The application of OFDM in optical fiber communication systems

Xuanjie Luo
Communication Engineering, The college of post and telecommunication of wit, Wuhan, Hubei, 430070, China
706569441@qq.com

Abstract. Orthogonal frequency division multiplexing (OFDM) is a special multi-carrier transmission technology. It utilizes digital signal processing (DSP) to perform inverse Fast Fourier transform (IFFT) and generates a set of orthogonal subcarriers for parallel transmission of low-rate digital signals, achieving the transmission of high-speed digital signals. It has the advantages of high spectral efficiency and anti-dispersion, and has broad applications in large-capacity and long-distance optical fiber communication systems and optical access networks. In this paper, the working principle, structure and application of OFDM in optical fiber communication systems are investigated. Then the problems which should be solved in the application of OFDM in optical communication systems are discussed. Finally, the development of OFDM system is prospected.

1. Introduction
Orthogonal frequency division multiplexing (OFDM) technology is a multi-carrier digital modulation technology developed with the maturity of digital signal processing (DSP) technology. Compared with other multi-carrier multiplexing technologies, OFDM signals satisfy orthogonality in both time and frequency domains, and have higher spectral efficiency and anti-multipath interference ability. It is easy to generate and demodulate OFDM signals with the help of DSP chips. Channel equalization and other operations are also relatively simple. Therefore, OFDM technology has been widely used in wireless, wired and broadcasting communications.

As a special multi-carrier transmission technology, OFDM technology can be seen as either a modulation technology or a multiplexing technology. The principle of OFDM is similar to that of traditional frequency division multiplexing (FDM). It uses DSP for inverse Fast Fourier transform (IFFT) in order to generate a set of orthogonal subcarriers for parallel transmission of low-rate digital signals, which could achieve the transmission of high-speed digital signals.

In optical fiber communication systems, the validity and reliability of data transmission depends not only on the performance of optical transmitter and receiver, but also on the influence of chromatic dispersion and polarization mode dispersion (PMD) of optical fiber links. With the development of communication technology and the continuous improvement of communication requirements, the data rate of single channel transmission in optical communication increases greatly, reaching 100 Gb/s. However, when the data rate reaches 100 Gb/s, the traditional optical fiber compensation becomes expensive and time-consuming, and it is difficult to accurately compensate the dispersion. Owing to the good computational characteristics of OFDM, it can be achieved by complex operation in frequency domain. As the dispersion of optical fibers is compensated effectively, OFDM technology is considered to be used in optical communication, namely, optical OFDM (O-OFDM). In this way, the
tolerance to optical fiber chromatic dispersion and PMD can be improved. In this paper, the basic principle of O-OFDM is introduced. Secondly, the application of OFDM in optical communication systems is introduced. Finally, the problems and potential solutions in O-OFDM are discussed.

2. The Principle of O-OFDM
The principle of O-OFDM is similar to that of OFDM. The only difference is that the signal is transferred from wireless signal in electrical domain to optical signal in optical domain. Figure 1 shows the structure block diagram of O-OFDM system. The transmitter includes OFDM baseband transmission, RF up-conversion and optical modulation. The receiver includes optical detection, RF down-conversion and OFDM baseband reception. The binary serial digital signal is input at the transmitter and divided into N-channel parallel data by S/P transformation. Each data is modulated by M-ary PSK or QAM method. The signal is mapped to the corresponding complex domain by constellation diagram. Then N parallel carriers are converted into serial ones by IFFT and are added as an OFDM symbol before each symbol. The cyclic prefix (CP) is added and then converted into OFDM baseband analog signal by digital-to-analog conversion. The baseband signal is modulated to RF carrier frequency and optical carrier in turn and then transmitted into single mode fiber (SMF). The DSP in receiver is essentially the inverse process of transmitter. The optical signal is converted into electrical domain by a detector (PD) and then the signal is converted into digital domain by analog-to-digital converter (ADC). Next, CP is removed and P/S conversion is performed. Then the signal is converted into frequency domain by FFT. Finally the signal is de-mapped and converted into serial data.

3. Application of OFDM in Optical Communication

3.1. Direct detection O-OFDM (DDO-OFDM) System
The architecture of DDO-OFDM system is similar to Figure 1. According to the different generation methods of O-OFDM signals, DDO-OFDM system can be divided into two types: linear mapping and non-linear mapping DDO-OFDM system. The difference between these systems is whether it is necessary to copy the baseband OFDM spectrum directly to the optical OFDM spectrum. In linear mapping DDO-OFDM system, the linear transfer of baseband OFDM spectrum is the spectrum of optical OFDM, that is to say, replication is direct. In this system, the transmission distance is affected by dispersion coefficient, so it is necessary to compensate the dispersion in electrical domain or optical domain. In addition, the different number of subcarriers will also affect the DDO-OFDM system, so the number of subcarriers should be reasonably selected according to the bandwidth utilization and bit error rate requirements.

