Research on Key Technologies of large capacity and long distance optical transmission systems

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Abstract.In recent years, with the rapid development of high-bandwidth applications and the rapid growth of Internet data services, the capacity of communication networks is growing rapidly. Optical fiber has become an ideal transmission medium for communication networks due to its advantages such as large bandwidth and low loss. Large-capacity and long-distance optical fiber communication networks have become the key research directions of optical communication systems. In this paper, the main technical means to achieve large-capacity and long-distance optical transmission are investigated. First, the application of orthogonal frequency division multiplexing (OFDM) technology in large-capacity transmission is briefly introduced, including its principle, main structure, advantages and disadvantages. Subsequently, wavelength division multiplexing (WDM) technology based on optical frequency comb is introduced. Finally, the methods to realize long-distance transmission are discussed, including Digital Backward Propagation (DBP), Phase-Conjugate Twin Wave (PCTW) and advanced modulation format.

1. Introduction
In recent years, with the vigorous development of cutting edge technologies such as interactive games, high-definition network television, and video conferencing, a large number of new things have emerged, which have greatly enriched people's lives. However, the data traffic generated by such high-bandwidth services is also exploding. At present, the number of global Internet users has exceeded 2 billion, and this number is still rising. According to Cisco’s forecast, global Internet traffic will reach 3.3ZB in 2021, a three-fold increase compared to 2016. The existing optical fiber backbone network transmission Capacity is under great pressure [1]. It is imminent to increase the capacity of the dense wavelength division multiplexing (DWDM) backbone transmission network. Building a large-capacity, long-distance optical fiber transmission network has become the main development direction of future communication technology.

Optical fiber communication emerged in the 1960s. In 1966, Kao and Hockham published a paper of great historical significance on the prospect of optical fiber transmission, proposed that light can be used for information transmission in a waveguide medium [2]. In 1970, the first low-loss optical fiber was successfully developed by Corning in the United States, marking the official arrival of the era of optical fiber communications. The development of optical fiber communication technology has gone through several important stages. First, in the late 1970s, communication systems used simple on-off keying (OOK) for transmission. In the early 1980s, the concept of coherent optical transmission was proposed, which greatly improved the sensitivity of signal detection at the receiver. However, due to the backwardness of optoelectronic devices and the lack of digital signal processing (DSP) technology
at that time, coherent optical transmission could not be applied on a large scale[3]; Next, Li Dingyi introduced optical wavelength division multiplexing (WDM) transmission technology, which successfully extended the distance and capacity of the optical fiber transmission system[5]. In the 1990s, WDM technology caused a 1000-fold increase in transmission capacity. At the beginning of the 21st century, the transmission capacity based on WDM technology reached its limit, and the research of coherent optical communication entered people’s sight once again. With the support of high-speed digital-to-analog converter and large-scale integrated circuits, researchers introduced high-speed DSP technology. Inaugurated the era of digital coherent optical transmission, and the transmission capacity of a single optical fiber has been rapidly increased; During 2005–2010, the emergence of coherent optical OFDM provided an effective breakthrough in the limitation of electronic bottlenecks and realized ultra-large capacity transmission (single Channel Tb/s or even 10 Tb/s) means. After more than 40 years of fast development, optical fiber communication has made brilliant achievements. Now, optical fiber communication is moving towards greater transmission capacity and longer transmission distance.

Although optical fiber has extremely large bandwidth and low loss, some disadvantages of optical fiber itself also restrict the transmission capacity of optical fiber. These characteristics include power attenuation, dispersion, and nonlinear effects. From the perspective of the impact on system transmission performance, it is manifested as optical signal-to-noise ratio (OSNR) limitation, dispersion limitation and nonlinearity limitation. As the transmission distance and capacity increases, the optical power is attenuated during the transmission process. In order to meet the OSNR requirement, the signal power of the linear transmission system needs to be increased. For this reason, the researchers introduced an erbium-doped fiber amplifier (EDFA) and successfully realized all-optical relay. However, while EDFA amplifies the signal power, it inevitably introduces amplified spontaneous emission (ASE). In the cascade system, ASE will continue to accumulate, making the OSNR limited. If the OSNR at the receiver cannot meet the requirements, the bit error rate will be too high. Common methods to solve this problem are using Raman amplification technology with negative equivalent noise index and remote pump amplification technology, using new optical fiber technology to reduce link loss, or using forward error correction (FEC) technology to reduce receivers requirements for system OSNR, etc. Furthermore, optical fiber is a nonlinear channel. the increase of optical power will cause serious fiber nonlinearity effect [6]. The nonlinear effect of optical fiber seriously affects the performance of the optical fiber transmission system, and is considered to be the main factor limiting the performance of the optical fiber transmission system.

