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Nonlinearity analysis and signal distortion cancelation in IMDD OFDM PON

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Abstract: A novel method of subcarrier evolution was proposed to analyze the nonlinearity of an intensity-modulation direct-detection (IMDD) orthogonal frequency division multiplexing (OFDM) passive optical networks (PON). The nonlinearity was mainly caused by the subcarrier-to-subcarrier intermixing interference (SSII) and the chirp from the modulation. The fiber disperssion results in that the optical subcarrier can not keep the best initial phase matching condition which exacerbates the signal distortion. A new modified Volterra digital filter was also proposed to cancel the signal distortion of the IMDD OFDM PON. The modified Volterra digital filter included not only the same samples but also the different samples. The corresponding experiments had been carried out to verify the effectiveness of the proposed signal distortion cancelation method. The proposed modified Volterra filter could bring about 3 dB power benefits than the previous work to meet the forward error correction (FEC) limit of 10^{-3}. The transmission penalty over 25 km at the FEC limit of 10^{-3} was lower than 0.5 dB. Finally, the system can reach a data rate of 24.5 Gbps, and the spectrum efficiency can achieve up to 7 $\text{bits}\cdot\text{s}^{-1}\cdot\text{Hz}^{-1}$. These experimental results prove that the modified Volterra filter can effectively compensate the linear and nonlinear distortion and therefore it can recover the signal at optical network unit (ONU).

Key words: signal and information processing; signal distortion cancelation; Volterra filter; subcarrier-to-subcarrier intermixing interference; passive optical networks; orthogonal frequency division multiplexing

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IMDD OFDM 无源光网中的非线性分析和信号失真消除

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摘 要: 提出一种子载波演化方法分析基于强度调制直接探测的正交频分复用无源光网络中的非线性。该无源光网络中的非线性主要来源于调制过程中的子载波混合干扰和啁啾。传输过程的光纤色散

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会导致调制时的各子载波最佳相位匹配条件不能维持，进一步导致信号恶化。设计了一种新的 Volterra 数字滤波器除信号失真。修正的 Volterra 数字滤波器不仅包含相同的采样点,还包括了不同的采样点。通过实验验证了该滤波器去除信号失真的效果;在 FEC 为 10^{-3} 的情况下,实验结果与已经报道的结果相比提升 3 dB 了功率效益；传输 25 km 光纤与背对背相比,FEC 为 10^{-3} 时的功率亏损小于 0.5 dB;系统的数据传输速率达到 24.5 Gbps,频谱效率达到 7 bits/s/Hz。实验结果表明提出的方法可以有效地消除信号的线性和非线性失真,能够有效地恢复信号。

关键词: 信号与信息处理； 信号失真消除； Volterra 滤波器； 子载波干涉； 无源光网络； 正交频分复用

0 Introduction

As many superior performances such as low building cost, high operation efficiency and friendly structure, passive optical networks(PON) dominate and lead the market of the access network[1-3]. With the required bit rate increasing, several multiplexing schemes based on PON technology have been proposed, such as time-division multiplexing (TDM) PON[4], orthogonal frequency-division multiplexing (OFDM) PON[5]. Transmission in TDM PON is primarily based on simple non return-to-zero(NRZ) on-off keying(OOK) modulation. However, it is hard to support the data rate higher than 10 Gb/s as serious distortion resulting from considerable inter-symbol interference(ISI) that is produced by fiber chromatic dispersion. In contrast, transmission in OFDM PON has higher tolerance for the dispersion by inserting a cyclic prefix(CP) in one OFDM symbol. In addition, on the basis of using higher order quadrature amplitude modulation(QAM) format, OFDM-PON effectively achieves high spectral efficiency and essentially reduces the bandwidth requirement of components. Meanwhile, to increase the economy PON systems, intensity-modulation direct-detection (IMDD) is expected. At present, directly modulated DFB laser (DML) and electro-absorption modulated laser (EML) are usually used as cost-effective transmitters, and PIN detectors are often installed for direct-detection at receivers[1].