Linear mapping DDO-OFDM is formally expressed as,
\[ s(t) = e^{j2\pi f_0} + \alpha e^{j2\pi (f_0 + \Delta f)t} \cdot s_B(t) \]  

In formula (1), \( s(t) \) is an optical OFDM signal; \( f_0 \) is optical carrier frequency; \( \Delta f \) is a protection bandwidth between the optical primary carrier and the OFDM band; and \( \alpha \) is a proportional coefficient to describe the relationship between the energy of the OFDM band and the primary carrier; \( s_B(t) \) is a given baseband OFDM signal, which can be expressed as:

\[ s_B(t) = \sum_{k=-N+1}^{N} C_k e^{j2\pi f_k t} \]  

(2)

c_k and \( f_k \) are the information symbols and frequencies transmitted by the \( k \)-th subcarrier respectively.

The directly modulated waveform in the non-linear mapping DDO-OFDM system can be expressed as follows:

\[ E(t) = e^{j2\pi f_0} A(t)^{1+c} \]  

\[ A(t) = p(t) = A_0 \sqrt{1 + \alpha \Re(e^{j2\pi f_{IF} t} \cdot s_B(t))} \]  

\[ m = \alpha \sqrt{\sum_{k=-N+1}^{N} |C_k|^2} \]  

(4)

(5)

In formula (3-5), \( E(t) \) is the optical OFDM signal; \( A(t) \) and \( P(t) \) are the instantaneous amplitude and power of the optical OFDM signal, respectively; \( C \) is the chirp constant of the direct modulation DFB laser; \( f_{IF} \) is the intermediate frequency of the electrical OFDM signal for modulation; \( m \) is the optical modulation index; and \( \alpha \) is the proportional constant, which is used to set the appropriate modulation index \( m \) to minimize the limiting noise.

The channel model of DDO-OFDM is no longer linear under the influence of various forms of optical dispersion, so the non-linear mapping DDO-OFDM is only suitable for short-range applications, such as multimode fiber (MMF) local area network (LAN) or short-range SMF transmission.

3.2. Coherent detection OFDM (CO-OFDM) system

In DDO-OFDM system, only the intensity information of the light can be detected but the phase information cannot be detected. In contrast, CO-OFDM system can compensate for the shortcomings of DDO-OFDM system, and it has very high receiver sensitivity, which could realize long-distance transmission. Figure 2 shows the schematic diagram of CO-OFDM system. Similarly, the number of subcarriers can directly affect the performance of CO-OFDM system. If the number is too large, it will cause interference between channels. If the number is too small, the utilization of spectrum will be reduced. Therefore, it is very important to control the number of subcarriers. In addition, in CO-OFDM system, different modulation format will also affect optical signal-to-noise ratio (OSNR), non-linear effect and optical fiber dispersion tolerance, which requires relevant technical personnel to choose a reasonable debugging mode after balancing the transmission distance, transmission capacity, spectrum utilization and bit error rate. It should be noted that the difference of differential group delay (DGD) can also affect the system performance. The system performance will improve with the increase of DGD, but beyond a certain value, the system performance will decline with the increase of DGD, because the main factor affecting the system performance becomes PMD.
CO-OFDM system can effectively compensate and estimate PMD in optical fibers. In order to improve the system capacity, it is necessary to introduce polarization division multiplexing (PDM) technology into CO-OFDM system, which can not only meet the basic requirements of the system for each component, but also further improve transmission rate. Thus, PDM CO-OFDM system has become an important solution for future ultra-large capacity, ultra-high speed and ultra-long distance transmission systems. SMFs usually have two polarization modes, and the transmission of optical signals is affected by the effects of polarization-dependent loss (PDL), PMD and chromatic dispersion.

3.3. Application of OFDM in access network
In access networks, multiple services are required to be allocated to multiple users at the same time. Current EPON and GPON architectures require complex scheduling algorithms and framing techniques to support various services. The performance of these TDM-PONs is sensitive to the delay of packet transmission and is vulnerable to other data traffic passing through the same link. In addition, WDM-PON can transparently distribute a variety of services, because each service can use a dedicated wavelength. However, multiple wavelengths may require multiple transceivers and arrayed waveguide gratings (AWG) or optical filters to distribute the wavelength to the corresponding receivers, thus increasing system costs and costs. In addition, WDM-PON lacks the flexibility to dynamically allocate resources among different services. The application of OFDM technology in PON can effectively reduce the cost of WDM-PON.

