Optical Fiber Technology 30 (2016) 12–16

Contents lists available at ScienceDirect

Optical Fiber Technology

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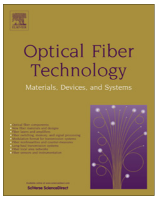

Regular Articles

Proposal of DCS-OFDM-PON upstream transmission with intensity modulator and collective self-coherent detection

Jing Zhang *, Heming Yang, Difu Zhao, Kun Qiu

Key Lab of Optical Fiber Sensing and Communications, Ministry of Education, University of Electronic Science and Technology of China, Chengdu 611731, China

ARTICLE INFO

Article history:
Received 10 July 2015
Revised 21 December 2015

Keywords:
Passive optical network
Optical orthogonal frequency division multiplexing
Digital coherent superposition
Self-coherent detection

ABSTRACT

We introduce digital coherent superposition (DCS) into optical access network and propose a DCS-OFDM-PON upstream transmission scheme using intensity modulator and collective self-coherent detection. The generated OFDM signal is real based on Hermitian symmetry, which can be used to estimate the common phase error (CPE) by complex conjugate subcarrier pairs without any pilots. In simulation, we transmit an aggregated 40 Gb/s optical OFDM signal from two ONUs. The transmission performance with DCS is slightly better after 25 km transmission without relative transmission time delay. The fiber distance for different ONUs to RN are not same in general and there is relative transmission time delay between ONUs, which causes inter-carrier-interference (ICI) power increasing and degrades the transmission performance. The DCS can mitigate the ICI power and the DCS-OFDM-PON upstream transmission outperforms the conventional OFDM-PON. The CPE estimation is by using two pairs of complex conjugate subcarriers without redundancy. The power variation can be 9 dB in DCS-OFDM-PON, which is enough to tolerate several kilometers fiber length difference between the ONUs.

1. Introduction

Recently, with the rapid development of multimedia-based services, the internet traffic grows in an exponentially speed, and over 40 Gb/s aggregated data rate is in demand for the next generation passive optical network (PON) [1–3]. Meanwhile, the bandwidth-elastic PON is necessary to meet the increasing requirement of the flexibility and dynamic characteristic for the future access network. Because OFDM has higher frequency efficiency and supports the software defined network (SDN), it has become an attractive solution to the future access network [4,5]. The directly modulated laser (DML) and direct-detection (DD) is a cost-effective solution for PON, however, the generated signals are double-sideband and frequency chirped by DML, which results in power fading and subcarrier-to-subcarrier intermixing interference (SSII) in direct-detection systems [6,7]. On the other hand, the linearity of coherent detection preserves the amplitude, phase and polarization information and hence, many channel impairments can be readily compensated by digital signal processing at the coherent receiver [8–10]. Self-coherent detection not only keeps the linearity merit of coherent detection, it also reduces the cost and improves the coherent performance by using the same laser source for the local laser and the optical carrier [10]. In addition, with advanced photonic integration techniques, self-coherent detection is becoming an attractive choice to overcome the power budget limitation and extend the fiber distance for long-reach PON [10]. In our previous works, we have demonstrated collective coherent reception and bandwidth-elastic access in OFDM-PON upstream transmission [11,12]. However, the laser phase noise at the transmitter and receiver generally becomes uncorrelated after kilometer fibers transmission. The ICI power increases and the transmission performance is limited. In 2013, X. Liu has demonstrated in *Nature Photonics* that the digital coherent superposition (DCS) can improve the tolerance to linear phase noise [13]. We have extended the DCS to optical OFDM (DCS-OFDM) and demonstrated that it can both improve the tolerance to the ICI resulted from the laser phase noise and the fiber nonlinearity [14,15].

In this paper, we propose a DCS-OFDM-PON upstream transmission scheme with intensity modulator (IM) and collective self-coherent detection. At each ONU, we simply transmit a real-valued OFDM signal with Hermitian symmetry to drive an intensity modulator biased at the null point, which can reduce the cost and avoid I/Q imbalance by using the optical I/Q modulator. The OFDM signals from different ONUs are aggregated at the remote node (RN), so we can use only one coherent receiver to collectively detect the whole OFDM signal. The laser phase noise results in CPE and ICI. At the receiver, we first conduct conventional OFDM signal

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* Corresponding author.
E-mail address: zhangjing1983@uestc.edu.cn (J. Zhang).

http://dx.doi.org/10.1016/j.yofte.2016.01.009

processing, i.e., synchronization, CPE and channel estimation. In this scheme, we estimate the CPE by complex conjugate subcarrier pairs from the Hermitian symmetry without any pilots and redundancy. After the conventional OFDM signal processing, we conduct DCS for OFDM subcarrier pairs with little additional complexity to improve the transmission performance.

2. Principle of DCS-OFDM PON

Fig. 1 shows the proposed DCS-OFDM-PON architecture, in which we mainly focus on the upstream transmission. We use the centralized laser which means optical carrier of each ONU is distributed from the same laser at the OLT. Therefore, all subcarriers suffer from the same laser phase noise. At each ONU, we pair up the OFDM subcarriers with Hermitian symmetry as $X(N-k)=X^*(k)$, which means the k-th subcarrier and its symmetric subcarrier are complex conjugated. There is only real part and the imaginary part is zero after IFFT. Therefore, the generated OFDM signal is a real-valued signal and we can use an intensity modulator biased at the null point to up-convert the electrical signal to the optical domain. Different ONUs occupy different frequency bands by adaptive bandwidth and modulation format distribution to realize flexible PON and bandwidth elastic access. The OFDM signals from different ONUs are aggregated at the remote node (RN) as a whole OFDM signal.

