Principle and Key Technologies of OFDM-RoF

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Abstract:
The merging of optical communication and wireless communication is a tendency in the development of future communication. Orthogonal Frequency Division Multiplexing (OFDM) technology is becoming a core technology in the physical layer of next generation wireless communication system. Taking advantages of both wireless communication and optical communication, OFDM Radio over Fiber (OFDM-RoF) system is characterized by high speed, large capacity and high spectral efficiency. However, it still has some problems to be addressed, including dispersion and nonlinearity effects. The nonlinearity effect of fiber and modulator can be mitigated by PAPR reduction algorithms, the dispersion effect can be eliminated using Cyclic Prefix (CP) and channel estimation, and the fiber nonlinearity can be reduced by techniques such as digital phase conjugation, Partial Carrier Filling (PCF), nonlinearity precompensation and serial correlation reduction.

1 Background and Technical Features of OFDM-RoF

Nowadays, the tendency of information industry is towards mobile, wireless, digital and broadband. Ultra-high speed and ultra-large capacity have become main objectives in transmission. With social informationalization going steadily on, many new services emerge, including Metro Ethernet Network (MEN), Internet Protocol TV (IPTV), High Definition TV (HDTV), mobile multimedia and video stream media. Meanwhile, the demands of human society for transmission bandwidths increase at a rapid speed. The coming of 3G era makes the dream of "accessing diverse multimedia information anytime, anywhere and anyway" a reality. However, the limited spectrum resources and finite transmission distance greatly restrain the development of wireless communications. One trend to future communications is to combine optical and wireless communications together. With high frequency bands between 40 GHz and 60 GHz, rich spectrums are available for wireless communications; what is more, they do not require any license. If they are used as carrier frequencies of wireless signals, they are quite enough for service requirements of ultra-wide band wireless communication. Hence, Radio over Fiber (RoF) technology is introduced.

RoF system uses fiber as the transmission link between Base Station (BS) and Central Station (CS) and directly uses optical carriers to transmit Radio Frequency (RF) signals. The fiber is only used for transmission; core functions such as switching, control and regeneration of signals are implemented at the CS, and BS performs Optical-to-Electrical (O/E) conversion. In this way, complicated and expensive devices are gathered at the CS shared by remote BSs, power consumptions and costs of BS are reduced, and wired transmission of low-cost, large-capacity RF signals as well as ultra-wide band wireless access is achieved.

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier transmission technique and the key idea of OFDM is to split a channel within the frequency domain into many orthogonal sub-channels, enabling low-rate subcarrier channels to carry high-speed data stream and transmit simultaneously. With the strength of frequency-selective fading-resistance, OFDM has become a core technology in next generation broadband wireless communication systems and has been incorporated into physical layer standards for wireless communications as well as digital audio and video broadcasting in Europe, Asia, Australia and other parts of the world[1].

Based on OFDM technology and optical communication, Optical OFDM (OOFDM) system[2] can construct high-speed, large-capacity and low-cost optical transmission network[3-4] and its channel capacity is highly scalable, allowing smooth upgraded or transition from existing networks. OOFDM technology can be also used in Worldwide Interoperability for Microwave Access (WiMAX) and Wireless Local Area Network (WLAN). Combined with RoF technology[5], OOFDM system can

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not only reduce multipath fading of wireless signals, but also improve signal quality. Moreover, the system can achieve seamless coverage, increase channel capacity and transmission rate, and simplify digital signal processing by means of adding BSs. Therefore, OOFDM system can be regarded as a specific deployment scheme of OFDM-RoF system. In this paper, we will discuss OOFDM system in detail to explain the principle and features of OFDM-RoF system.

Due to its unique advantages, OOFDM has been studied around the world. In many international conferences, such as Optical Fiber Communication Conference and Exposition (OFC) 2008, OFC 2009, European Conference on Optical Communication (ECOC) 2007 and ECOC 2008, OOFDM transmission theory and technology are hot topics. The advantages of OOFDM system include:

(1) It does not require complicated chromatic dispersion management during transmission. Hence, it can achieve high-speed data transmission, simplify the network, reduce construction, running and maintenance costs, and adapt itself to dynamically changing network environment.

