Experimental emulation of nonlinear distortion suppression by FrOFDM subcarriers

Yu Yamasaki1, a), Tomotaka Nagashima1, Gabriella Cincotti2, Satoshi Shimizu3, Kuninori Hattori4, Masayuki Okuno4, Shinji Mino4, Akira Himeno4, Naoya Wada3, Hiroyuki Uenohara5, and Tsuyoshi Konishi1

Abstract Fractional orthogonal frequency division multiplexing (FrOFDM) exhibits considerable flexibility in the axis of multiplexing and a medium characteristic between OFDM and Nyquist optical time division multiplexing. FrOFDM subcarrier effect on nonlinear distortion in long haul transmission has not experimentally been verified. In this work, we used a highly nonlinear fiber under relatively short transmission conditions for experimental emulation of nonlinear signal distortion under long haul transmission conditions considering no phase modulation in time domain for non-telecom application. We examined the suppression effect on the distortion and confirmed that, FrOFDM subcarriers greatly suppress nonlinear distortion.

Keywords: fractional Fourier transform, long haul transmission, nonlinear distortion, orthogonal frequency division multiplexing, peak-to-average power ratio

Classification: Optical hardware (fiber optics, microwave photonics, optical interconnects, photonic signal processing, photonic integration and modules, optical sensing, etc.)

1. Introduction

Effective use of network resources is indispensable for improvement of the spectral efficiency characterizing an entire network in an elastic optical network [1, 2]. Orthogonal division multiplexing (OFDM) and Nyquist optical time division multiplexing (N-OTDM) are essential technologies for achieving high spectral efficiency [3, 4, 5, 6, 7, 8, 9, 10]. Furthermore, OFDM allows high tolerance of residual dispersion and the required performance of the receiver can be reduced by inserting a cyclic prefix (CP) [11]. This multiplexing scheme is, however, characterized by nonlinear distortion resulting from the high peak-to-average power ratio (PAPR) and many methods for suppressing the effects of nonlinear distortion have been proposed [12, 13, 14, 15]. The N-OTDM technique is a multiplexing scheme in which Nyquist pulses are temporally arranged and, hence, PAPR can be reduced [16]. However, a high-performance receiver is required for high-quality reception of the signal [16, 17, 18]. Transmission should be performed in accordance with the transmission lines and performance of receivers in order for optimal utilization of network resources in the elastic optical network. In other words, flexible control of the CP-insertion effect and PAPR reduction, in accordance with the transmission conditions, is important.

A fractional Fourier transform (FrFT)-based multiplexing scheme, fractional OFDM (FrOFDM), using an intermediate domain in the time-frequency plane exhibits considerable flexibility in the axis of multiplexing and a medium characteristic between OFDM and N-OTDM [19, 20, 21, 22, 23, 24, 25]. Therefore, FrOFDM can improve the signal quality or extend fiber span via PAPR reduction [25, 26, 27] and reduce the required performance of receivers through CP insertion [24], which allows flexible selection of the transmission scheme.

To date, relatively short distance FrOFDM transmission has been experimentally demonstrated [22, 28]. However, experimental verification of the suppression effect on nonlinear distortion in long haul transmission is lacking due to the difficulty of obtaining long haul transmission experimental equipment of more than several hundred km. In general, nonlinear distortion is evaluated based on the signal quality after transmission using a long haul single mode fiber (SMF) or a recirculating fiber loop [29, 30]. In this work, we adopt the simple method using highly nonlinear fiber (HNLF) for the emulation of long haul transmission that allows demonstration of the suppression effect on nonlinear distortion without the aforementioned equipment. In long haul transmission over 800 km assuming a metro network [29], we demonstrate and evaluate the effect by measuring the nonlinear spectral change before and after transmission. Experimental results show that nonlinear distortion is greatly suppressed in FrOFDM.

2. Nonlinear distortion suppression using fractional OFDM

OFDM is a multiplexing scheme based on Fourier transform. The temporal waveform of an n-th OFDM subcarrier is defined as follows (number of subcarriers: N, symbol duration: T):

\[ \phi_n(t) = \text{rect} \left( \frac{t}{T} \right) \cdot e^{-j2\pi n t} \quad n = 1, 2, \ldots, N \]  

Moreover, the temporal waveform of an n-th FrOFDM subcarrier based on FrFT, which is the generalized form of
Fourier transform, is expressed as follows:

\[
\phi_p(t) = \text{rect}\left(\frac{t}{T}\right) e^{j\pi\left[n^2 \sin^2(\frac{p \pi}{2}) \frac{t^2}{T^2} \cos(\frac{p \pi}{2}) - 2n \frac{t^2}{T^2}\right]}
\]

(2)

Where, \( p \) is the fractional parameter. The FrOFDM symbols are rotated by an angle \((1 - p)\pi/2\) from OFDM symbols in the time-frequency plane. When \( p = 1 \), the rotation angle is 0 and eq. (2) becomes a temporal waveform of an OFDM subcarrier. Therefore, FrOFDM can be considered a generalized OFDM. The signal performing FrFT of \(-p\) at the transmitter can be received by performing FrFT of \( p \) at the receiver. FrFT can be implemented using passive optical components such as wavelength selective switches (WSS) and arrayed waveguide gratings [23].