Large-capacity, long-distance transmission is the goal of optical fiber communication development. In this paper, the main technical means to achieve large-capacity and long-distance optical transmission are investigated. First, the application of OFDM technology in large-capacity transmission is briefly introduced, including its principle, main structure, advantages and disadvantages. Subsequently, WDM technology based on optical frequency comb is introduced. Finally, Digital Backward Propagation[7], Phase-Conjugate Twin Wave[8] and advanced Modulation Format are discussed to compensate the nonlinear effects to realize long distance transmission.

2. Large-capacity optical transmission technology
In order to achieve Tb/s-level ultra-large-capacity transmission, the internationally recognized methods are coherent optical OFDM (CO-OFDM) and WDM.

2.1. CO-OFDM
OFDM technology divides a wide channel into several orthogonal sub-channels, and converts a series of high-speed data streams into a series of low-speed sub-data streams for orthogonal parallel transmission through serial-to-parallel conversion. Parallel data streams are modulated to each sub-carrier for data transmission. Since the frequency spectrum between adjacent sub-carriers is orthogonally overlapped, the transmission system has high spectral efficiency[9]. Fig. 1 describes the basic model of digital coherent optical communication. The structure of the system is mainly
composed of three parts: modulation transmitting end, optical fiber link and digital receiving end. First, after OFDM preprocessing, the electrical signal is sent to the I/Q modulator at the modulating transmitting end, and the data information is loaded on the amplitude, phase, frequency and other different components of the optical carrier. Then the modulated optical carrier propagates through the optical link, and during the propagation process, the signal will be lost in the optical fiber, causing performance degradation. The receiving end is composed of a coherent receiver and a digital signal processing module. The received signal light and the local oscillator light generated by the local oscillator are both input into a 90-degree optical mixer for mixing, and then sampled by high-speed A/D Perform DSP processing at the receiving end to achieve signal demodulation and compensation.

![Coherent optical OFDM system architecture](image)

Fig.1. Coherent optical OFDM system architecture

Compared with other communication technologies, optical OFDM mainly has the following advantages: (1) High spectrum utilization rate (2) Robustness to dispersion. (3) Easy to realize digital signal processing. (4) Scalability and compatibility. However, the coherent optical OFDM system also has two problems. The first is the high peak to average power ratio (PAPR), high PAPR will damage the orthogonality between the various subcarriers during the process of modulating signals, resulting in inter-symbol crosstalk (ISI) and the degradation of the transmission signal; the second is the sensitivity to frequency and phase noise. Compared with the direct detection, the coherent receiving system introduces the local oscillator signal light, and needs to add a frequency offset compensation algorithm to compensate for the frequency offset; Furthermore, the coherent receiving system needs to recover the amplitude and phase information of the original signal at the same time. These characteristics determine that the receiver is sensitive to noise, and phase estimation and compensation algorithms need to be added [10].

2.2. WDM technology based on optical frequency comb

WDM technology couples a group of optical waves of different wavelengths carrying information into the same optical fiber for transmission via a multiplexer, so that the transmission capacity of a single optical fiber can be exponentially increased. WDM technology can be combined with coherent optical OFDM to dramatically increase the transmission capacity and fully expand the available limited optical fiber bandwidth; it can also use the coherent receiver with high receiving sensitivity and spectral efficiency to achieve large-capacity, long-distance transmission. It is the current mainstream direction of development.

