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# 基于光环路正交频分多址无源光网络的光拍频噪声避免方案及性能仿真

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**摘　要**：在正交频分多址无源光网络上行传输中，不同光网络单元的上行信号如果采用相同波长的不同激光器将会产生光拍频噪声，使得光网络单元的无色性难以实现. 本文以正交频分多址无源光网络为研究对象，通过对系统结构的研究和相关公式的推导，分析了信号上行传输中光拍频噪声的产生原因和避免方式. 针对下行发送上行载波结合光线路终端相干接收的光拍频噪声避免方案进行了仿真研究. 分析了系统的抗色散方案以及色散累积和训练序列长度对系统性能的影响，给出了优化的参数设置，为系统实际应用提供了理论参考.

**关键词**：光通信；无源光网络；仿真分析；正交频分多址无源光网络；光拍频噪声；物理层损伤
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# The Simulation of Optical Beating Interference Avoidance Scheme and System Performance in Orthogonal Frequency Division Multiple Address Passive Optical Network System Based on Optical Loop

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**Abstract**: In Orthogonal Frequency Division Multiple Access Passive Optical Network (OFDMA-PON) upstream transmission, the Optical Beating Interference (OBI) will be produced if each ONU uses different lasers with the same wavelength. The colorless ONU is hard to achieve with the presence of OBI. The OFDMA-PON system structure was studied and the related formulas were derived to analyze the generation and avoidance of OBI. The OBI avoidance scheme that sending optical carrier used in upstream by downstream transmission combined with coherent detection in optical line terminal was simulated. Via simulation, the anti-dispersion scheme and the effects of dispersion accumulation and the length of training sequence on system performance were studied, and the parameter configuration was optimized to provide a theory reference for practical application.

**Key words**: Optical communication; Passive Optical Network; Orthogonal Division Multiple Access PON; Optical Beating Interference; Physical layer impairments
**OCIS Codes**: 060.2330; 060.2360; 060.4510; 070.6020

## 0 Introduction

As a primary candidate for next generation access network utilization, Orthogonal Frequency Division Multiple Access Passive Optical Network (OFDMA-PON) has caused a wide attentions of researchers in

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optical field since its prominent advantages of high spectral efficiency, and robust against inter symbol interference and chromatic dispersion[1-9]. However, in the upstream transmission process, if different Optical Network Unit (ONU) adopts different lasers with same wavelength, with the influence of factors like temperature, the optical frequency fluctuation will be generated, which will lead to the Optical Beating Interference (OBI)[10-11]. OBI is a big obstacle for the implementation of OFDMA-PON. If we want to adopt OFDMA-PON in next generation PON version 2 (NG-PON2), OBI is an issue that should be solved.

Some avoidance schemes of OBI have been proposed like ONUs adopting a large enough optical carrier wavelength space in the upstream transmission or transmitting an empty carrier in the downstream transmission to ensure the accurate alignment of optical spectrum[12-13]. However, the former scheme increases the difficulty in the realization of ONU, which results in the additional cost, but the latter scheme transfers the cost of laser in ONU side to Optical Line Terminal (OLT), and together with the benefit of coherent detection, which can achieve a better utility.

In this paper, the transmission performance and the avoidance scheme of OBI in 20-Gb/s OFDMA-PON upstream transmission system were researched via constructing the simulation platform based on optical loop scheme, and the relative optimized system configuration and algorithm parameters configuration were studied, which provides a reference for the practical system application. Theoretical analysis of the feasibility of the scheme that treats the transmitted empty carrier in downstream transmission as the upstream carrier is given. Via constructing the coherent receiving OFDMA-PON (CO-OFDMA-PON) simulation system of the scheme mentioned above, we have researched the system transmission performance and the parameter configuration that adopts digital signal processing (DSP) and found that the upstream transmission scheme in CO-OFDMA-PON can very well avoid the impairments caused by OBI. Since the techniques of coherent detection is utilized together with the DSP techniques, we can achieve further improvement of transmission quality.

# 1 Formula Derivation and Theoretical Analysis

Orthogonal Frequency Division Multiple Access (OFDMA) is a derived multiple access scheme that makes use of the transmission character of OFDM signal and it distributes different subcarriers to different users to realize the dynamic distribution of bandwidth resource. Fig. 1 demonstrates the architecture of system structure diagram of OFDMA-PON.

