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Maximizing Capacity in Optical Fiber Networks: Overcoming Dispersion and Nonlinear Barriers for Next-Generation Transmission

Meshari Ibrahim Alhamdan[1], Mansour Mohammed Alhazmi[2],
Maher Musaed Althobyani[3], Mohammed Ali Aljohani[4], Majed Ali Alshamrani[5]

[1]Technical College of Telecom & Information, Riyadh
[2]Technical College of Telecom & Information, Jeddah
[3]College of Applied Technology, Yanbu
[4]College of Applied Technology Yanbu
[5]College of Applied Technology Yanbu

The Technical and Vocational Training Corporation (TVTC), Saudi Arabia.

ABSTRACT

High bit rate fiber transmission has become an important telecommunication infrastructure due to the increase in growth and demand for capacity in world-wide optical networks. Many telecommunication companies use optical fibers for different applications such as internet communication, to transmit telephone signals, or for cable television signals. The process involved in communications using fiber-optics follows specific steps: a transmitter creating the optical signal, the fiber relaying the signal, receiving the optical signal which then is converted to an electrical signal. Optical fibers have many advantages over existing copper wire over long-distance and high-demand applications due to lower attenuation and interference while providing enormous and unsurpassed transmission bandwidth. However, signal distortions are a limitation in optical fibers due to dispersive and nonlinear effects. Compensating for fiber dispersion and nonlinear effects improves transmission performance. In recent years, a lot of research has been conducted on dispersed managed systems, modulates on formats, and fiber types to achieve higher transmission capacity. The major purpose of optical fiber communication systems is to transmit the highest amount of data over the longest distance possible with the fewest errors possible to achieve the maximum system's capacity.

INTRODUCTION

A cylindrical dielectric waveguide is the mere definition of an optical fiber. It is composed of low-loss materials which usually is fused with high grade silica glass. A refractive index, the center of the waveguide, is placed slightly higher than the cladding, which is the outer medium. The position of each object allows total internal reflection to occur by that guiding the light along the fiber axis. Hence, fiber optics acts as a medium which uses light to carry information between two different points. Fiber optics do not have electrical characteristics on the contrary to copper form of transmission. A transmitting device, in basic fiber optic systems, converts electrical signals to light signals. The light is then carried by an optical fiber cable which is then converted back to an electrical signal by a receiver. Fiber optic systems can be very simple, such as local area networks, or very complex and expensive, such as cable television trucking.

Due to the high and rapid increase in commercial and consumer demand for internet services and telecommunication capacity, fiber optics communication use became very popular. The required information capacity is provided by such a technology with a capability larger than that of copper cable or wireless connections. Wavelength division multiplexing introduced a significant improvement to the transmission capacity in optical communication.

Over the last four decades, tremendous changes in the field of communication led to several economic and technological benefits. Low-loss optical transmission fibers have played a major role in ensuring the success of technologies involving optical communication. Around the year 1975, studies on fiber-optic communication systems started to take their turn in the research world. In the 1990's, the commercial introduction of optical amplifiers revolutionized the fiber optic telecommunication systems. This enabled optical signals to be conveyed over long distances without the need of it to be regenerated (Li, Willner et al. 2008).

Several advantages are offered by fiber optics such as bandwidth (10^{13} to 10^{14} Hz), cost in comparison to metallic conductors, and resistance to nuclear radiation and electromagnetic interference. However, many challenges are encountered with any communication system and the two major performance limiting factors in fiber optics are dispersion and attenuation. Dispersion has a great effect on optical fiber communication performance due increased inter chip interference and less optical power received (Kaur and Kaur 2014). Attenuation then is a consequence of the loss of optical power as light travels down the fiber. Microbending or macrobending can be the cause behind attenuation. The question is then how can dispersion and attenuation be minimized in order to achieve higher performance from optical fiber communication? The literature demonstrates several methods that compensate for dispersion and fiber materials that reduce attenuation for better transmission. However, further research is required across different fields to find the appropriate and specific materials and methods for ultimate performances.

LITERATURE REVIEW

Two types of dispersion are known to exist in optical fibers; modal (inter-modal) and chromatic (intra-model) dispersion. Compensating for signal distortions is a concept that dates to a few years back. In 1994, a dispersion compensating fiber (DCF) was designed and fabricated by Antos and Smith (Antos and Smith 1994). The fiber, having a large negative waveguide dispersion, is specific to the LP_{01} mode in order to compensate for transmission fiber dispersions. The positive dispersion magnitude in the transmission fiber in this case is equal to the negative dispersion in the DCF, due to its specific length, leading to a net pulse broadening of zero. For compensations in fiber-optic networks, fiber Bragg grating (FBG) was employed by Hill et al. (Hill, Takiguchi et al. 1994).When the sign of dispersion can be controlled easily and reflection mode is in play, FBGs exhibit large dispersion. Compensation for dispersion of very long optical fibers have been shown to be achievable by relatively short Bragg grating.

