Dispersion-A Bottleneck in Optical Fiber Communication

Prof. C.D.Bhos Prof.S.D.Pansare Prof.Ms.R.P.Labade

Amrutvahini College of Engineering, Sangamner, Savitribai Phule University of Pune

bhos.chandrakant@rediffmail.com sdp221597@yahoo.co.in rplabade@gmail.com

Abstract:

This paper gives a review of various reasons for dispersion and few possible solutions to minimize it. We have presented the overview of dispersion effect in optical fibers and three methods to compensate it namely Optical Phase Conjugation, Convex Optimization and Electronic Dispersion compensator. Optical fiber communication has become one of the most attractive communication methods now days. It is all due to its advantageous features, which includes enormous potential bandwidth, very low transmission loss, no electromagnetic interference, no crosstalk, low cost compared to other mediums etc. Optical fiber communication is found to be applicable in various practical applications including a backbone for the internet traffic. But beyond all these positive factors, it has some major problems associated with it which affect its performance badly. These mainly include attenuation and dispersion. In broad view attenuation affects signal to noise ratio and dispersion affects bandwidth i.e. indirectly a maximum data rate which an optical fiber communication system can offer.

Keywords: optical fiber, dispersion, optical phase conjugation ,convex optimization, electronic dispersion compensation etc.

I. HISTORY OF OPTICAL COMMUNI-CATION

Since very long period human being is using light as a carrier for transferring information. Simple systems such as signal fires, reflecting mirrors were used to serve a means for communication. In 1980s Alexander Graham Bell invented a method for transmission of speech using light beam with the help of photo phone. However, although some research in optical communication continued in the early part of the twentieth century, it was applicable only for short distance communication due to lack of proper optical source and medium.

The development in optical fiber communication was progressed further and in the early 1960s the laser was invented which became a very suitable optical source. In 1966 Kao and Hockham and Werts proposed an optical communication via optical fibers fabricated from glass to avoid degradation of the optical signal by the atmosphere . Initially the optical fibers exhibited very high attenuation (i.e. 1000 dB/km) . But within the space of 10 years optical fiber losses were reduced to below 5 dB/km and suitable low-loss jointing techniques were also developed.

The optical fiber communication wavelength range is mainly divided in three windows. [1] Initially in early 1970s the optical fiber had a low loss window around 850nm. Also the semiconductor optical sources were made of GaAs which emitted a light at nearly 800nm. This 800nm band is called the 'First window'. After some improvements in the manufacturing process nearly about 1980s the low loss profile was shifted to 1310nm and other around1550nm. These are called second and third window respectively. In third window loss decreased up to 0.2 dB/km.