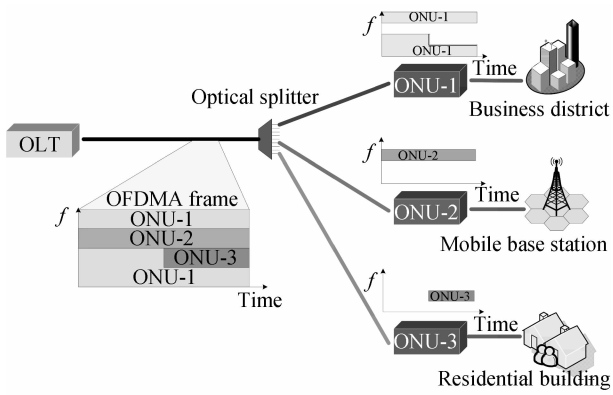


Fig. 1 The structure of OFDMA-PON system

Fig. 2 illustrates the schematic of direct detection OFDMA-PON (DD-OFDMA-PON). When $n=2$, the condition of two ONUs is simulated. First map the binary signal with $m$-QAM and then implement the serial-to-parallel conversion (S/P). After inverse fast Fourier transform (IFFT), the signal now is in time domain and cyclic prefix (CP) is inserted subsequently. In order to turn the complex signal to real form, up-conversion is utilized to turn the baseband signal to radio frequency domain. After modulated by Mach-Zehnder modulator (MZM), the signal is then transmitted over optical link. At the receiver side, direct detection is used, and after down-conversion, S/P conversion, CP removing and $m$-QAM demodulation have been performed, we finally get the binary signal.

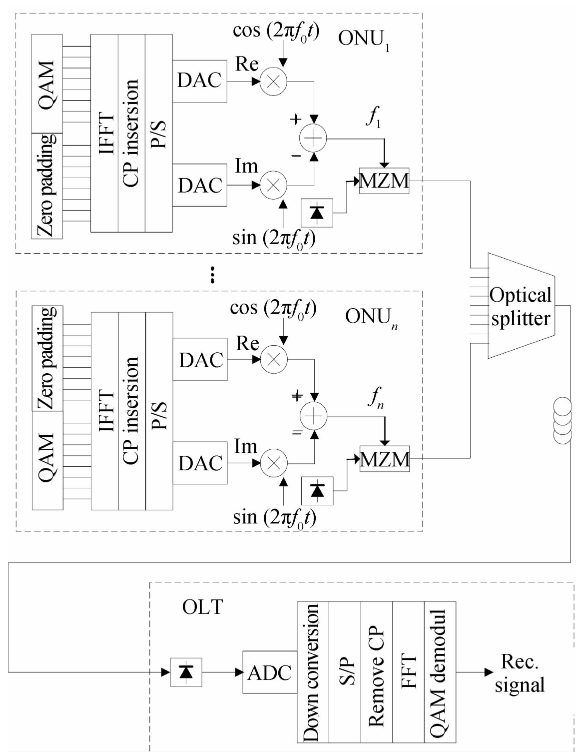


Fig. 2 The schematic of DD-OFDMA-PON system

Assuming the radio frequency domain signal of $ONU_1$ and $ONU_2$ are $M_1$ and $M_2$ respectively. Then the two modulated ONU optical signals can be represented as

$$(A_1+M_1)\cos(2\pi f_1 t) \quad (1)$$

$$(A_2+M_2)\cos[2\pi(f_1+\Delta f)t] \quad (2)$$

$A_1$ and $A_2$ represent the optical carriers for the two ONU upstream signals respectively, and $A_1 \gg M_1$, $A_2 \gg M_2$. Even if we adopt lasers with the same wavelength, due to the influence factor like temperature in practice application, the upstream frequencies of different lasers cannot be exactly the same. Assuming the time-varying frequency difference between $ONU_1$ and $ONU_2$ is $\Delta f$, $f_2 = f_1 + \Delta f$, $A_1 = A_2 = A$, and the direct detection process can be regarded as computing the square of signal, then after the photoelectric conversion, the signal is represented as

$$[(A+M_1)\cos(2\pi f_1 t)+(A+M_2)\cos(2\pi f_2 t)]^2 \quad (3)$$

Due to the low-pass principle of phototube and the DC block filter in system, the final signal in radio frequency domain will be

$$(AM_1+AM_2)+(M_1^2/2+M_2^2/2)+\cos[2\pi\Delta f t][A^2+A(M_1+M_2)+M_1M_2] \quad (4)$$

The first part in Eq. (4) is the useful signal, the second part is the Signal-to-Signal Beating Interference (SSBI) caused by signals themselves and they distribute in low frequency portion, the third part is the beating interference caused by signals from different $ONU_s$ and centers in $\Delta f$, which is just the OBI. Since the power of optical carrier in direct detection scheme is much larger than the power of signal, therefore OBI is the dominant factor and its power is much larger than the power of useful signal. We can achieve from Eq. (4) that the bandwidth of OBI is twice the bandwidth of useful signal. As the modulation scheme we adopted is up-conversion, the bandwidth after modulation is $f_{RF}+B$, which is shown in Fig. 3.