One of the studies on solutions to minimize dispersion theoretically suggested the use of a phase conjugation mirror that compensates signal propagation distortions (Pepper and Yariv 1980). In addition, another study adopted numerical demonstration of removing the effect of group-velocity dispersion (GVD) and SPM by the conjugation of the signal near the mid-point of the fiber-optic link (Fisher, Suydam et al. 1983). Four wave mixing FWM compensation using mid-point OPC was demonstrated in wavelength division multiplexing (WDM) systems by Watanabe and Chikama (Watanabe and Chikama 1994). Later on, polarization multiplexed signals were also shown to be compensated for dispersion by OPC (Martelli, Boffi et al. 2009). Mid-point optical phase conjugation (OPC) are limited in compensation performance when there is no symmetry between the power profile with respect to OPC location. Systems using lumped amplification, for example EDFA, are known for this non-symmetrical association on the contrary to fiber-optic systems with Ramam amplification which have a better symmetry of power profile. Using mid-point OPC has been shown by Solis-Trapala et. al. (Solis-Trapala, Inoue et al. 2014) to significantly improve performance in a WDM system that incorporates bidirectional Raman pumping amplification and dispersion-flattened non-zero dispersion-shifted fibers (NZDSFs).

Other forms of compensation of fiber dispersion and nonlinear effects known as the optical back propagation (OBP) were also proposed by Kumar et al. (Kumar and Yang 2011) The first study demonstrated the OBP module to compensate fiber dispersive and nonlinear effects through its special design and by being placed at the end of a fiber-optic link. The OBP undoes distortions by reversing signal propagation and that is due to the OBP module design which consists of DCFs and nonlinearity compensators. A pair of highly nonlinear fibers (HNLFs) are utilized for the nonlinearity compensator with an effective negative nonlinear coefficient. Good transmission performance is provided by this OBP scheme but it increases the complexity of the receiver due to the requirements of pumps and their polarization alignment with signal. To improve the OBP scheme, the module was then designed to consist of an OPC in addition to two types of fibers, HNLFs and short lengths of high-dispersion fibers (HDFs). These components in this OBP scheme were linked in a similar way as in the split-step Fourier scheme (SSFS) that was used to solve the non-linear Schrodinger equation (NLSE). In comparison to the mid-point OPC, using lumped amplifiers, OBP scheme has shown to provide better transmission performance. To further improve the OBP scheme the minimal area mismatch (MAM) technique was introduced. This enhanced the reach in comparison to when uniform spacing for the given step size is used. (Shao and Kumar 2012, Kumar and Shao 2013)

Recent advances in digital dispersion compensation (DSP) added to the compensation techniques to impair signals in coherent fiber-optic communication systems. Chromatic dispersion was demonstrated to be compensated in a study by Taylor (Taylor 2004) through the use of coherent detection and DSP without the need to use optical phase locked loops (OPLLs). In another study, using a finite impulse response (FIR) filter was shown to compensate for dispersion in the time domain (Savory 2008). This type of filter has a non-recursive structure and its implantation can be by utilizing a tapped delay line. One disadvantage of such filters is that in long-haul systems high power consumption is required due to the high number of FIR traps needed with the increase of accumulated dispersion. An alternative solution was set forward by Goldfarb and Li (Goldfarb and Li 2007) which demonstrated the use of infinite impulse response (IIR) filters to compensate chromatic dispersion. In comparison to FIR filters, IIR filters are more computational efficient but require buffering. Thus it is more efficient to use fast Fourier transforms (FFTs) instead of time domain filters when compensating for large accumulated dispersion in the frequency domain. In polarization multiplexed coherent systems, the use of a digital equalizer was also investigated for compensation of chromatic dispersion and PMD. Ip and Kahn (Ip and Kahn 2007) found that when the oversampling rate is at least 3/2 and enough equalizer taps are used, full compensation of chromatic dispersion and first order PMD distortion is achieved. In a coherent fiber-optic system which uses homodyne detection, compensation of dispersion was achieved using DSP.

Another form of dispersion compensation technique is through using digital back propagation (DBP). In this scheme, the converted optical signal into a digital signal is passed through a virtual fiber. This fiber and the transmission fiber have the same magnitude of loss, dispersion and nonlinear coefficient but are opposite in sign. Several enhancements were introduced to using DBP for compensation. Liu et al. (Li, Chen et al. 2008) demonstrated that by using dispersion folded DBP in dispersion managed WDM fiber-optic systems, intra-channel and inter-channel nonlinear impairments are successfully mitigated. However, in polarization multiplexed WDM systems, compensation performance of DBP can be affected due to PMD. In order to have a better understanding of this effect, Yaman and Li (Yaman and Li 2009) investigated PDM transmission systems with DBP implementation. It was observed that the DBP technique is substantially impaired in PMD systems when simulations were applied. For effective compensation then in these systems, DBP implementation has to be at every fiber span to keep up with the rotations of the polarization status. An improved split step DBP technique was then reported by Mateo et al. (Mateo, Zhou et al. 2011) to compensate for PDM transmission systems. A channel-by- channel basis of DBP implementation was adopted which is based on the Manakov equations, coupled equations. Also, new terms in the split step formulation were included to take into account the inter-polarization mixing effects. However, this introduced an additional challenge which is the substantial increase in DBP step size and computational complexity.

