Flexible OFDM-based access systems with intrinsic function of chromatic dispersion compensation

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A B S T R A C T
Cost-effective and tunable chromatic dispersion compensation in a fiber link are still an open issue in metro and access networks to cope with increasing costs and power consumption. Intrinsic chromatic dispersion compensation functionality of optical fractional orthogonal frequency division multiplexing is discussed and experimentally demonstrated using dispersion-tunable transmitter and receiver based on wavelength selective switching devices.

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1. Introduction

Novel power-efficient and cost-effective systems are required in short-reach links, such as metro and access networks, to support the increasing demand of higher bit rate and larger spectral efficiency. Optical orthogonal frequency division multiplexing (OFDM) is a good solution to increase data rate and spectral efficiency [1–3]. The peak to average power ratio (PAPR) problem comes to be serious with increased number of OFDM subcarriers because their coherent superposition could lead to nonlinear impairments due to high peak power optical signals. Such nonlinear impairments degrade the signal quality and limit the available number of subcarriers.

OFDM also offers the main advantage of inherent CD robustness because data are transmitted over a set of subcarriers with a smaller bandwidth. Nevertheless, optical OFDM subcarriers travel a dispersive link with different delays, and compensation techniques are required at the receiver (Rx), to synchronize the OFDM symbols [8,9]. Digital signal processing (DSP) is an effective approach for long-haul applications, to compensate the CD, as well as mitigate nonlinear impairments [10–12]. However, DSP-based CD compensation requires coherent detection, which is not suitable for metro and access networks, due to increasing costs and power consumption. Cost-effective and tunable approaches for CD compensation are still an open issue, and many different schemes have been proposed in literature [8,9,13].

In the present paper, we demonstrate the intrinsic CD compensation ability of Fr-OFDM in addition to other possible advantages of PAPR reduction and subcarrier diversity enlargement. The eye diagrams after 20 km-SMF transmission are clearly open and demonstrate the effectiveness of the proposed approach.

2. Fr-OFDM transmission system and intrinsic CD compensation ability

2.1. Fr-FT

The FrFT is a generalization of the FT, that deals with the intermediate domain between time and frequency axes. The FrFT is defined as [14,15],
where the Kernel $K(p, t, u)$ is given by:

$$K(p, t, u) = \frac{e^{j\pi p^2}}{\sqrt{j \sin (p \pi / 2)}} e^{-j \pi (t^2 + u^2)/8 (\sin (p \pi / 2) - 2 \tan (p \pi / 2))}. \tag{2}$$

The general FT and inverse FT correspond to the cases for $p = 1$ and $-1$. As shown in Fig. 1, the general FT can be seen as the projection of a given signal on the frequency axis (a rotation of $\pi/2$ with respect to the time axis in time-frequency domain). The FrFT can be interpreted as the projection of the signal on an intermediate axis that forms an angle $p\pi/2$ with $0 < |p| < 2$.

2.2. Fr-OFDM transmission system

The impulse response along with time axis and the corresponding transfer function along with frequency axis of the $n$th Fr-OFDM subcarrier is given by,

$$h_n(t) = |\sin (p \pi / 2)|^{-\frac{1}{2}} e^{j \pi (p - \sin |\sin (p \pi / 2)|)} e^{j \pi \left[\frac{1}{4} (\pi^2 + \pi^2 t^2) \tan (p \pi / 2) - 2nf T_0 \tan (p \pi / 2)\right]} \tag{3}$$

$$H_n(f) = \cos (p \pi / 2)^{-\frac{1}{2}} e^{j \pi (p - \cos |\cos (p \pi / 2)|)} e^{-j \pi \left[\frac{1}{4} (\pi^2 + \pi^2 f^2) \tan (p \pi / 2) - 2nf T_0 \tan (p \pi / 2)\right]} \tag{4}$$

where $t$ is time, $f$ is frequency, $T$ is the symbol duration, and $p$ is the fractional parameter ($p = 1$ for standard FT), $N$ is the total number of subcarriers, respectively [4,5]. Eq. (4) contains a frequency dependent chirp factor $C(f)$ of the form,

$$C(f) = \exp \left[-j \pi (f^2 T_0^2 \tan \left(\frac{p\pi}{2}\right))\right]. \tag{5}$$

From Eqs. (4) and (5), the chirp effects in Fr-OFDM subcarriers can be derived from their Quadratic Phase Modulation (QPM) factors and can inherently reduce PAPR in transmission.