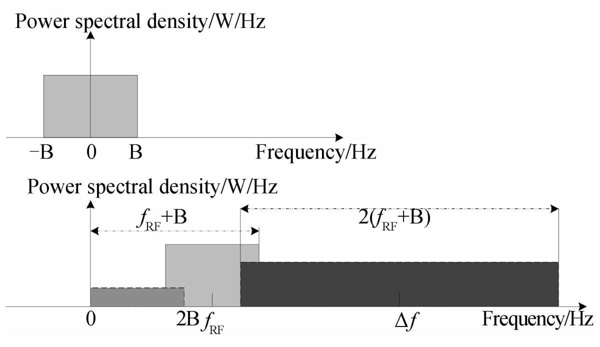


Fig. 3 The spectral of OFDM baseband signal and radio frequency domain signal with OBI and SSBI

The spectrum of OBI shown in Fig. 3 center in $\Delta f$, and the bandwidth is $2(f_{RF}+B)$. Therefore in order to separate the OBI and useful signal, $\Delta f$ should be $2(f_{RF}+B)$ at least. When $\Delta f=0$, the optical carrier frequencies of the two ONUs are exactly aligned and the radio frequency signal can be represent as

$$2(AM_1+AM_2)+(M_1^2/2+M_2^2/2)+A^2+M_1M_2 \quad (5)$$

As the SSBI can be ignored and the DC component can be filtered, they won't interfere with the useful signals. Therefore, OBI is the main influence factor and should be avoided[14]. From Eq. (4) it can be seen, there are two avoidance schemes

1) Adopt a large enough optical carrier wavelength space among ONUs. As the amplitude of SSBI is very small, we can ignore it and just need to separate the OBI from the useful signal. In order to realize it, $\Delta f$ should be twice the signal bandwidth according to the derivation above. However, this scheme will need up-converter in electrical domain or adopting optical carriers with different frequencies, which is difficult for the colorless ONU realization.

2) Ensure the accurate alignment among the upstream wavelengthes adopted by different ONU. Because of the complex environment, the temperature and humidity factors which can lead to the laser frequency drifting, it is not easy to realize accurate alignment among OUN upstream signal optical currieries. If the loopback scheme is adopted, in which the OLT will transmit a seed wavelength that will be used as upstream optical carrier along with the downstream signal to the ONUs, we can realize the accurate alignment of frequency. In addition, from the observation of the OBI generation reasons, it can be seen that the shift of upstream optical carrier component is the main factor. Therefore, we can consider reducing or eliminating this part by adopting coherent detection at the OLT side and utilizing a local oscillator to generate the optical carrier component to replace the component A in Eq. (4). In this way, the frequency fluctuation can be avoided.

The advantage of loopback scheme is that it can realize the colorless of ONU in the presence of adopting coherent detection at OLT side, which will not cause significant increase of system total cost as the expense of OLT is undertook by all ONUs.

## 2 Simulation System and Results

Fig. 4 illustrates the simulation platform of CO-OFDMA-PON system. At the OLT side, coherent receiver is utilized. The optical carrier generated by local oscillator will be mixed with the upstream signals, which can avoid the frequency drift, so that the generation condition of OBI is fully eliminated.

In this scheme, the signals of the two ONUs are separated by mapping them to different subcarriers. After the up conversion with same frequency, the signals are transferred to radio frequency domain to avoid the distortion caused by SSBI. The scheme uses different subcarriers to distinguish signals of various ONUs, which is different from the scheme mentioned in Ref. [11]. Besides, the scheme also adopts zero-padding to subcarriers to provide the guard-band to avoid the interference of signals transmitted by different ONUs.

