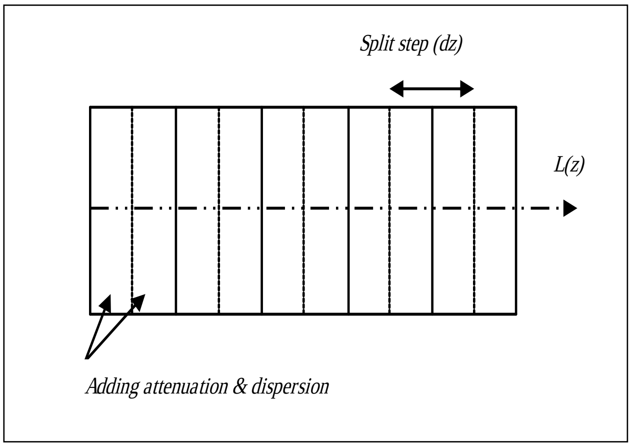

Figure (2): Split-step Fourier method.

In the simulation the input signals taken as Gaussian pulses, with bite rate of 5Gbps, are converted in to a shape that the computer can deal with it. So, the signals must first be represents in the form of numeric arrays. These arrays contain samples of the amplitude profile at N equally spaced points [Saeid (2013)]. The sampling resolution must be fine enough to resolve all spatial feature of the amplitude profile, at the same time it must sparse enough to allow reasonable processing speed on a computer.

V. Results and Discussion:

In the simulation of this work, Gaussian pulse has taken as an input signal with bit rate of 5Gbps. Two optical transmissions affect that limit system speed and transmission distances are studied, which are the effects of attenuation and dispersion using MATLAB [Chapra (2008), Moler (2004) &Halvorsen (2011)]. Figure (4) illustrates the effects of attenuation and dispersion both at the same time at distances 15, 25, 50, 75 and 100 km, respectively.

It is clear from the comparison between the results at deferent distances, that the effects of chromatic dispersion and attenuation increases linearly with increasing the distance along the fiber optic communication systems. As the input signal propagates degradation occur due to these effects and eventually lead to errors in detected signal which is lead to detection problems. Therefore at certain distances there is need for repeaters and dispersion management system to overcome such signal distortions.

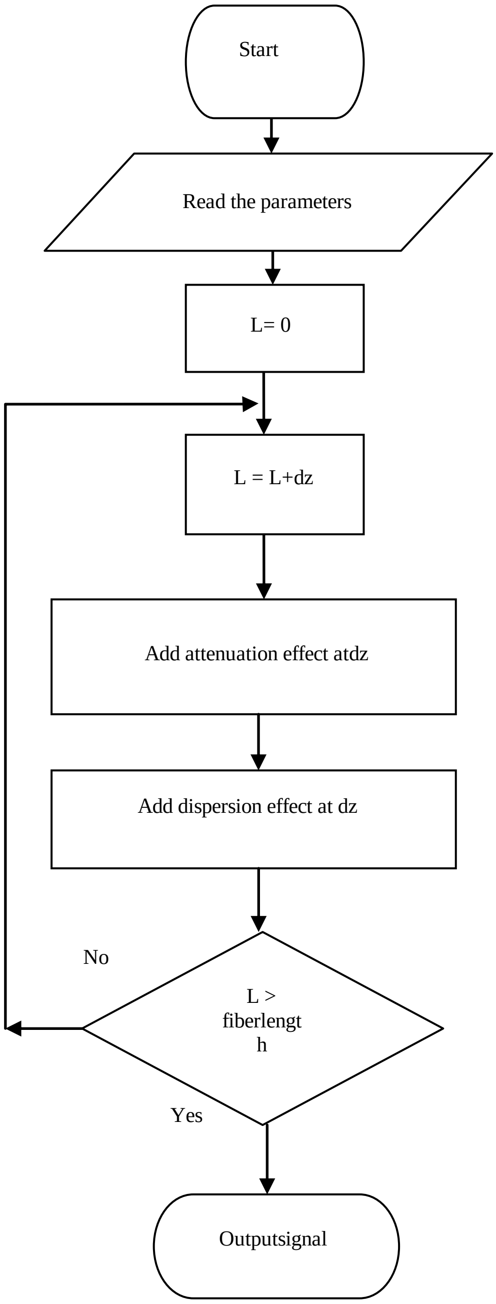

Figure (3):Flow chart of thesimulation.

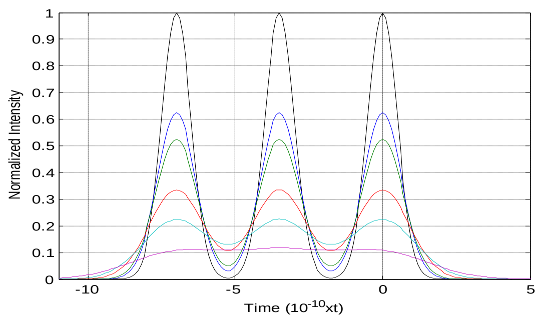

Figure (4): Effects of attenuation and dispersion both at the same time,
at distances 15, 25, 50, 75 and 100 km, respectively.

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