In OFDM, PAPR becomes high when many subcarriers are in phase, as shown in Fig. 1. The peak power decreases, owing to fiber dispersion and the consequent phase shift of each subcarrier. Temporal waveforms with high PAPR are periodically generated by Talbot effect [31] that many subcarriers are superimposed with subcarriers of the neighboring symbol through propagation of further fiber.

In contrast, each subcarrier of FrOFDM is characterized by a distinct phase. The signal power diffuses in the time domain and barely forms the temporal waveform with high PAPR occurring periodically in OFDM. As a result, the nonlinear distortion is suppressed. In addition, a FrOFDM symbol can be converted into a Nyquist pulse train by passing through a fiber with appropriate dispersion [20]. An enhanced suppression effect of nonlinear distortion can therefore be obtained.

From the above, FrOFDM can mitigate PAPR. However, its effect varies with the value of \( p \). Fig. 2 shows the possibility of nonlinear distortion for each fractional parameter when \( N = 32 \). We define the possibility of nonlinear distortion as the total power of the waveform that is more than 20% of the highest peak, which is formed in OFDM during lossless 80 km SMF transmission. As shown in Fig. 2, \( p = -0.1 \) yields the largest suppression effect on nonlinear distortion. Therefore, we selected the case for \( p = -0.1 \) in order to experimentally examine the tolerance to the nonlinear distortion.

3. Experiment

We perform experiment to emulate nonlinear distortion in long haul transmission under the condition yielding the highest suppression effect of the distortion. In this experiment, we focus on the point just after multiplexing, which is the highest PAPR periodically formed in OFDM, and examined the suppression effect on nonlinear distortion using FrOFDM. We investigate cases for \( p = -0.1 \), which yields the highest suppression effect of nonlinear distortion. Fig. 3 shows the experimental setup.

We use a mode-locked fiber laser (MLFL) with a repetition frequency of 30 MHz and a center wavelength of 1550 nm as a seed pulse. The seed pulse is multiplexed using WSS and the average power is adjusted to \(-15.75\) dBm using an optical amplifier. The subcarrier spacing is set to 10 GHz. We measure spectra before and after transmission. In order to examine the nonlinear distortion tolerance of the FrOFDM subcarriers of \( p = -0.1 \) with the largest PAPR suppression effect, we experimentally emulate long haul transmission using FrOFDM. We investigate cases for \( p = -0.1 \), which yields the highest suppression effect of nonlinear distortion. Fig. 3 shows the experimental setup.
sion through a ~0.28 km SMF ($D = 17$ ps/nm/km, $\gamma = 1.3$ W/km) at launch power of 9.5 dBm and baud rate of 10 Gbaud. Fig. 4 shows the simulation result of peak power of the OFDM symbol at each distance when the number of subcarriers is 16. Unlike Fig. 1, it seems not to be generated temporal waveforms with high PAPR. This is because the peak power becomes small due to transmission loss. High PAPR temporal waveforms generated by Talbot effect are appeared around 73 km. Owing to the high peak of the symbol and the fiber loss, more than 1/16 of the spectral change in the 80 km transmission is induced in the range up to 0.28 km. Moreover, to adjust the launch power to the general condition, some of the power can be converted into a loop number of transmission. Therefore, we can regard this experimental condition as an over 10-time repetition of transmission through an 80 km SMF at a baud rate of 10 Gbaud and launch power of 2.3 dBm. The transmission distance is more than 400 km, corresponding to long haul transmission. Multiplexed signals are non-modulated because we evaluate the nonlinear distortion by comparing the spectra before and after transmission. This experimental condition can be considered as a transmission under the worst conditions in terms of nonlinearity. However, for the telecommunication application, the phase of each subcarrier is modulated with different value in time domain, symbol by symbol. After transmission via positive dispersion fiber, the subcarriers are interfered with different symbols in time domain. The high PAPR rarely appears again which was shown at the input of fiber except when nearby symbols are modulated with the same phase value. In this sense, this experiment considering no phase modulation in time domain is closely related to non-telecommunication application.

Fig. 4  Peak power for each transmission distance in OFDM when the number of subcarriers is 16.

Fig. 5 shows the spectra of FrOFDM with $p = -0.1$, which exerts the largest suppression effect on nonlinear distortion. The FrOFDM spectra are almost unchanged for any number of subcarriers.