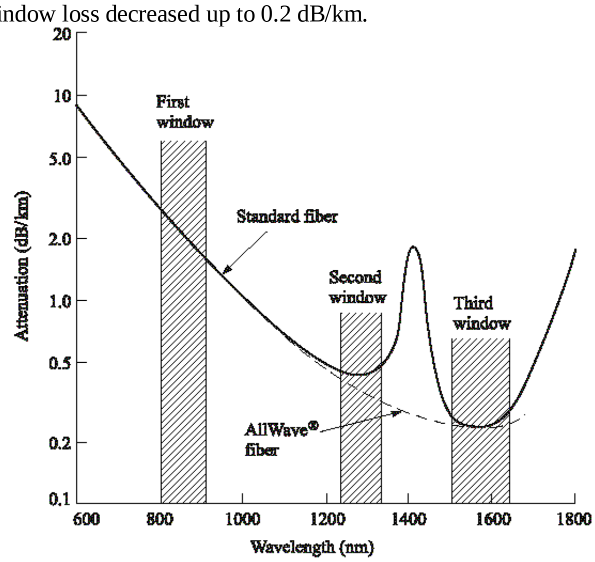


Figure 1: History of Attenuation in Optical Fibers

II. OPTICAL FIBER TECHNOLOGY

A. Basic Structure of Optical Fiber

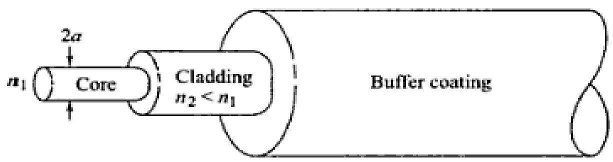
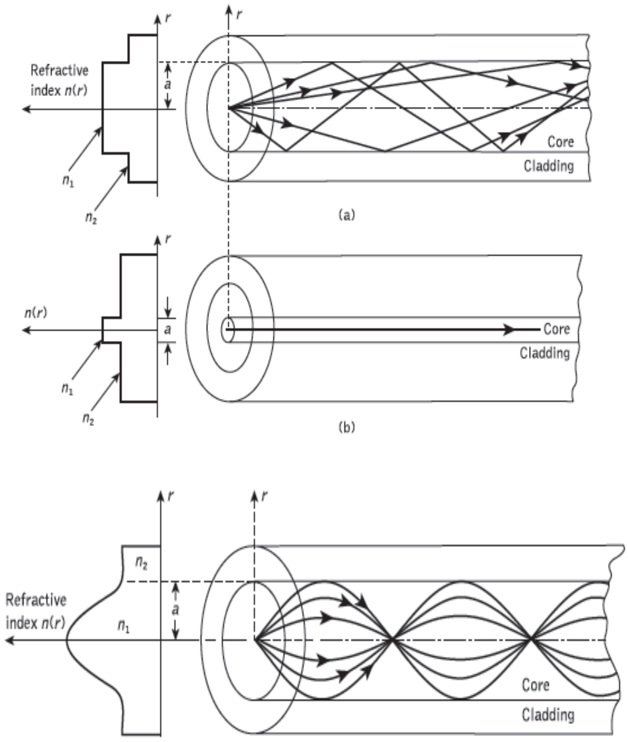


Figure 2: Basic Structure of Optical Fiber Cable

Basically the optical fiber cable consists of three major parts concentric to each other. These are core, cladding and buffer coating. The fiber core is the innermost part which is involved in actual transfer of light signal though it. It is surrounded by an outer cladding which forms a suitable waveguide in conjunction with core for light transmission. For achieving the total internal reflection within a fiber core refractive index of fiber core must be greater than that of cladding i.e n1> n2. Outermost part i.e. buffer coating serve as protective covering for the fiber which increases the mechanical strength of a fiber cable. The light travels though the fiber core by total internal reflection.

B. Types of Optical Fiber

Optical fiber can be categorized according to refractive index profiles of core and cladding and , number of supported modes. [2] According to refractive index profiles of core and cladding fibers are classified as Step Index (SI) fiber and Graded Index (GI) fiber. Whereas according to number of supported modes they are classified as Single Mode (SM) fibers and Multimode (MM) fibers.



(c)

Figure 3: Fiber Types a) Multimode Step Index b) Single Mode Step Index c) Graded Index

III. DISPERSION IN OPTICAL FIBERS

When a light signal propagates though a fiber, it undergoes various loss mechanisms such as absorption, scattering, bending etc. which mainly decreases a strength of light signal.. Along with all these losses a light signal is also affected by another very strong degradation mechanism called as dispersion. In broader sense, dispersion is defined as broadening of a light pulse in time domain as it passes though a fiber. To explain the concept of dispersion consider an optical fiber communication system involving digital signal transmission. Suppose two pulses representing logic are coupled inside a fiber. As these pulses travel along a fiber, they start to broaden due to dispersion. At time instant t1, these pulses are separate. At t_2, due to broadening they overlap with each other, but they are distinguishable. At further distance i.e. at time t_3 they overlap more and at this instant they are barely distinguishable. At instant t_4, they broaden further and overlap greatly with each other and now they are not distinguishable. This situation is called as a Inter Symbol Interference (ISI). This is illustrated in figure 4.

Mathematically, let us consider τ is a pulse width transmitted in a fiber. Suppose after some distance along the fiber, due to dispersion pulse width broadens by same amount τ and it becomes 2τ. The digital bit rate must be

$$B_T \leq 1/2\tau$$

For NRZ pulse stream, maximum bit rate and bandwidth B are related as

$$B_T \max = 2B$$

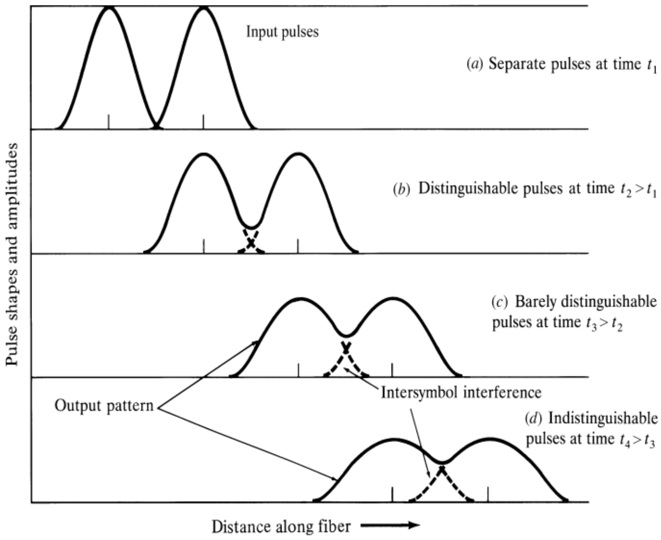


Figure 4: Dispersion in Optical Fiber

Dispersion is a phenomenon related to the variation in velocity of different frequencies (wavelengths) or different modes. The velocity of different frequencies can be different due to intrinsic properties of the medium or due to dispersive nature of the bound structure like the optical fiber. [3] If β is propagation constant, ω is angular velocity, λ is wavelength and c is velocity of light in air, then