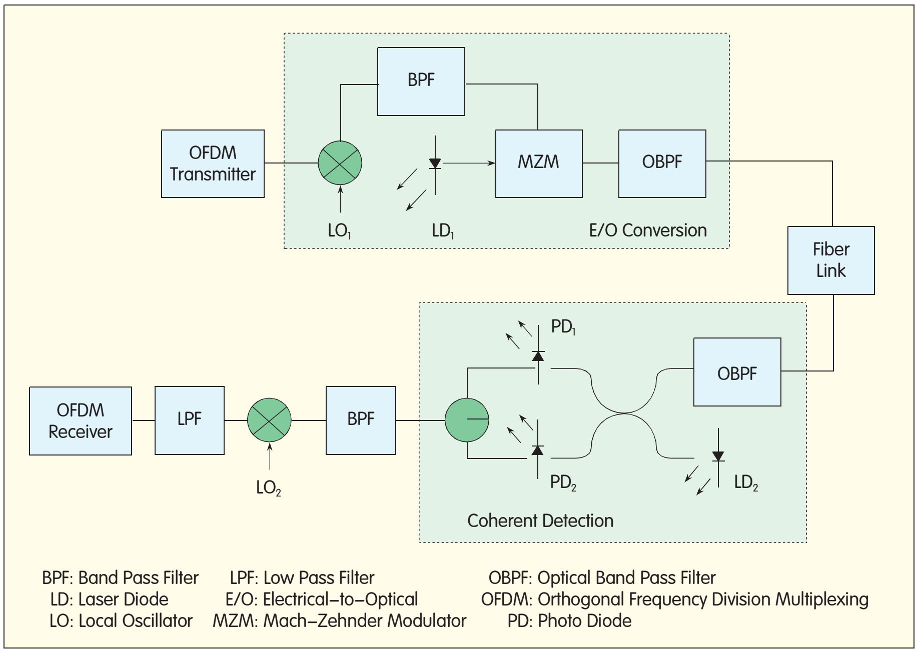
(2) It can utilize spectrum resources to the utmost extent, thus improving spectral efficiency.

(3) It is compatible with Wave Division Multiplexing (WDM) systems, so it can take advantage of their huge investments in optical links and optical amplifiers. Upgrading from WDM system to OOFDM system only requires certain changes at transmitting and receiving ends.

Despite these advantages, OOFDM system has the following disadvantages, which bring new issues to be addressed.

(1) In OOFDM system, signals of several sub-channels are simply superimposed. If the phases of these signals are the same, the transient power of superimposed signal will be much more than their average power, leading to a high Peak-to-Average Power Ratio (PAPR). The high PAPR is likely to induce signal distortion and Inter-Symbol Interference (ISI) and decrease the system's Signal-to-Noise Ratio (SNR), so stringent requirement is imposed on linear range of the transmitter.

(2) OOFDM technology can



▲Figure 1. Conceptual diagram of CO-OFDM system.

effectively solve chromatic dispersion problem in optical transmission, but with many subcarriers, narrow frequency interval and high PAPR, the system's performance will be significantly affected by fiber nonlinearity.

(3) OOFDM system is quite sensitive to phase noises. These noises include optical device's phase noise, Amplified Spontaneous Emission (ASE) noise and nonlinear phase noise. Phase noises deteriorate orthogonality among subcarriers and greatly decrease system performance.