Fig. 2 shows the rotated situation of Fr-OFDM subcarriers in time and frequency domain for a Fr-OFDM transmitter (Tx) and a receiver (Rx) in the Fr-OFDM transmission system, respectively. As shown in Fig. 3(c) and (d), this suggests that we can use FrFT subcarriers to compensate CD in a flexible way by varying the parameter. The value of $p\pi/2$ is related to axis rotation in the time-frequency plane. On the other hand, the spectral phase shift $\phi(f)$ due to CD in a fiber link is given by,

$$\phi(f) = \exp \left(-j \pi cDL \frac{f^2}{f_0^2}\right). \tag{6}$$

where $c$ is the velocity of light, $D$ is the dispersion parameter, $L$ the fiber length, and $f_0$ the center frequency, respectively. In spectral domain, the spectral phase shift $\phi(f)$ is multiplied by $H_n(f)$ after passing through a fiber link. Since Eq. (4) includes the chirp factor $C(f)$, it could have the ability of CD to cancel the spectral phase shift $\phi(f)$ in Eq. (6). As compared with Eq. (6), the following condition,

$$\tan \left(\frac{p\pi}{2}\right) = -\frac{cDL}{T_0^2} \tag{7}$$

enables us to achieve CD compensation. Without CD, the receiver performs the inverse Fr-FT to rotate back the signal along the frequency axis based on the condition: $p_{tx} + p_{rx} = 2m$. Therefore, the relation of $p$ parameters at the Tx and Rx for CD compensation is given by,

$$p_{rx} + p_{tx} = \frac{2}{\pi} \tan^{-1} \left(-\frac{cDL}{T_0^2}\right) = 2m. \tag{8}$$

Fig. 4 shows the Fr-OFDM transmission system with the intrinsic CD post compensation function. As shown in Fig. 2, fractional parameters $p_{tx}$ and $p_{tx}$ for Tx and Rx are basically set as $2 - \alpha$ and $\alpha$, respectively. With CD corresponding to $p_{CD}$ in a fiber link, $p_{tx}$ or $p_{rx}$ at the Tx (pre-compensation) and at the Rx (post-compensation) should be tuned to proper fractional parameters according to Eq. (8). For example, fractional parameters $p_{tx}$ and $p_{rx}$ for Tx and Rx can be set as $2 - \alpha$ and $\alpha - p_{CD}$, as shown in Fig. 4.

3. Experimental demonstration

3.1. Experimental setup

Fig. 5 shows the experimental setup for the dispersive Fr-OFDM system. We used the transfer functions for a 12-channel Fr-OFDM system [11]. For $D = 0$, the transfer functions at Tx with $p = 1.8$ and Rx with $p = 0.2$ satisfy the matching condition of Eq. (7). In general, the $p$ factor is chosen so as to optimize the peak to average power ratio (PAPR) of the multiplexed signals [4]. The equivalent $p$ parameter of a 20-km SMF is $p = 0.1693$, so in the case of CD compensation, transfer functions at the Tx with $p = 1.8$, and Rx with $p = 0.0307 (\approx 0.2 - 0.1693)$ are used. The filter functions of Eq. (4) are implemented on a wavelength selective switch (WSS) both at the Tx and Rx.

We use a 10-GHz optical pulse train from a mode locked laser diode (MLLD) as an input light source. The pulse width and the center frequency of the input pulse are 1.5 ps (full-width at half
maximum) and 193.245 THz, respectively. The input pulse train is modulated by 10 Gbit/s pseudo random bit sequence (PRBS) signal in on-off keying (OOK) format, with pattern length of \(2^{31} - 1\). The modulated data signal is split into three and sent to different optical delay lines (ODLs) to synchronize the signals, with pattern decorrelation. Then, the three signals are fed to the first WSS (Finisar 4000S). It works as an Fr-OFDM Tx for 3 (channel 1, 2 and 3), but it can multiplex 12 channels in total. Therefore, the three channels are multiplexed into a 30-Gbit/s Fr-OFDM signal at the WSS output.