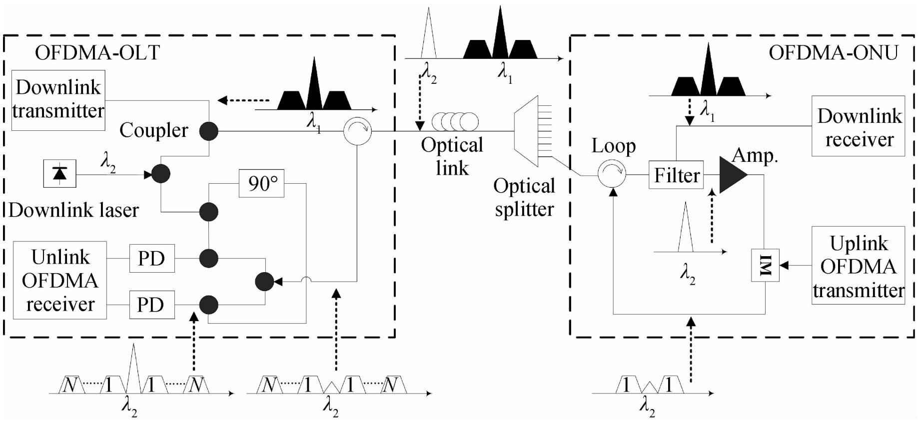


Fig. 4 The structure of CO-OFDMA-PON system

Table 1 shows the main parameter configuration of system. The spectra of the OFDM signal is all centered in 193.4 THz which is 1 550 nm in wavelength.

**Table 1 Basic parameters of simulation platform**

| Parameters | Value |
|---|---|
| DAC Sampling Rate | 10 Gsample/s |
| FFT Length | 256/512/1024 |
| Modulation Format | 16QAM/32QAM |
| Total Uplink Rate | 20 Gb/s |
| Up-conversion Frequency | 7.5 GHz |

## 2.1 The Effect of Random Phase Noise on System Performance

The random phase noise of optical carrier is one of the significant factors that affect the system performance, and the laser linewidth is the main source that causes random phase noise. Whether the system is feasible in the presence of random phase noise is a considerable issue, so the relationship between system $Q$ factor and laser linewidth is studied firstly, and the simulation result is shown Fig. 5.

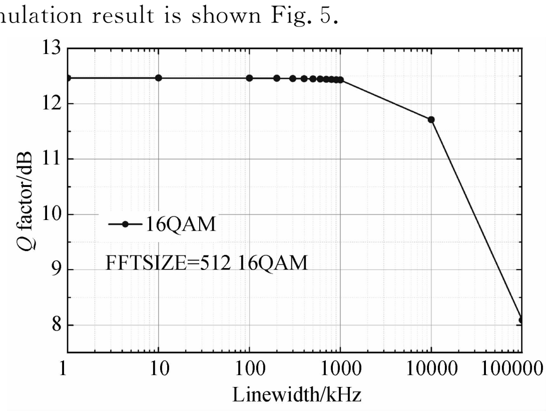


Fig. 5 The relationship between $Q$ factor and laser linewidth

From Fig. 5 we can see that when the linewidth is under 1 MHz, it doesn't cause obvious influence on the system performance. Normally, the laser linewidth is around 100 kHz, and with such condition, the system can afford good performance in random phase noise resistance. In the following simulations, we will set the laser linewidth as 100 kHz.

In addition, since the distances between OLT and different ONUs are various, the signals of different ONUs will experience different phase variations. In the proposed scheme, Training Sequence (TS) which can be used for channel estimation is adopted. The transfer matrix obtained from TS can help us to compensate the phase rotation efficiently. Therefore, because of the function of TS, the phase variation can be estimated and eliminated. As a result, the phase variations of different ONUs will not cause significant influence on system performance.

## 2.2 The Simulation of System OSNR Tolerance

As Signal-to-Noise Ratio (SNR) is a measure of signal strength relative to background noise that used in analog and digital system, Optical Signal to Noise Ratio (OSNR) which represents the ratio of signal power to the noise power in a given bandwidth is proposed to be used in optical communication system.

Fig. 6 depicts the relationship between $Q$ factor and OSNR corresponding to different TS length in 16

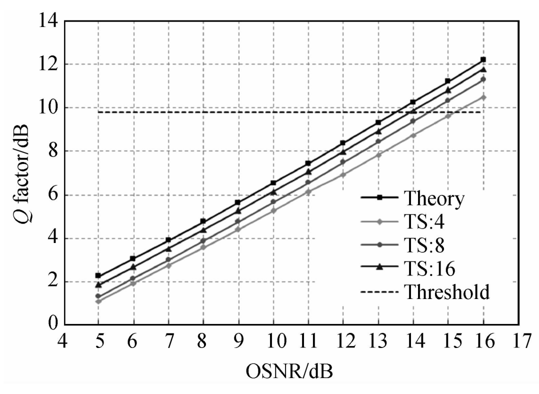


Fig. 6 The simulation results of $Q$ factor versus OSNR and TS length

QAM system. We can see that the system OSNR tolerance is 14 dB in theory, at when the system Bit Error Rate (BER) can reach e-3. Only TS equals to 16 can satisfy such condition and the larger the TS length is, the better the system performance will be. Therefore, in order to see the effects of other parameters clearly, we set the OSNR as 16 dB and TS length as 16 in the following simulations.