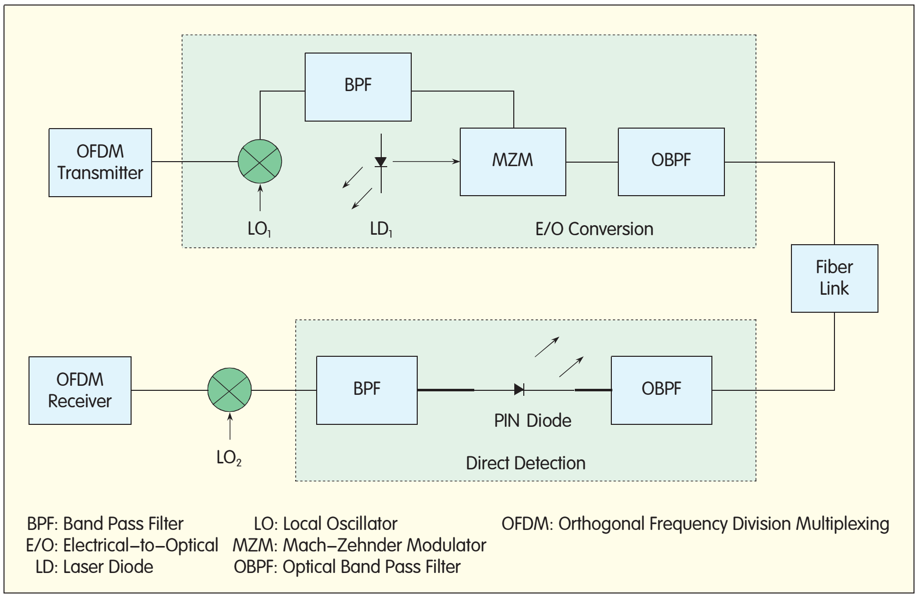
2 Principle of OOFDM System

An OOFDM system typically consists of five parts: OFDM transmitter, Electrical-to-Optical (E/O) conversion, fiber link, photodetection and OFDM receiver. By the implementation of the receiver, it can be further divided into two kinds: Coherent Optical OFDM (CO-OFDM) and Direct Detection Optical OFDM (DDO-OFDM). In CO-OFDM system, coherent heterodyne (or homodyne) detection is adopted at the receiver end; while in DDO-OFDM, PIN photodiode is used to directly convert optical power into current at the receiver end. Figure 1 is a typical CO-OFDM system[6]. DDO-OFDM system, shown in Figure 2, is similar to CO-OFDM except that their detection modes are different.

Figure 3 illustrates the operating principle of OFDM transmitter, where processing steps include constellation mapping, multiplexing with Inverse Fast Fourier Transform (IFFT), over-sampling, inserting pilot symbol, inserting training sequence, inserting Cyclic Prefix (CP), adding window and reducing PAPR.

CO-OFDM system uses Mach-Zehnder Modulator (MZM) to modulate RF OFDM signals into optical domain, and uses existing WDM fiber transmission link as its fiber link. Supporting high-speed, large capacity and low-dispersion transmission, OFDM technology greatly simplifies dispersion compensation.

In CO-OFDM system, coherent detection scheme is adopted. Two pairs of balanced receivers are used to conduct homodyne detection and restore the signals into RF signals and then baseband signals by means of O/E conversion. The advantage of this detection method is the output signals are of good quality and with high SNRs, but it requires the linewidth of the laser to be within 100 KHz, so the costs of related products are very high. So far, Intel Company has launched the laser that approximates such linewidth. In



▲Figure 2. Conceptual diagram of DDO-OFDM system.

DDO-OFDM system, PIN receiver is used to perform O/E conversion. Although its output signals are not as good quality as those in CO-OFDM system, the system cost is lower. The coherent detection method is suitable for long-haul fiber transmission, while direct detection method is applicable to short-distance fiber transmission. As for the applicability of RoF technology, a compromise between performance and cost has to be made.

Figure 4 shows the operating principle of OFDM receiver, where the processing steps include removing training sequence, OFDM symbol synchronization, carrier synchronization, Fast Fourier Transform (FFT), window synchronization, removing CP, removing pilot symbol, channel estimation, eliminating distortion arisen from nonlinearity of optical devices, dispersion and fiber nonlinearity and ASE noises by electrical equalization technology, demodulating OFDM symbols using FFT algorithm and inverse constellation mapping.

3 Dispersion Effect in CO-OFDM System and Its Elimination

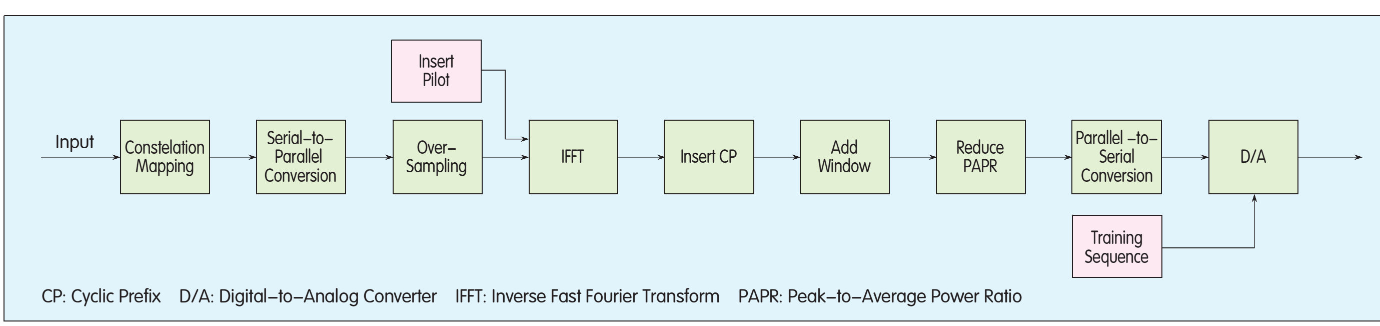
In fiber transmission, the presence of chromatic dispersion reflects in the decrease of signal's peak power and extension of signal waveform in time domain, and in frequency domain, it reflects in different phase shifts with different frequencies. Adopting multi-carrier modulation, OFDM technology induces different phase shifts for subcarriers at different frequencies, which in turn results in ISI.