Traditional WDM transmission systems often use Distributed Feedback(DFB) Laser as laser carrier sources. However, due to the gradual increase of system capacity, WDM systems require more and more wavelengths. Therefore, it is necessary to use multiple lasers with different wavelengths as the carrier. However, due to process and technical limitations, it is difficult to make the characteristics
of each laser exactly the same, so that the system cannot be kept stable, and it is not easy to continuously change the number of channels and their intervals, which brings inconvenience to the expansion and reconstruction of the system. In order to further expand the transmission capacity of the optical fiber transmission network, the most important challenge is to produce low-noise laser carriers with flexible wavelength spacing, which is currently mainly based on optical frequency comb technology [11]. Optical Frequency Comb is a series of equidistant spectral lines with constant mode spacing and ultra-low phase noise. It is shaped like a comb. In a sense, the multi-carrier light source can be regarded as optical frequency comb. The structure of the WDM transmitter and receiver based on the optical frequency comb are shown in Fig. 2 (a) and (b).

In the transmitter, a continuous laser generator can generate laser light with a continuous change in wavelength within a certain range, and then a series of flat spectral lines with equal frequency intervals are generated by the optical comb generator. The baseband OFDM signal is superimposed with the optical signals of different frequencies, and then it passes through the multiplexer to realize WDM. At the receiver, the received multi-carrier OFDM signal firstly passes through a demultiplexer to obtain each orthogonal OFDM signal, and then it is mixed with the discrete spectral lines obtained from local laser and the optical frequency comb. Finally, the result is input into the coherent receiver to obtain the in-phase component and the quadrature component in the OFDM optical signal, completing the demodulation of the data.

At present, there are mainly the following schemes for generating optical frequency comb generators: The first scheme is the mode-locked laser method, which uses a mode-locked laser to generate a multi-carrier light source with a wider bandwidth and higher stability. However, the spectral line spacing is limited by the size of the laser cavity, which is not flexible enough, and the generated multi-carrier light source is multi-longitudinal mode, which requires complex control to ensure stability[12]. The second scheme is called the nonlinear effect method, which mainly expands the frequency spectrum of the multi-carrier light source through technologies such as optical four-wave mixing and self-phase modulation. The center frequency of the multi-carrier light source is flexible adjustable, but this scheme also has its significant disadvantage, that is, the flatness of the
multi-carrier light source is poor [13]. The third scheme is the micro-cavity method, which is more advantageous for system integration and has higher stability, but it also has obvious disadvantages, that is, the cavity design is more complicated and the economic cost is higher[14]. The fourth scheme is the electro-optic modulator method, which has the advantages that not only the center frequency and spectral line spacing of the generated multi-carrier light source are flexibly adjustable, and the flatness is better, but also the structure is simple and easy to implement [15]. However, this scheme also has disadvantages. The bandwidth of the generated multi-carrier light source is easily restricted by the bandwidth of the modulator. The number of spectral lines is usually small, and the out-of-band rejection ratio and stability need to be improved.

This article mainly discusses the fourth scheme, which uses a combination of optical modulators. The combined structure of the two main optical modulators is given below.

(1). The cyclic shift device, as shown in Fig.3, is a single-sideband single-loop cyclic frequency shift structure based on an IQ modulator. It includes an IQ modulator, a tunable optical bandpass filter and two optical amplifiers. The band-pass filter can control the number of sidebands generated, and the optical amplifier is used to compensate for the loss in frequency conversion. An optical sideband with a center frequency of f0 is initially input, and the input frequency f1 is divided into two parts. Each time the cyclic coupler passes, one part is sent to the output end, and the other part is returned to the input end of the optical IQ modulator. After N cycles, an optical frequency comb with frequencies f1, f2, f3, …, fn will be generated[16].

![Fig.3. Schematic diagram of multilateral band generation structure of cyclic frequency shifter](image)

(2). Optical modulator cascade device. As shown in Fig. 4, it can be generated by cascading two phase modulators or cascading two intensity modulators. The first-stage modulator is used to generate multi-carriers, and the second-stage modulator introduces a small frequency difference signal to make the output multi-carrier flatter. The advantage of using a phase modulator is that it can output a stable frequency comb without controlling the modulation bias voltage. The advantage of using an intensity modulator is that the bias voltage can be controlled to further refine the optical frequency comb signal.