To quantify the suppression effect and determine the validity of the method using HNLF, we calculate the spectral change (SC) from spectra before ($S_{\text{before}}$) and after transmission ($S_{\text{after}}$):

$$SC = 1 - \frac{\sum S_{\text{after}} S_{\text{before}}}{\sqrt{\sum S_{\text{after}}^2} \cdot \sqrt{\sum S_{\text{before}}^2}} \quad (3)$$

Fig. 6 indicates the SC for each number of subcarriers. From comparison with OFDM, it can be seen that nonlinear distortion is greatly suppressed in FrOFDM. Fig. 7 shows the simulation result of SC after 800 km transmission with 80 km SMF having the above fiber parameters, amplification and dispersion compensation as one span. The subcarrier spacing, and the symbol length are 10 GHz, and 1, respectively. The launch power is 2.3 dBm, same as in the experiment and the PAPRs at the input of the fiber are shown in Table I. As mentioned above, PAPRs of FrOFDM are much lower than those of OFDM. In this simulation, random combination of subcarrier phase modulation is not considered in order to compare experimental result. Even though only SMFs
are used in Fig. 1, a dispersion compensation fiber (DCF) is used to compensate dispersion in this simulation. The reason is that currently, dispersion is mainly compensated by digital signal processing [32] and FrOFDM is expected to use under such a condition, on the other hand, this emulation emphasizing nonlinearity furthermore is similar to the fiber link using DCF that the temporal waveforms with the highest PAPR are always generated after amplification. High PAPR is generated periodically even if only SMFs are used. However, it is necessary to consider being smaller SC difference than fiber link using DCF due to the timing gap between amplification and high PAPR generation [26] when using this emulation as a fiber link with only SMF.

Table I  PAPRs at the input of the fiber under each transmission condition with no modulation.

| N  | 40  | 50  | 60  | 70  | 80  |
|----|-----|-----|-----|-----|-----|
| PAPRave [dB] | 16.0 | 17.0 | 17.8 | 18.5 | 19.0 |
| PAPRv [dB]   | 5.70 | 5.93 | 6.78 | 6.18 | 4.24 |

In terms of the nonlinear distortion tolerance of the FrOFDM subcarriers of $p = -0.1$, the result in Fig. 6 is well consistent with that in Fig. 7 and it indicates that the emulation of nonlinear signal distortion in a long haul transmission condition using HNLF is a valid simple method. The experimental emulation results in Fig. 6 confirms that the FrOFDM subcarrier is tolerant of nonlinear distortion in long haul transmission over 800 km. On the other hand, the tendencies of the OFDM subcarriers of $p = -1$ in Fig. 6 and 7 are different and this is because nonlinearity in this emulation is intentionally emphasized and dispersion is small enough to ignore. In general, as the number of subcarriers increases, preservation time of the temporal waveform with high peak power becomes short, whereas peak power becomes high [26]. In this emulation, the temporal waveform maintains high peak because of negligibly small fiber dispersion and SC becomes high with increasing the number of subcarriers. Under such a disadvantageous condition, the FrOFDM subcarriers of $p = -0.1$ can keep its nonlinear distortion tolerance.

In Fig. 7, the same phase is considered for all subcarriers. Since, however, for communication purpose, each subcarrier will have different phase randomly depending on the original arbitrary data, we discuss the consideration of random phase modulation between subcarriers. Fig. 8 show the simulation result of SC of 16 quadrature phase modulation (QAM) signals after transmission with the same fiber link as the simulation of Fig. 7. The subcarrier spacing, and the symbol length are 10 GHz, and 1023, respectively. The launch power is 2.3 dBm, same as in the experiment and the PAPRs at the input of the fiber are shown in Table II. Although the difference between PAPRs of OFDM and FrOFDM become small by random phase modulation, PAPRs of FrOFDM are still low in most cases. SC in the FrOFDM subcarriers of $p = -0.1$ increases compared with no modulation because the phases that are originally different from each other can be coincide by phase modulation. However, SC of FrOFDM is smaller than that of OFDM and magnitude correlation of SC corresponds with the result of Fig. 7. In addition, SC suppression ratio is consistent with the signal quality degradation reported in [26]. This result indicates that modulation is required for the detailed emulation of nonlinear distortion.

Table II  PAPRs at the input of the fiber under each transmission condition with random phase modulation.

| N  | 40  | 50  | 60  | 70  | 80  |
|----|-----|-----|-----|-----|-----|
| PAPRave [dB] | 11.0 | 10.6 | 11.5 | 11.1 | 11.7 |
| PAPRv [dB]   | 10.4 | 10.9 | 10.4 | 10.8 | 11.3 |

4. Conclusion

We have demonstrated (via experiments) the suppression effect on nonlinear distortion in long haul transmission using FrOFDM subcarriers. The point just after multiplexing, which is the highest PAPR periodically formed in OFDM, was emphasized. We adopt the simple method of using HNLF to emulate this distortion in long haul transmission under the severe condition in terms of nonlinearity. The emulation indicates that FrOFDM has the high tolerance to nonlinear distortion.

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