However, the DML and EML have high chirp parameters. When the bandwidth of the modulated signal is higher than 3.5 GHz, it will give rise to intrinsic chirp problem in the OFDM PON[6]. More seriously, with the fiber-dispersion effect on the chirped signal, it results in severe power fading and signal distortion. As a consequence, it exacerbates signal distortion. Under the stimulation of the integration factors mentioned above, different model have been proposed to theoretically analyze the nonlinearity of the IMDD based OFDM PON[6-7], and some methods were invented to remove the signal distortion resulted by the nonlinearity. In references[6], [8], [10], the distortion has been viewed as the form of subcarrier-to-subcarrier intermixing interference (SSII), and many SSII cancellation schemes have been proposed to eliminate the nonlinear distortion [6,11-15]. In these schemes, interweaves code technology claims that it can improve the BER performance, however, interweaves code of the preprocessing unit increases the computation complexity of the transmitter. Pre-emphasis technique firstly estimates channel response, then change the power ratio of every subcarrier based on the estimated channel response, and the subcarrier with different SNR can carry different QAM number to bring benifits of data rate. However, it is required that estimating channel response frequently when the system is unstable. The method of the pre-emphasis pilot frequency reduced the spectrum effectiveness. As an alternative approach, nonlinear Volterra filtering has been proposed to compensate the signal distortion in Ref. [16]. Different from above methods, it is high-speed real-time processing, and more importantly, extra bandwidth and computation of optical line terminal (OLT) are not required. Although the nonlinear Volterra method can improve the signal performance, only same samples were considered in the second and third order terms in[16], therefore, it can not agree with the practical situation very well.

The mechanism of the nonlinearity and signal distortion based on the small-signal analysis method are analysed in this work, and an digital filter based on Volterra algorithm to conceal the signal distortion is proposed. Different from the previous work, the interactions of the different samples is considered. Experimental verification have also been carried out by an EML based OFDM PON. In experiment, the received signals are equalized through the Volterra algorithm based digital filter. The results show that the proposed Volterra algorithm based filter can obtain obviously bit error rate (BER) improvements than that of in the previous works.

1 Theoretical analysis of SSII

To analyze the nonlinearity of an IMDD OFDM PON, we give a qualitative comparison analysis between the amplitude modulation (AM) and the intensity modulation (IM) in electrical to optical(E/O) conversion at first. The amplitude modulation can be demonstrated conceptually by Fig.1(b). Given an electrical OFDM, signal can be expressed as $\mathbf{X}=\sum_{n=1}^{N} v_n\exp(jn\omega t)$. After amplitude modulation, the amplitude and phase of every electrical OFDM subcarrier are up-converted to the corresponding optical subcarrier. If the AM modulator(e.g. MZM modulator) works in linear range, we can describe the optical field as $\mathbf{E}\propto\sum_{n=1}^{N} v_n\exp(jn\omega t)$, which means that the information of any optical OFDM subcarrier is only determined by the corresponding electrical subcarrier. After direct detection, the received signal is $\mathbf{I}\propto\left|\sum_{n=1}^{N} v_n\exp(jn\omega t)\right|^2$.

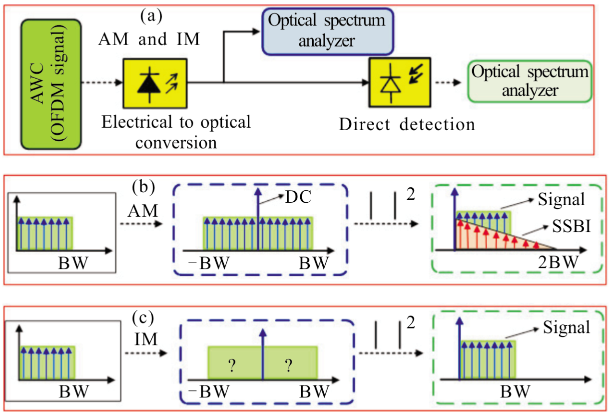

Fig.1 (a) Schematic diagram of the AMDD and IMDD system, (b) signal spectrum of the AMDD, and (c) the IMDD