In OFDM-PON, as a multi-access technology, OFDMA can dynamically allocate different subcarriers to multiple users, so that resource allocation in both time and frequency domains can be achieved simultaneously. It can transparently support various services and dynamically allocate bandwidth in these services. OFDM-PON can be combined with TDM-PON to provide additional resource management functions.

The working principle of OFDM-PON is shown in Figure 3. OFDMA uses both OFDM and TDMA technology, where the subcarriers of OFDM are dynamically allocated to different services in different time slots of TDMA.

In OFDM-PON, the whole bandwidth is divided into orthogonal subcarriers, and one or more subcarriers are allocated to each ONU. Some subcarriers can be used for specified services. Some subcarriers are used for the TDM (T1/E1) service in business district and the radio frequency service of mobile base station. Some subcarriers are allocated to the packet IP service, which is shared by
ONU1 and ONU3 in frequency and time domain. The allocation of subcarriers and slots is controlled by OLT.

In upstream direction, all analog signals transmitted through transparent pipelines are extracted by band pass filters, and the interference can be minimized due to their orthogonal characteristics. Each ONU requires a different wavelength to avoid beat noise. In downstream direction, OLT uses some reserved subcarriers as transparent channels, encapsulating packet-based data in the remaining subcarriers and slots according to frequency and time-domain scheduling. OFDM frames and other analog signals are mixed by an electronic synthesizer to drive an optical modulator. When mixed signals arrive at these ONUs, each ONU extracts its own data or signals from the relevant subcarriers, pipes and slots.

Figure 4 is the experimental setup reported by NEC Laboratory for 10 Gb/s OFDM-PON upstream service transmission. 256 subcarriers were used in the experiment, which were divided into two groups, and allocated to ONU1 and ONU2 respectively. Experimental results show that the transmission of WiMAX signal in OFDM-PON will not affect the service of conventional OFDM-PON.

![Figure 3. The principle diagram of OFDM-PON uplink transmission and framing](image)

Figure 4. Experimental setup for OFDM-PON

Figure 5 shows experimental setup for MIMO OFDM-PON reported by NEC Laboratory USA in 2009. MIMO PDM direct detection technology is adopted to demonstrate 40 Gb/s signal transmission over 20 km SMF. The optical attenuator with 15 dB loss is used in the experiment, which
is equivalent to 1:32 optical splitter. Figure 6(a)–(e) show the waveforms of the signals in point a–e in Figure 5, respectively. The detailed parameters of the experimental configuration are described in Ref.

![Figure 5. Experimental setup for MIMO OFDM-PON](image)

**Figure 5. Experimental setup for MIMO OFDM-PON**

![Figure 6. MIMO OFDM-PON principle constitutes X and Y polarization state diagrams of relevant points in the Figure 5](image)

**Figure 6. MIMO OFDM-PON principle constitutes X and Y polarization state diagrams of relevant points in the Figure 5**

### 3.4. MF OFDM Transmission System

MMF has large core diameter area than SMF, which allows more optical power to enter the optical fiber transmission without serious fiber nonlinearity. MMF supports more than 45 modes at the wavelength of 1550-nm. From the prospect of information theory, the more modes could support larger capacity signal transmission. Because of the large core diameter area of MMF, it is easy to couple with the light source, and the coupling efficiency is also high. However, the mode dispersion of MMF will seriously limit the transmission capacity and distance of MMF. Currently, MMF has been widely used in LAN and optical interconnection with a rate of less than 10 Gb/s. OFDM decomposes the high-speed data stream into many low-speed sub-data streams. By utilizing orthogonal and partially overlapping sub-carriers in frequency domain to transmit simultaneously in the channel, the influence of mode dispersion of MMF can be overcome, thus improving the signal rate and extending the transmission distance.

E. Giacoumidis and J. M. Tong reported that 19.375 Gb/s optical fast OFDM signal was transmitted 500 m over a 3 dB MMF with an effective bandwidth of only 150 MHz km. The system is
expected to increase the speed of the installed MMF 10Gb/s system and Ethernet backbone network to 19.375Gb/s.

W. Shieh believes that MMF transmission of CO-OFDM technology is the way to the future 1Tb/s Ethernet. At the same time, he also believes that long-distance transmission of CO-OFDM signal by MMF may make a SMF break through 100Tb/s.

As a summary, the application of O-OFDM technology mainly focuses on two aspects. One is to apply O-OFDM technology to optical bone network to achieve high-speed, long-distance, non-dispersion compensation data transmission. The other is to use O-OFDM in optical access network, especially in the multi-mode optical access network, in order to achieve low-cost upgrading of the system.

4. Discussions

Although great progress has been made in the research of O-OFDM, there is still a long way to go for its practicality. Especially with the progress of communication technology and optoelectronic device manufacturing technology, there are still some technologies and problems that need to be further studied.