Many experimentations throughout the years have managed to advance compensation techniques and various types of optic fibers to increase the performance of optic-fiber use in several technologies.

Evaluation and analysis:
The use of several dispersion compensation fibers and techniques has become the focus in fiber-optic communication for better performance and two of the popular ones are FBG and DCF.

Fiber Bragg grating as mentioned earlier acts as a reflection filter. The device shifts the FBG wavelength by using a thin metal film to change the applied current. For post dispersion compensation, a compact tunable fiber Bragg grating can be used which enables operation of launch power at a wider range than with DCF. Complete restoration of a distorted signal by nonlinear effects is a limitation with a tunable fiber Bragg grating although it reduces the majority of the incurred penalty. Another type of Bragg grating, multi-channel chirped fiber Bragg grating, functions as a dispersion compensator. This compensator has a small-sized module and an insertion loss that is fixed. It also can compensate different dispersion orders of each individual channel and has the ability to operate over a wide bandwidth. Another comparative advantage over conventional DCF is that nonlinearity can be greatly reduced with the use of Multi- channel chirped fiber grating (MC-CFBG).

FBG sensors have been applied in many sectors such as in mines, for the electric power industry, for temperature measurements, and in civil engineering. In electric power industry for example, FBG sensors are best to use due to protection to electro-magnetic interference. The fiber has low transmission loss giving it the advantage of being used for long-distance distant operations. These fibers have promising prospective. (Inoue, Shigehara et al. 1995)

The dispersion compensating fiber (DCF) on the other hand is efficient in upgrading installed links which are of single mode fiber. This dispersion compensating fiber is used for long-haul systems to provide compensation of group velocity dispersion completely. The full dispersion compensation happens only if the nonlinear effects are negligible inside the fiber due to a low average optical power. This technology has an advantage of providing a broadband operation with a dispersion that is smooth. It also provides good optical characteristics. Nowadays, DCF allows for 100% of SSMF dispersion slope to be compensated and E-LEAF. However, the modules that are based on first generation DCF have a limitation due to slope-mismatch. Although DCF have undergone improvements recently, it still presents a large insertion loss. Another limitation is that modules of dispersion compensation based on DCF are bulky. In the future, reducing the size is expected to improve compactness by reducing bend loss. (Arora, Garg et al. 2011)

In fiber-based methods another disadvantage is observed which is the extra fiber loss, in addition to high nonlinearities and DCF additional costs. The mismatching of the properties of glass between the cladding and the core limits the maximum dispersion to about -100 ps/nm/km.

One study has shown that when a DCF of 24km for pre and post compensation is used an improved compensation scheme is achieved compared with other schemes (Arora, Garg et al. 2011). Another study compared DCF to Fiber grating compensation in OCDMA systems and demonstrated that it is a better compensator (Singh and Singh 2012).

As a result, each technique or fiber has its own advantages and disadvantages and each have certain characteristics which enables their use in a specific domain. The knowledge of the different criteria of each system and technology dictates adequate dispersion compensation techniques and fibers to achieve error free transmission. The question is whether combining a certain dispersion compensation scheme with FBG as filter, will that lead to complete dispersion compensation in the presence of high data rates and low channel spacing?

CONCLUSION

The industry of fiber optic communications has introduced a revolution within the industry of telecommunications. It provided more reliable links for telecommunication, higher-performance with decreasing bandwidth cost. A necessity in optical fiber systems however is compensation for dispersion since without it output pulses overlap due to pulse spreading. If the input pulse spreads, the dispersion limit of the fiber gets exceeded and the output data then will become imperceptible. Several dispersion compensation techniques have been introduced over the years with Dispersion Compensating Fibers and Fiber Bragg Grating being two of many. DCF has many advantages although it gives insertion losses and large footprint. On the other hand, Chirped Fiber Grating, a small all-fiber passive device, is a preferred because of low insertion loss, small footprint, negligible nonlinear effects and dispersion slope compensation. However, a certain extent of complexity in architectures using FBG introduces a limitation. From all the studies in the literature different techniques have been demonstrated by researches for dispersion compensation in optical systems. For further future work comparative studies between different dispersion techniques using the same fiber can be performed. Also, more studies to reduce third order dispersion are required.

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