In OOFDM system, the propagation of OFDM signals that are modulated into optical domain satisfies the nonlinear Schrodinger equation, so the phase shift arisen from chromatic dispersion can be calculated with the equation below.

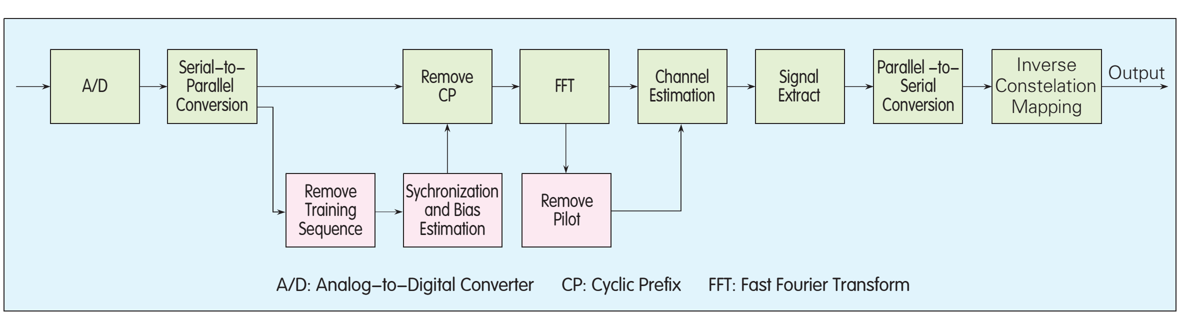
$$\phi = \Phi_0 + \frac{c\pi}{f_{LD}^2} D_t f^2 \quad (1)$$

where c is the velocity of light, f_{LD} is the center frequency of the laser, D_t is accumulated dispersion parameter, and $\Phi_0=\beta_0 z$ is the phase shift induced at the center frequency.

As dispersion-induced signal distortion can be regarded as linear channel distortion, CP and electrical equalization technology are usually adopted in OOFDM system to combat



▲Figure 3. Processing at OFDM transmitter.



◀Figure 4. OFDM receiver.

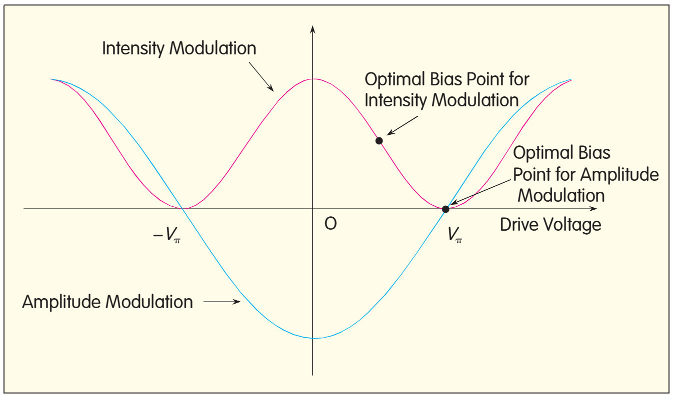


Figure 5. Relationship between bias voltage of MZM and output signals.

dispersion effect. This approach simplifies dispersion processing mechanism at the receiver as well as simplifies or even cancels dispersion compensation, achieving dynamic reconfiguration of optical networks.

In OOFDM system, CP should be longer than the delay arisen from dispersion. Theoretically, if the CP is long enough, dispersion effect can be minimized, but spectral efficiency of OFDM system will decrease considerably. Therefore, electrical equalization technology is applied in addition to CP at the receiver. This processing with this technology goes as follows: First, pilot sequence and training sequence of proper lengths are added at transmitter, and frequency response of pilots is estimated based on Least Square (LS) and Minimum Mean Square Error (MMSE); then interpolation algorithm is used to estimate frequency responses of other locations on the basis of the estimated ones, then the transfer function of the entire channel is worked out; finally, equalization processing is performed according to the channel transfer function.