The higher PAPR of O-OFDM system aggravates the influence of non-linearity on system performance. Currently, most systems mainly utilize the method of reducing PAPR in electrical field to reduce its impact. However, in some methods of reducing PAPR through hardware in the electrical field, the signal will appear peak regeneration after a series of processing. At the same time, because the generation of O-OFDM signal needs to modulate the electrical OFDM baseband signal to the optical domain, it is also possible to appear peak. Moreover, the methods to reduce PAPP in electrical domain may not be applied to O-OFDM systems.

With the development of optical fiber manufacturing technology, some new types of optical fibers, such as large effective area fibers (LEAF), can be used to improve systems performance deteriorated by non-linearity effects. If the O-OFDM system can suppress PAPR in optical domain by means of optical device manufacturing technology, it can not only reduce the influence of optical fiber nonlinearity, but also reduce the complexity of OFDM transceiver technology in the electrical domain. Therefore, reducing the PAPR of O-OFDM system in optical domain is a promising technology to be further investigated.

The bottleneck of electronic devices limits the further improvement of system capacity. In order to achieve high-capacity communication, high-order modulation formats and various multiplexing technologies are adopted. However, these technologies cannot solve the problem of data limitation in effect. Breakthroughs in data processing speed of IFFT/FFT, DAC and ADC in electrical domain are the promising methods to improve capacity and the best ways to improve the real-time transmission performance of the system.

In addition, O-OFDM signal generation, transmission, reception and processing operations can be realized in all-optical method. It can not only greatly improve the performance of OFDM system, but also promote the development and application of new optical communication technology in the future.

5. Conclusions

O-OFDM technology has high spectrum efficiency and uses efficient IFFT/FFT algorithm and DSP chip to realize orthogonal modulation and demodulation of subcarriers. It can effectively eliminate symbol interference (ISI) and carrier interference (ICI) and compensate the dispersion of long-distance optical communication links. Moreover, it can achieve asymmetric transmission of services by allocating different number of subcarriers in upstream and downstream links. Because of these advantages, OFDM can be applied to wide area network (WAN), metropolitan area network (MAN), LAN, indoor network and free space optical communication systems. OFDM is a promising technology in the field of optical fiber communication, but there are still many problems that should be further investigated. The most important disadvantage of OFDM is its high PAPR and sensitivity to
phase noise, frequency deviation and I/Q imbalance in wireless communication. In addition, the cost of transmitter and receiver implementation in OFDM system is higher than other modulation modes.

References

[1] Buchall Fdischler R. et al., “Optioned sensitivity direct detection O-OOFDM with multi level subcarrier modulation” [C]. Optical Fiber communication National Fiber Optical Engineers Conference, OFC/NFOEC,1-3(2008).

[2] Moreolo M S.Muoz Rjunyent G. et al., “Novel Power Efficient Optical OFDM Based on Huntley Transform for Intensity-Modulated Direct-Detection Systerms- Lightwave Technology”, IEEE, 28(5):798-805(2010).

[3] D. Zhi, et al., “A Bandwidth Efficient De-sign of IM/DD Optical OFDM”[A]Conference on Quantum electronics and Laser Science. June1-2 (2009).

[4] W.Yumin, et al., “Key Technologies and Applications for OFDM”[M]. Beijing: China MachinePress, 2006 (in Chinese).

[5] Ramaswami R, Sivarajan N., et al., “Optical Networks: a Practical Perspective”[M].Second Edition,San Francisco:Morgan Kaufman Publisher,(2002).

[6] Hillerkuss D, Schellinger T, et al., “Single source optical OFDM transmitter and optical FFT receiver demonstrated at line rates of 5.4 and 10.8 Tbit/s”[C]. OFC, PDPC1(2010).

[7] T. Chao, et al., “200 Gs/s real-time optical-sampling- baaed orthogonal frequency division multiplexing system”[C]. OFC, OWO5(2010).

[8] W. shieh, et al., “Coherent optical OFDM: Has Its Time Come?”[J].Journal of Lightwave Technology, 7,234-255(2008).

[9] W. shiehp, et al., “MD- Supported Coherent Optical OFDM Systems” [J].IEEE Photonics Technology Letters, 19,134-136(2007).

[10] J. $,et al., “Optical OFDM . A Candidate for Future Long-Haul Optical Transmission Systems”[C].OFC/NFOEC(2008).

[11] Q. Dayou, et al., “10Gb/s OFDM-PON for Delivery of Heterogeneous Services”[C].OFC, OWH4(2008).

[12] Q. Dayou, et al., “40Gb/s MI-MO-OFDM-PON Using Polarization Multiplexing and Direct-Detection”[C]. OFC, OMV3(2009).