Group Velocity is

$$v_g = \frac{\partial \omega}{\partial \beta} = 2\pi c \frac{\partial}{\partial \beta}(1/\lambda)$$

Group Delay per unit length $t_g = 1/v_g$

Pulse Broadening $\tau = \frac{dt_g}{d\lambda}\sigma_\lambda = -\frac{\sigma_\lambda}{2\pi c}\left\{2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right\}$

Dispersion $D = \frac{dt_g}{d\lambda} = -\frac{1}{2\pi c}\left\{2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right\}$

= Pulse broadening per unit distance per unit spectral width (ps/Km/nm)

Dispersion is broadly classified as Intramodal Dispersion and Intermodal Dispersion.

A) Intramodal Dispersion (Chromatic Dispersion):

It is within a single mode of a light. It is due to finite bandwidth of a fiber. It is sub classified into:

i) Material Dispersion: It is due to intrinsic property of a glass material.

ii) Waveguide Dispersion: It is due to bound mediums dispersive property i.e. velocity is a function of frequency.

B) Intermodal Dispersion: It is due to different velocities of different modes of a light signal.

All these mechanisms contribute to a overall dispersion inside a fiber. Typically for a single mode fiber dispersion varies as a function of wavelength as shown in figure 5.

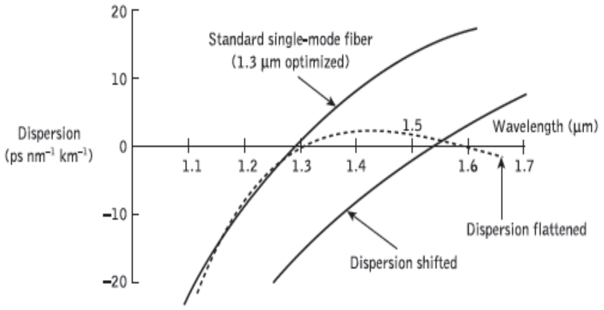


Figure 5: Overall Dispersion for SM Fiber

In simple sense, to reduce the dispersion, the separation between the two consecutive pulses should be more i.e. within a given time number of pulses to be transmitted should less. All this means that possible data rate is less. Hence the dispersion phenomenon reduces the data rate i.e. bandwidth of a system. Hence for achieving the higher bandwidth, dispersion should be minimized by some means. There are various method to do this out of which some are presented next.

IV. FOUR WAVE MIXING ALONG WITH OPTICAL PHASE CONJUGATION

Coherent OFDM system can be dispersion compensated by using the cyclic prefix and four wave mixing (FWM) technique [4]. It uses phased-array effect among the individual subcarriers. But it has one major drawback that a long cyclic prefix is required to compensate the dispersion at the receiver side, thus reducing the data rate..This method improves spectral efficiency. In this technique, dispersion-compensating fibers are placed periodically along the optical fiber link. It decreases the channel memory and allows a reduction in the cyclic prefix overhead. However, the FWM tolerance of such dispersion-managed (DM) links may suffer considerably. Optical phase conjugation (OPC) technique can be applied to DM OFDM systems.

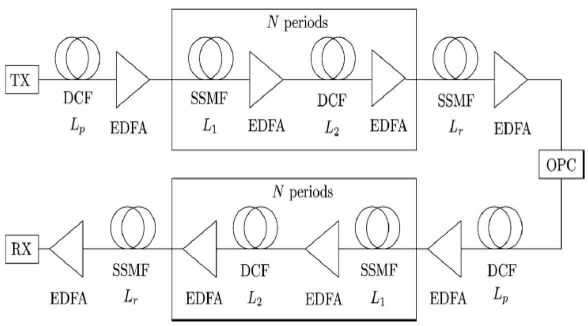


Figure 6: Dispersion profile of a DM OFDM system with a midway OPC module employing pre- and post-compensating fibers.

FWM lights are generated inside the arrays of SSMF and DCF also. The OPC module creates destructive interference between these two lights for a large number of FWM processes. This can be further enhanced by careful adjustment of either the fiber parameters or the compensating span lengths. This dispersion compensation strategy is generally used for applications requiring more flexibility in design rather than higher degrees of nonlinear tolerance.