![Fig.4. The schematic diagram of optical frequency comb based on cascaded IM/PMs](image)

The WDM technology based on the optical frequency comb has many advantages. First, the WDM technology adopts a simple way to enhance the system’s ability to resist multipath interference, ensuring that the signals transmitted by each sub-channel will not interfere with each other; second, when the channel exhibits slow fading, it can optimize the information distribution in each sub-channel according to their SNR, so that the transmission capacity is improved. Third, the multi-carrier system using WDM technology is also more resistant to narrowband interference. Finally, the optical frequency comb is inherently composed of many equidistant spectral lines with constant...
mode spacing and ultra-low phase noise, which overcomes the shortcomings of discrete laser sources that are difficult to manage, and is an ideal light source for large-capacity optical fiber transmission systems. Based on that, in recent years, many researchers paid attention to the combined application of OFDM and WDM technology in high-speed and large-capacity digital coherent optical transmission systems, and have made major breakthroughs in related experiments. In 2012, Zhang Xiang reported the mixed signal of 32-QAM and 64-QAM based on Nyquist-WDM super channel, the total transmission rate reaches 2 Tbps, and the transmission distance of ULAF reaches 1200 Km [17]. In 2014, Zhang Junwei et al. reported the transmission of 4.4 Tbps Nyquist-WDM signal over 3000 km optical fiber [18].

3. Long-distance optical transmission technology
At present, the nonlinear effect is a recognized limitation for long distance optical fiber transmission. Aiming at the problem of non-linear effects, compensation and suppression technologies in the electrical domain are mainly used, including DBP, PCTW and advanced modulation format Method. The following will focus on these three methods.

3.1. DBP
DBP algorithm is one of the most basic nonlinear compensation methods. The basic idea is to establish a virtual optical fiber by inverting the Nonlinear Schrodinger equation (NLSE) [19] to compensate for the linear and nonlinear damage in the actual optical fiber transmission process. The parameters of the virtual optical fiber and the real transmission optical fiber parameters are opposite to each other. The inversion of the NLSE equation can be achieved by the Split-Step Fourier Methods (SSFM)[20]. The SSFM algorithm divides the optical fiber transmission link into many small sections of optical fiber with length h and performs inversion, which is also called the simulation step length. The simulation step h determines the accuracy and complexity of the SSFM algorithm, and the accuracy is higher when the simulation step h is small. Therefore, in order to obtain better nonlinear compensation performance, the simulation step h in the DBP algorithm needs to be set small, which leads to the high implementation complexity of the algorithm. At the same time, the algorithm also needs to know in advance the various parameters of the transmission fiber such as length, chromatic dispersion coefficient, etc. On the other hand, the DBP algorithm has a better effect on compensation of nonlinear damage in the channel, but it has a poor effect on compensation of nonlinear damage between channels. At this stage, the main research is how to reduce the complexity of the DBP algorithm and improve the performance of the DBP to compensate the nonlinear damage of the WDM channel. At present, the ESSFM (enhance SSFM) algorithm with a single step structure has been proposed, which is used for the low-complexity LDBP algorithm of the sub-carrier multiplexing modulation system, and the simplified algorithm such as the DBP algorithm in the nonlinear Fourier domain, which greatly reduces the amount of calculation, but the complexity of these algorithms is still too high; at the same time, researchers have also proposed a large number of DBP algorithms suitable for WDM systems. However, these algorithms require smaller simulation steps than single-channel, resulting in a sharp increase in complexity and difficult to apply to the actual system. In summary, the current DBP algorithm is still in the theoretical development stage. With the deepening of research, the DBP algorithm, which is easy to implement and adapts to WDM channels, is expected to become the main method of nonlinear effect compensation in the future.

3.2. PCTW
PCTW Algorithm is a phase conjugate nonlinear solution based on digital signal processing technology proposed by X.Liu in 2013 [21]. PCTW transmits two signals with mutually conjugate phases on the two polarization states of the fiber. From the nonlinear Schrodinger equation, it can be seen that when the fiber line is dispersion symmetric, the nonlinear damage to the mutually conjugated signal is also phase conjugate. At the receiving end, this conjugation relationship can be used to strip the nonlinear damage from the received signal, and then restore the original signal. The PCTW
scheme has good performance and simple algorithm structure, which can be well adopted by actual systems, but it comes at the expense of half the spectrum efficiency. It is still a major issue to study how to improve the spectrum efficiency of the system while maintaining the performance advantages of the traditional PCTW. T. Yoshida once proposed a dual PCTW scheme using quadrature pulse shaping[22], but this algorithm achieves the same spectrum efficiency transmission by increasing the signal modulation order, and does not fundamentally solve the problem; it also should be noted that the performance gain of PCTW is mainly reflected in lower order modulation format such as QPSK and 8QAM, which is not applicable to high-order signals of 16QAM and above.