### 2.3 The Simulation of System Dispersion Accumulation Tolerance

Chromatic dispersion in optical fiber is one of the critical physical impairments in optical communication. As a special multicarrier modulation scheme, OFDM has good anti-dispersion performance. Since the symbol rate is low, the tolerable delay spread is long; on the other hand, with the help of Cyclic Prefix (CP), good orthogonality among subcarriers is achieved. Combined with TS, which can be used to conduct channel estimation, the system can tolerate very large dispersion accumulation in fiber link.

Fig. 7 shows the simulations of the relationship between $Q$ factor and the dispersion accumulation in fiber link when subcarrier number is 256 and 512 respectively. The analysis results show than:

1) As the dispersion accumulation increases, the system performance decreases. When CP ratio is 2/256, system can endure 1000ps/nm dispersion accumulation. In accordance with the dispersion coefficient of standard single mode fiber (SSMF) G.652 which is 16 ps $\cdot$ nm$^{-1}$ $\cdot$ km$^{-1}$, the length of the tolerable transmission distance is about 80 km, which can sufficiently satisfy the requirement of NG-PON2. Therefore, we will set the CP ratio as 2/256 in CO-OFDMA-PON system.

2) When the delay spread is within the length of CP, chromatic dispersion accumulation will not affect the orthogonality among subcarriers. We can use TS to recover the phase rotation of signals carried by different subcarriers and it won't cause significant effect on system performance. However, when CP length is shorter than the delay spread, TS will not work well and the system dispersion tolerability will decrease severely.

3) The larger the OFDM subcarrier number is, the better the system dispersion tolerance will be. Considering that the system complexity is positively correlated to FFT length, 512-subcarrier will be a good choice. In addition, the system noise will affect the algorithm accuracy, so this method cannot fully compensate the impairments caused by chromatic dispersion which will cause 0.5 dB penalty.

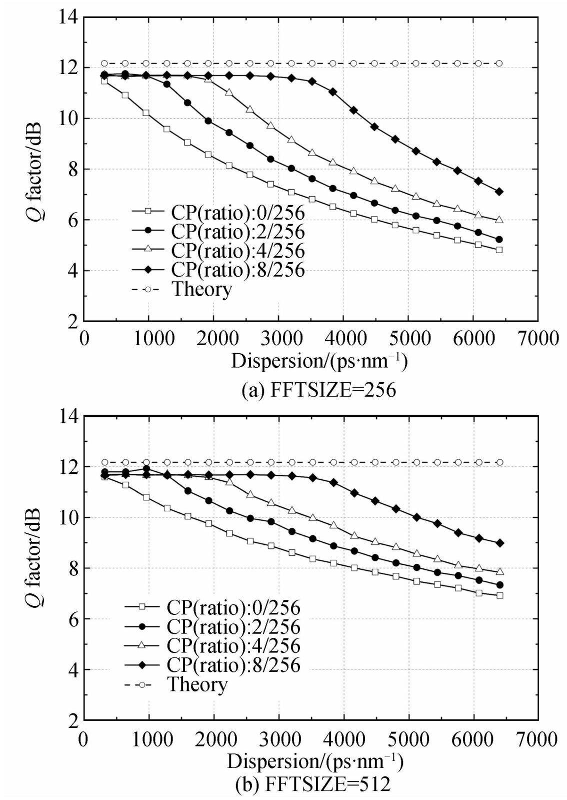


Fig. 7 The relationship between $Q$ factor and dispersion accumulation

## 3 Conclusion

In this paper, the OBI issue in OFDMA-PON system was studied. Through formula derivation, theoretical analysis and system simulation, we choose the loopback CO-OFDMA-PON as the upstream transmission system structure and research the relationship of $Q$ factor with different laser linewidths, dispersion accumulations and CP lengths which can provide some theoretical reference for the practical application of CO-OFDMA-PON system.

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