It shows that the received signal includes the desired signal, which is the beating terms between the DC and all subcarrier, and the signal distortion, which is caused by a subcarrier-signal beat interference(SSBI). The SSBI can be cancelled by designing a frequency gap between intermediate frequency (IF) carrier and the OFDM signal. The intensity modulation and direct detection can be conceptually demonstrated by Fig.1(c). If an electrical OFDM signal is converted to optical domain through an intensity modulation (eg. EML based modulation), the optical signal can be expressed as $\mathbf{E}\propto\sqrt{\mathbf{p}}=\sqrt{1+\mathbf{X}}$, where 1 represents the DC term. It is not hard to find that the information of any optical OFDM subcarrier are determined by all electrical subcarriers. Therefore, in principle, we can not depict the optical OFDM subcarrier as Fig.1(b). Expanding the $\mathbf{E}\propto\sqrt{\mathbf{p}}=\sqrt{1+\mathbf{X}}$ to Taylor series, we can find that the optical signal includes not only the original signal $\mathbf{X}$ but also the nonlinear terms ($\mathbf{X}^2$, $\mathbf{X}^3$, …). If the nonlinear terms higher than second is neglected, we can redraw IMDD as shown in Fig.2. In optical domain, there are not only the desired subcarriers but also the second order subcarriers. The second order subcarriers are viewed as SSII. To avoid the signal distortion, only the best phase matching condition in intensity modulation process is held in the transmission. Unfortunately, the best phase matching condition can not be kept as the fiber dispersion, which results in the signal distortion and power fading. In addition, the EML or DML has high transient chirp and adiabatic chirp, which results in severe power fading and signal distortion.

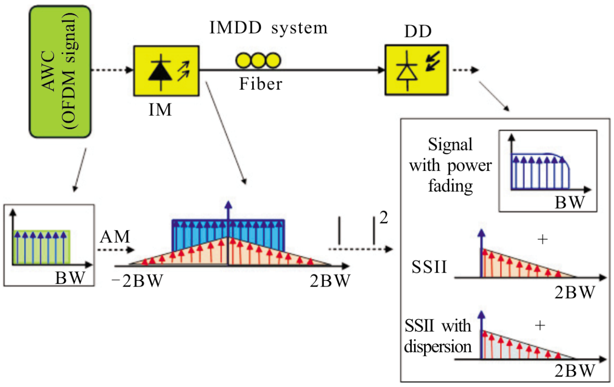

Fig.2 Schematic diagram of the IMDD system and the corresponding frequency when the the nonlinear terms higher than second are neglected

2 SSII cancellation based on the Volterra algorithm

From the analysis above, we can see that the signal distortion of an IMDD OFDM PON is mainly caused by the SSII and the chirp of the modulator. The fiber dispersion leads to a problem that the optical subcarrier can not keep the best initial phase matching condition which exacerbates the distortion. In time domain, the process can be viewed as an issue that the received signal are affected by the earlier received signal. It can be compensated by the adaptive Volterra filter. Based on the Volterra series, the **n**th sample of the output signal waveform of the adaptive filter is represented as:

$$\mathbf{y}(\mathbf{n})=\sum_{l_1=1}^{\mathbf{L}}\mathbf{w}_1(l_1)\mathbf{x}(\mathbf{m}-l_1)+\sum_{l_1=1}^{\mathbf{L}}\sum_{l_2=1}^{\mathbf{L}}\mathbf{w}_2(l_1,l_2)\mathbf{x}(\mathbf{m}-l_1)\mathbf{x}(\mathbf{m}-l_2)+\cdots+\sum_{l_1=1}^{\mathbf{L}}\sum_{l_2=1}^{\mathbf{L}}\cdots\sum_{l_k=1}^{\mathbf{L}}\mathbf{w}_{\mathbf{k}}(l_1,l_2,\cdots,l_{\mathbf{k}})\prod_{i=1}^{\mathbf{k}}\mathbf{x}(\mathbf{m}-l_l)+\cdots \tag{1}$$