3.3. Advanced modulation format

The modulation format of the signal not only affects the information transmission rate of the system, but also affects the nonlinear tolerance of the system. For example, the high-order modulation format 16QAM is more susceptible to nonlinear damage than the low-order modulation format BPSK. Therefore, by carefully designing the modulation format, the nonlinear tolerance of the system can be improved, the nonlinear damage can be alleviated, and the transmission performance can be improved. For single-carrier modulation formats, advanced modulation techniques to improve nonlinearity tolerance mainly include two types[23]: constellation geometric shaping (Geometric Shaping) and constellation probability shaping (Probabilistic Shaping). Geometric shaping refers to change the equal distance, equal probability distribution constellation diagram to a non-equal distance, equal probability constellation diagram, to maximize the minimum Euclidean distance between the constellation points. It is achieved without introducing any redundancy; In probability shaping constellation diagram, the constellation points are equally spaced, and each constellation point may have a different probability when a certain redundancy is introduced. The shaping constellation is shown in Fig. 5. After the signal with the traditional rectangular QAM constellation undergoes constellation shaping, the information rate can be closer to the Shannon limit under the same SNR condition. Therefore, the key theory and application research of signal shaping technology has attracted wide attention at home and abroad, and has become an important subject in the field of optical communication technology, which is of great significance to the development of ultra-high-speed optical communication networks in the future.

![Fig.5. The constellation diagram when the SNR is 25dB.](image)

- a) Standard 256QAM
- b) Circular 256QAM with geometric shaping
- c) 256QAM with constellation probability shaping

4. Summary and Conclusion

With the continuous increase of the transmission capacity of the optical fiber backbone network and the increase of transmission distance, large-capacity and long-distance optical transmission has become an important direction for the development of optical communications. The current mainstream 100 Gb/s large-capacity long-distance transmission system uses the DWDM and OFDM technology. This combination successfully breaks through the bandwidth limitations of existing electronic devices, and achieves high spectrum efficiency and simple structure. It has always been the main realization form of high-speed optical fiber communication. Combining WDM technology with OFDM technology can significantly increase the existing single optical fiber communication capacity, making the transmission capacity of the backbone network leap from the original 10Gb/s to the current
200-400Gb/s, Tb/s level. The ultra-large capacity transmission has also been successfully achieved under experimental conditions. In the future, the optical transmission system will develop in a dynamic, flexible and reconfigurable direction. Including the flexible adjustment of modulation format, signal bandwidth and FEC redundancy, etc. In addition, the use of few-mode fibers[24], few-core fibers[25], and the latest orbital angular momentum[26] all provide solutions for breaking the transmission limit of a single fiber, becoming a new research hotspot.

As for the problem of long-distance transmission in optical fiber communication systems, this article discusses that nonlinear effects are the main reason for the current limitation of optical fiber transmission distance, and then proposes corresponding compensation methods, including DBP, PCTW and advanced modulation formats.

In practical applications, the DBP algorithm can well compensate for the damage in the channel, but the ability to compensate for the damage between the channels is limited, and the complexity is too high, and it is currently difficult to implement quickly through hardware. N. Alic’s research pointed out that the WDM system using the same light source ensures the consistency of the wavelength fluctuations of different channels and can significantly improve the compensation performance of the DBP algorithm [27] This shows that the optical frequency comb technology may be helpful to improve the DBP algorithm; The phase conjugated twin wave algorithm is simple in structure, but sacrifices half of the spectrum efficiency, and is not suitable for high-order modulation formats. Compensating for these two defects is the main direction of the future; constellation geometric shaping improves the linear OSNR performance, but when there is nonlinear damage, the performance decreases. Constellation probability shaping needs to adjust the probability distribution according to the characteristics of the nonlinear channel, which can well improve the channel capacity and transmission performance. In the future, a modulation format that combines geometry and probability optimization has great application prospects.

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