4 Nonlinearity Effect in O-OFDM System and its Elimination

4.1 Nonlinearity of MZM and PAPR

Most OOFDM systems use a MZM as the optical transmitter to implement E/O conversion. MZM is a kind of nonlinear modulator. The relationship between its bias voltage and output signals is shown in Figure 5. When the signal amplitude goes beyond the maximum linear conversion interval of MZM, irrecoverable distortion is induced, and the system's bit error ratio is reduced. As a result, it is required not only to process the signal, letting its mean amplitude be within MZM's linear interval, but also to select the optimal bias point so as to minimize inter-modulation distortion. The high PAPR of the OFDM technology may bring about deep modulation of MZM, leading to higher inter-modulation distortion and reduction in bit error ratio. Therefore, it is quite critical for MZM to reduce PAPR.

4.2 FWM and PAPR

Being robust against dispersion effect, OFDM technology can be applied in ultra-long haul fiber transmission, but it is very sensitive to nonlinearity effect. For one-way WDM channel, frequency interval between OFDM subcarriers of a channel is often very narrow, so phase matching, which is a condition of Four-Wave Mixing (FWM), is likely to occur. Consequently, serious FWM noises are superimposed onto the subcarriers and SNRs are reduced. FWM products are directly related to the power of each subcarrier[7]. If the average power of OFDM symbols is reduced, the system's capability against FWM can be dramatically improved. The direct method to mitigate FWM product is to reduce the peak power of OFDM, that is, to reduce PAPR of OFDM symbol.

4.3 FWM and Serial Correlation Between Subcarriers

FWM is related not only to the power of OFDM signal, but also to the correlation between OFDM subcarriers. In the case of independent identical distributions $E(X_i)=0$ and $D(X_i)=\sigma^2$, FWM variance can be computed. For example, FWM variance of subcarrier d can be expressed as[8]:

$$D_d=\frac{1}{2}(\gamma Z_{eff}P)^2\alpha^6[3-\frac{9}{N_c}-(\frac{2d+1-N_c}{N_c})^2] \quad (2)$$

where N_c is the number of subcarriers, P is the average power of normalized OFDM symbols, γ is the nonlinear coefficient, α is loss coefficient and Z_{eff} is effective fiber length. If M-ary Phase-Shift Keying (MPSK) scheme is used as digital baseband modulation and Euclidean distance $|x_d|=1$, $\sigma^2=1$ is met, the SNR of subcarrier d can be expressed as:

$$SNR(d)=20\lg(\frac{\alpha}{\gamma Z_{eff}P})-10\lg[\frac{3}{2}-\frac{9}{2N_c}-\frac{1}{2}(\frac{2d+1-N_c}{N_c})^2] \quad (3)$$

Supposing $\gamma\approx 2\text{w}^{-1}\text{km}^{-1}$, $p\approx 1\text{mw}$, $\alpha\approx 0.2\text{dB/km}$, and $N_c\approx 1,024$, $SNRs$ of subcarrier d are:

$$SNR_{min}=SNR(\frac{N_c}{2})=25.5\text{ dB}$$
$$SNR_{max}=SNR(0)=SNR(N_c-1)=27.2\text{ dB} \quad (4)$$

However, it is difficult to realize independent distribution in channel-coding. Therefore, the nonlinear noises would be higher than that of Equations (3) and (4). An intuitive approach is to modify the serial approaching independent distribution, i.e., one can destroy the serial correlation by reducing the symbol auto-correlation function. If small auto-correlation function is promised, the time-domain signal will not fluctuate drastically, leading to a weak fiber nonlinearity.

4.4 Nonlinear Distortion Processing Mechanism of OOFDM System

(1) Partial Carrier Filling

The most direct method of suppressing FWM is to destruct its phase matching condition. Partial Carrier Filling (PCF) is such an algorithm. It first fills specific OFDM subcarriers with null subcarriers, where "0" is always transmitted; then it changes FWM's phase matching condition to make FWM products fall onto the null subcarriers; finally, it discards the null carriers at the receiver. In this way, nonlinearity is mitigated. PCF improves the system performance at the cost of bandwidth, and significantly decreases the system's spectral efficiency.