where $\mathbf{x}(\mathbf{m}-l_l)$ is the $(\mathbf{m}-l_l)$th sample of the received signal, $\mathbf{w}_{\mathbf{k}}(l_1,l_2,\cdots,l_{\mathbf{k}})$ is the weighting factor of the **k**th order, and **L** is the memory length. The first term in Eq.(1) indicates a linear filter, and the others are nonlinear filters. $\mathbf{w}_{\mathbf{k}}(l_1,l_2,\cdots,l_{\mathbf{k}})$ is the function of the signal input. In this work, the second order Volterra filtering are considered, and the nonlinear terms higher than second order are neglected. Different from the previous work, in which the second order term is just considered same sample (ie. $l_1=l_2=l_3$), the proposed scheme includes both the same samples and the different samples. To directly understand the adaptive Volterra filter, we give an example in which memory length is three. In order to recover the signal, we must sum the first and the second term as shown in Fig.3. The second terms contains not only the weighting factor of same samples $\mathbf{w}_{1,1}^{2}$, $\mathbf{w}_{2,2}^{2}$, $\mathbf{w}_{3,3}^{2}$, but also the weighting factor of different samples $\mathbf{w}_{1,2}^{2}$, $\mathbf{w}_{1,3}^{2}$, $\mathbf{w}_{2,3}^{2}$. In other words, the current received sample is affected by the nearest two samples.

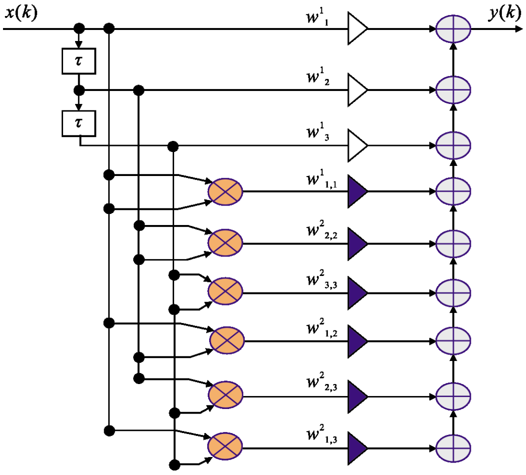

Fig.3 Concept of the adaptive Volterra filter with the memory length of 3 samples

3 Experimental setup

Figure 4 illustrates the experimental setup of IMDD OFDM PON. The OFDM signals are generated by an arbitrary waveform generator (AWG, Tektronix7122B). The sampling rate and DAC resolution of AWG are 12 G Samples/s and 8 bits, respectively. Other parameters of the OFDM signals are a DFT size of 512 and a subcarrier number of 298, which result in the total bandwidth of 3.5 GHz, and a cyclic prefix of 1/32 block time.

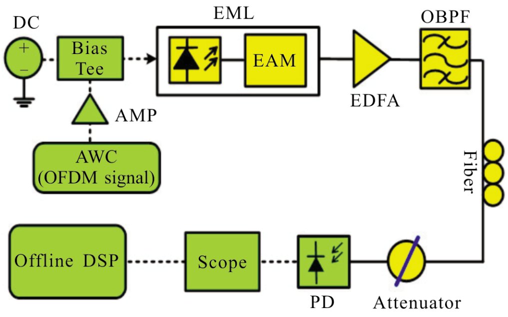

Fig.4 Experimental setup of the IMDD OFDM PON

The optical transmitter is composed of an EML, a booster, and an optical band-pass filter(OBPF). The EML(CIP 10G-LR-EAM-1550) is integrated with an electro-absorption modulator (EAM) and a distributed feedback (DFB) laser. With 1.4 V EML bias voltage, the output power is 1.2 dBm centered at 1 548.66 nm. An Erbium Doped Fiber Amplifier (EDFA) enables the launch power of 15 dBm. The EDFA output is launched into an optical band pass filter (OBPF) to remove thermal noise. To avoid the nonlinearity of the fiber, the fiber input power was set as 9 dBm.