V. ADAPTIVE OPTICS USING CONVEX OPTIMIZATION

Another method available for dispersion compensation is to use adaptive optics using convex optimization. [5] This method significantly reduces the inter symbol interference generated due to dispersion mechanism. In this technique, the spatial profile of light launched into a multimode fiber is shaped using a Spatial Light Modulator (SLM).

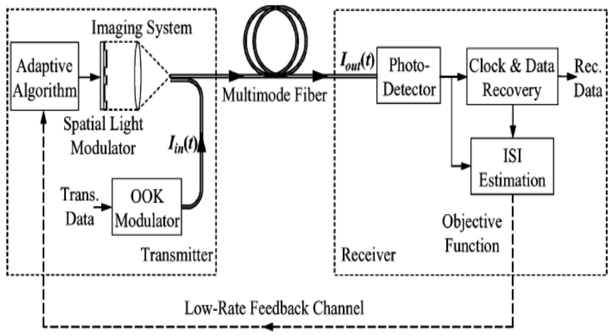


Figure 7: Adaptive Transmission System

The effectiveness of this system can be shown by observing the eye patterns of the signals.

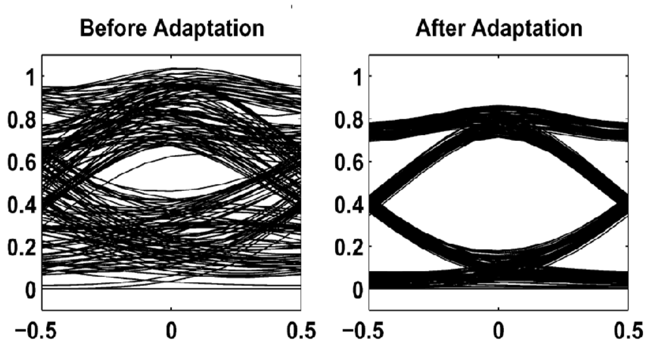


Figure 8: Eye diagram before and after adaptation-1-km, 50μm-core graded-index MMF, with random mode coupling, center launch.

VI. ELECTRONIC DISPERSION COMPENSATOR

This method utilizes linear and non linear equalization techniques. [6] A non linear equalizer called Decision Feedback Equalizer (DFE) is used in a system. This can effectively compensate the non linear dispersion effects generated along the fiber link. But, at very high data rate, the implementation of DFE is difficult due to first feedback-loop latency requirement. Solution to this problem can be implemented by using an Analog DFE which consist of four-tap linear analog feed-forward filter and one-tap non linear analog feedback filter. Figure 10 shows the significant improvement in the Eye diagram after the use of ADFE.

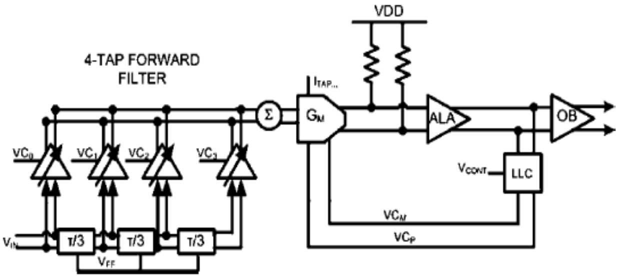


Figure 9: Adaptive DFE

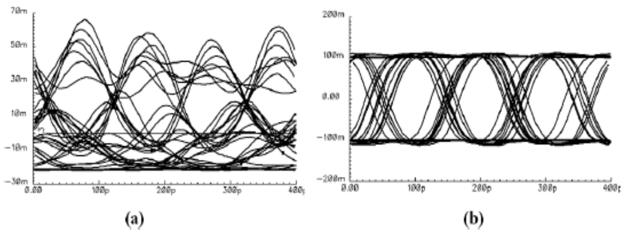


Figure 10: Eye Diagrams for a) 10Gbps after 120km SMF b) After ADFE

VII. CONCLUSION

Dispersion is one of the major problem associated with optical fibers. It significantly decreases the bandwidth of a system. We reviewed three methods for dispersion compensation. Each has its own pros and cons. Optical phase conjugation method utilizes cyclic prefix which degrade the maximum possible data rate of the system. Convex optimization method includes the use of Spatial Light Modulator and no need of any cyclic prefix. The last discussed method i.e. electronic dispersion compensator utilizes an electronic circuitry for dispersion compensation. It utilizes linear as well as nonlinear method for equalization. This is more suitable method avoiding necessity of cyclic prefix and can enhance the performance at very higher data rates. In this paper, we have discussed only three methods out of many possible methods to achieve the dispersion compensation which may give even better results. By compensating the dispersion inside a fiber one can apply optical fiber technology for long-haul applications and at very higher data rates.

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