(2) PAPR Reduction Algorithm

In OOFDM system, the nonlinearity

effect arisen in Mach-Zehnder modulation and fiber transmission is affected by peak powers of signals, and it induces signal distortion and decreases system performance. The most direct method to mitigate nonlinearity effect is to reduce PAPR of OFDM system.

Roughly, existing PAPR reduction schemes fall into three kinds[9]. The first kind is called signal pre-distortion technology, which implements nonlinear distortion processing, such as limiting signal amplitude, removing peak signals, which clip the signals whose powers exceed the threshold. The second kind is coding scheme, which tries not to use those coding patterns that may generate large peak power signals. The third kind is probability algorithms. They use different scrambling sequences to weight OFDM symbols, thus the OFDM symbols with small PAPRs are selected to transmit. Examples of such algorithms include Partial Transmit Sequence (PTS) and Selected Mapping Technique (SLM).

(3) Nonlinearity Precompensation

In OOFDM system, chromatic dispersion does not induce strong walk-off effect, but it causes serious nonlinear phase distortion, which leads to rotation of constellation points. The strong nonlinearity effect may even result in decision region errors or reduction of bit error ratio. As a result, in order to further mitigate fiber nonlinearity, it is required to process the signals and introduce pre-distortion phase before E/O conversion.

Nonlinearity precompensation technique uses distributed FFT algorithm[10], which functions like a "virtual fiber". After being processed with FFT, all OFDM symbols are multiplied by a phase factor $\theta(t)$:

$$\theta(t)=P(t)\cdot s\cdot L_{eff}\cdot 2\pi\cdot n_2/(\lambda_0 A_{eff}) \quad (5)$$

where $P(t)$ is transient optical power, s is the number of segments of fiber in distributed FFT, L_{eff} is the effective length of each fiber segment, n_2 is nonlinear coefficient, λ_0 is the wavelength of the laser and A_{eff} is effective area of fiber.

(4) Digital phase conjugation

In fiber communication system, a phase conjugator is often placed at the middle point of fiber to mitigate phase noises induced by fiber nonlinearity . But optical networks tend to be dynamically reconfigurable. In this case, using a phase conjugator is not flexible enough because it would fail to process dynamic optical links. In OOFDM system, many digital signal processing technologies are used, for example, the above-discussed nonlinearity precompensation technique at transmitter, which can also be used at the receiver. Therefore, at the receiver, the functions of phase conjugator can be realized by means of digital signal processing. In this way, nonlinearity effect in dynamically reconfigurable optical network is suppressed at the price of adding computation complexity.

5 Conclusions

Enjoying a promising prospect in RoF and ultra-long haul transmission, OOFDM technology has drawn attentions worldwide and raised many new research topics. The research on these topics will no doubt promote the merging of optical communication with wireless communication and quicken their development.

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Biographies

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Li Weilin is studying for his master degree at the Institute of Optical Communication and Optoelectronics, Beijing University of Posts and Telecommunications (BUPT), majoring in electromagnetic field and microwaves. Currently, he is engaged in the research of combination of OFDM technology with optical communication and with RoF technology.

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Zhang Jie is a professor and doctoral advisor at BUPT and the deputy director of the Institute of Optical Communication and Optoelectronics, BUPT. He has taken charge of more than 10 key research projects at national or provincial level. His research areas include automatically switched optical network, optical transport network, packet transport network and ultra-high speed optical transmission technologies. Up to now, he has been granted seven invention patents, and has published 15 ITU-T standard proposals, five books and over 100 papers which can be indexed by SCI/EI.

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Gu Wanyi is vice director of Academic Committee of BUPT, director of Academic Committee of School of Telecommunication Engineering of BUPT, a member of IEEE, a senior member of China Institute of Communications, and the leader of Optical Communication Group of Beijing Communication and Information Association. She has been mainly engaged in research and teaching in the fields of high speed optical communication, WDM optical transport network and intelligent optical networks, and has undertaken and completed more than 10 key projects granted by National High Technology Research and Development Program of China ("863" program), and National Natural Science Foundation of China or related ministry. She has been awarded six Science and Technology Advancement Prizes due to her excellent research achievements. So far, she has owned seven invention patents, three utility model patents and has published over 200 papers.