The optical signal is detected by a low speed PD with a bandwidth of 10 GHz. The PD input power is controlled by an optical attenuator. The signal is captured by a digital oscilloscope (Tektronix ® DPO 71604) with a sampling rate of 80 G Samples/s. Finally, the OFDM signal is demodulated using an off-line Matlab ® program. Equalization is realized by a modified adaptive Volterra filter, and the memory length was set as 6. The second order Volterra filtering coefficients are considered, and the nonlinear terms higher than second order are neglected. The BER is determined by error count[17].

4 Experiment results and discussion

In order to test the effect on eliminating the nonlinearity of IM, we first measured performance of the recovered signal at back to back(BTB). Figure 5(a) shows the BER of the recovered signal by using three digital filters. At BTB, the factors that result in the signal distortions include SSII and thermal noise of active devices such as EDFA, AMP and PD, and the quantizing noise of the oscilloscope. It should be noted that the BER without equalizing is not shown because the BER can not achieve the forward error correction limit (FEC) of 10^{-3}, even if the PD input power achieved -2 dBm. The corresponding constellation is shown in Fig.5(b), which can not be distinguished at all. The conventional one tap equalizer can improve the BER performance, but it only compensate the linear distortion. Volterra digital filter[8] can cancel linear and nonlinear distortion. However, as the Volterra digital filter in Ref.[8] has not considered interaction effects of different samples,

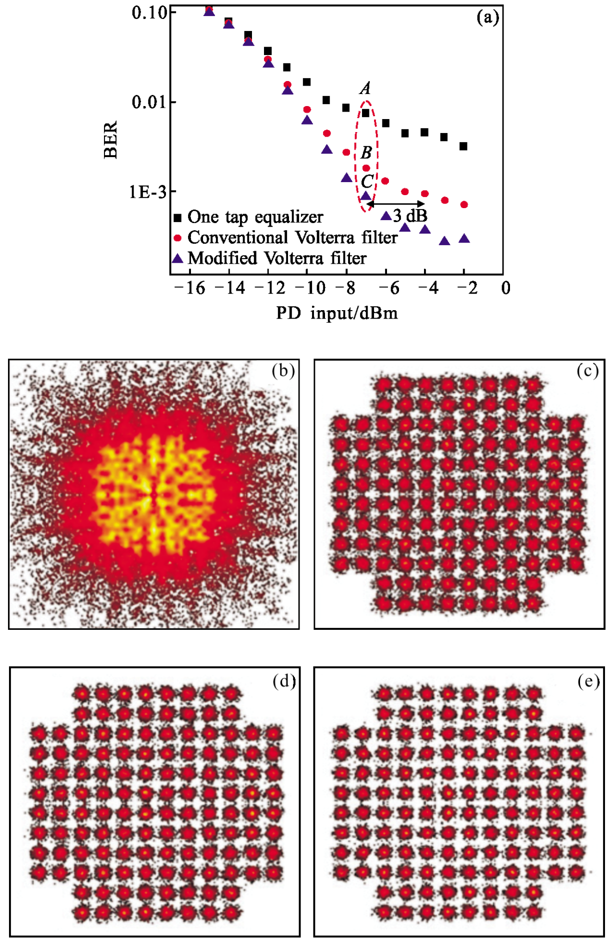

Fig.5 BER curves and constellation diagrams of the BTB based on three equalizing method