The 30-Gbit/s Fr-OFDM signal is transmitted through a 20-km SMF and received by the second WSS (Finisar 1000S). Although a \(1 \times 3\) WSS is the ideal receiver of 3-channels, at this time in the laboratory a WSS with only 1 channel was available. Therefore, we consecutively changed the filter function installed on the \(1 \times 1\) WSS, to receive the three channels one after the other.

### 3.2. Simulation results

Fig. 6 shows the eye diagrams of the received signals at channel 2 of the Rx which is used as a data signal after various length transmissions. From Fig. 6(a–c); the results for \(p_{\text{rx}} = 0\) (without the intrinsic CD compensation function), the pulse-like data signals are stretched due to CD in proportional to the lengths of fiber links. On the other hand, if we properly set the Rx fractional parameter as \(p_{\text{rx}} = p_{\text{CD}}\) for CD compensation, the pulse-like data signals are well compressed, as shown in Fig. 6(d–f).

### 3.3. Experimental results

In advance to experimental demonstration, we verified the effectiveness with the intrinsic CD compensation function in simulation. From Fig. 6(a–c); the results for \(p_{\text{rx}} = 0\) (without the intrinsic CD compensation function), the pulse-like data signals are stretched due to CD in proportional to the lengths of fiber links. On the other hand, if we properly set the Rx fractional parameter as \(p_{\text{rx}} = p_{\text{CD}}\) for CD compensation, the pulse-like data signals are well compressed, as shown in Fig. 6(d–f).

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Fig. 7 shows the eye diagrams of the received signals at channel 2 of the Rx. We used channel 2 as data signal (Fig. 7(a and c)), and channels 1 and 3 as inter channel interference (ICI) signals (Fig. 7(b and d)).

Fig. 7(a and b) show the eye diagrams when the fractional parameter of the Rx is \(p = 0.2\). The received data signal at channel 2 has an almost closed eye because ICI from the subcarriers 1 and 3...
seriously reduce the signal quality. On the other hand, if we properly set the Rx fractional parameter as $p = 0.0307$, for CD compensation, the signal quality is much improved, and ICI from the subcarriers 1 and 3 at the central time gating position has been eliminated, as shown in Fig. 7(d).

4. Discussion

In order to quantify the reliability improvement of a Fr-OFDM based transmission by the intrinsic CD compensation function, we achieve simulation of bit-error-rate (BER) assessments. BER is estimated from the signal quality after 20 km transmission. We consider a single channel of the twelve channel Fr-OFDM transmission system for a comparison of with or without the intrinsic CD compensation. Fig. 8 shows BER characteristics with or without the intrinsic CD compensation function. With the intrinsic CD compensation function, an error-free operation ($\text{BER} < 10^{-9}$) after transmission is achieved in simulation and we confirm the reliability improvement of a Fr-OFDM based transmission with the intrinsic CD compensation function.

Various diversity of dispersion compensation functionality can be expected furthermore according to Eq. (8). For instance, Eq. (8) can be modified into,

$$p_{\text{tx}} + \frac{2}{\pi} \tan^{-1} \left( -\frac{cDL}{T^2/\omega^2} \right) = 2m,$$

by neglecting $p_{\text{rx}}$. Tx can function as a pre-dispersion compensator and we can obtain a dispersion compensated pulse after passing through a Fr-OFDM Tx and the corresponding length fiber. In fact, the generation of a sinc-shaped Nyquist pulses have already demonstrated using a WSS and the time-lens effect based on this concept [16,17]. It is also a kind of intrinsic chromatic dispersion compensation functionality of Fr-OFDM.
5. Conclusion

Intrinsic chromatic dispersion compensation functionality of Fractional OFDM was experimentally demonstrated using a dispersion-tunable transmitter and receiver based on WSS devices. The eye diagrams of all the OFDM subcarriers after 20 km-SMF transmission are clearly open. Fr-OFDM based transmitters and receivers with the intrinsic CD compensation could avoid frequent replacement of fiber-optic cables so as to adapt to their practical CD change. Such an intrinsic function in transmitters and receivers could provide a cost-effective and tunable chromatic dispersion compensation technique in a fiber link to solve increasing costs and power consumption in the future metro and access networks.

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