At the OLT, we use only one coherent receiver to realize self-coherent detection and collective detect the whole OFDM signal. Let Y_j denote the received OFDM signal for the j-th ONU. $Y=[Y_1,\cdots Y_j,\cdots Y_n]$ is the whole received OFDM signal from different ONUs and can be expressed as,

$$Y(k)=X(k)\cdot I(0)+ICI(k), \tag{1}$$

Where $X(k)$ and $Y(k)$ are the transmitted and received OFDM signals for the k-th subcarrier, and each ONU uses the Hermitian symmetry as $X(N-k)=X^*(k)$. After conventional OFDM signal processing, we apply DCS for the symmetric subcarrier pairs from Eq. (1),

$$\left[\hat{Y}(k)+\hat{Y}^*(N-k)\right]/2=X(k)\cdot|I(0)|+\mathrm{ICI}_{\mathrm{DCS}}(k), \tag{2}$$

Where $\hat{Y}(k)$ is the received OFDM signal after CPE compensation and $\mathrm{ICI}_{\mathrm{DCS}}$ is the ICI of OFDM signal after DCS processing. It is demonstrated to be cancelled to the second order by Taylor expansion of the ICI [14]. The ICI power with or without DCS can be expressed as [14],

$$\frac{\langle|\mathrm{ICI}_{\mathrm{DCS}}(k)|^2\rangle}{\langle|\mathrm{ICI}(k)|^2\rangle}=\frac{23\pi\Gamma}{210} \tag{3}$$

Where $\Gamma=N\beta T$, N is the FFT length, T is the sampling period and β is the 3-dB bandwidth of the Lorentzian shape of the spectral power density of a laser. From Eq. (3), the improvement by DCS is decided by the ratio of laser linewidth to OFDM subcarrier symbol rate. For a practical OFDM transmission system, Γ is generally much smaller than the unity and the ICI noise is reduced by DCS. In the proposed architecture, although we have used the same laser, the laser phase noise becomes uncorrelated after tens of kilometers fiber transmission, which degrades the transmission performance and causes ICI power increasing. Therefore, we can use DCS to improve the tolerance to ICI.

Besides ICI, CPE is another laser phase noise effect for optical OFDM system. The difference is that ICI is an additive noise while CPE is a multiplication noise. For simplicity, we ignore the second item in Eq. (1) to study the CPE compensation in our system. Since we have used the Hermitian symmetry at the transmitter, the received signal for conjugated subcarriers pairs can be written as [16],

$$\begin{aligned}Y_{i,k}&=X_{i,k}\cdot H_k\cdot\exp(j\Phi_i)\\ Y_{i,N-k}&=X_{i,k}^*\cdot H_{N-k}\cdot\exp(j\Phi_i)\end{aligned} \tag{4}$$

where, $X_{i,k}$ and $Y_{i,k}$ are the transmitted and the received signals for the i-th symbol and the k-th subcarrier, H_k is the channel response, Φ_i is the CPE. We only consider the chromatic dispersion for channel response and has $H_k=H_{N-k}$. Because optical OFDM is insensitive to fiber dispersion and the channel response can be estimated by training symbols [17]. Since the CPE means the phase drift within one OFDM symbol, it can be considered as constant and common to all the subcarriers. Therefore, we can estimate the CPE by multiplication of the received conjugated subcarrier pairs [17]. As mentioned above, we have used Hermitian symmetry for OFDM signal generation so we can utilize this feature to estimate the CPE without any pilots and redundancy. The CPE can be expressed as,

$$\hat{\Phi}_i=\arg\left(\sum_k Y_{i,k}\cdot Y_{i,N-k}\right)\Big/2 \tag{5}$$

CPE compensation is used to optimize the transmission performance in our scheme, especially when there is relative transmission time delay.

3. Numerical investigation

VPItransmissionMaker 9.1 is used for simulation. To investigate the proposed DCS-OFDM-PON upstream transmission, we take two ONUs as example. At each ONU, we transmit 400 OFDM symbols with Hermitian symmetry and the symbols are transferred to the

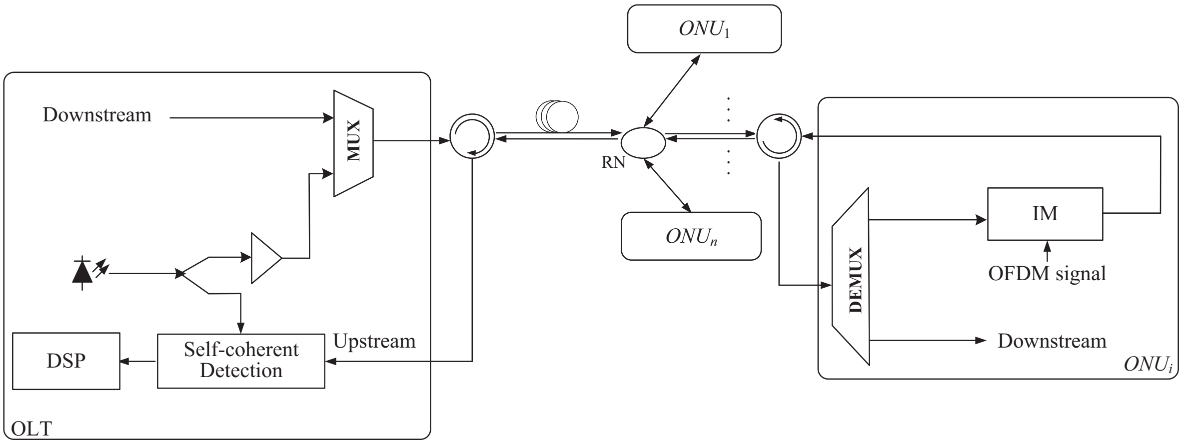

Fig. 1. The schematic of DCS-OFDM-PON upstream transmission.