the nonlinear distortion such as the SSII can not be cancelled very well. By using the modified Volterra digital filter, which includes not only the nonlinearity of same samples but also that of different samples, the nonlinear distortion is further compensated. As shown in Fig.5(a), the proposed modified Volterra filter has about 3 dB power benefits than the Volterra digital filter in Ref.[8] to meet the forward error correction (FEC) limit of 10^{-3}. Figure 5 (c)-(e) show the constellation of the received signals when the PD input is -7 dBm. The constellation is easiest to distinguish when the received signal is compensated by the proposed digital filter. The corresponding BER value is shown as **A**, **B**, **C** in Fig.5 (a), respectively. When the PD input power is higher than -3 dBm, the BER no longer reduces or becomes constant afterwards. The reason is that thermal noise of EDFA, AMP and PD, and the quantizing noise of the oscilloscope are white noise, which can not be compensated by the Volterra filter.

We also give a comparison of the BER curves in the cases at BTB and after 25 km fiber transmission, which is depicted in Fig.6 (a). As the dispersion induced distortion can be compensated very well, the transmission penalty over 25 km at the FEC limit of 10^{-3} is lower than 0.5 dB. Figure 6 (b)-(c) show the constellation of the received signals when the PD input is -7 dBm. The constellations are both distinguished easily, and there are almost no difference. The corresponding BER value is shown as **A**, **B** in Fig.6(a), respectively. As the launch power of the transmitter can achieve up to 9 dBm and the BER can achieve FEC limit of 10^{-3} when PD input power is higher than -7 dBm, it indicates that there is 16 dB power budgets in the case of FEC limit of 10^{-3}. In addition, because the signal bandwidth and the QAM number are 3.5 GHz and 128 QAM, respectively, the system can support a data rate of 24.5 Gbps. More importantly, it achieves a superior performance of 7 bits·s^{-1}·Hz^{-1}.

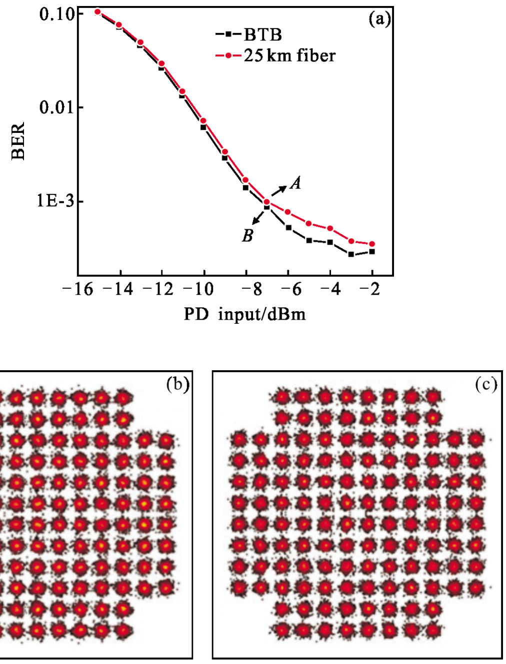

Fig.6 BER curves and constellation diagrams at the cases of the BTB and 25 km fiber transmission

5 Conclusion

In this paper, we proposed a novel method of subcarrier evolution to analyze the nonlinearity of an IMDD OFDM PON. The nonlinearity are mainly caused by the SSII and the chirp from the modulation. We also proposed a modified Volterra digital filter to cancel the signal distortion of the IMDD OFDM PON. Different from the previous work, the modified Volterra digital filter includes not only the same samples but also the different samples. In other words, the interactions of the different samples was considered in the modified Volterra digital filter. The corresponding experiments have been carried out to verify the effectiveness of the proposed equalizing method. The proposed modified Volterra filter has about 3 dB power benefits than the previous work to meet FEC limit of 10^{-3}. Based on the modified Volterra digital filter, the IMDD OFDM system has 16 dB power budgets in the case of FEC limit of 10^{-3}. Finally, the system can support a data rate of 24.5 Gbps, and the spectrum efficiency can achieves up to 7 bits·s^{-1}·Hz^{-1}.

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