Nonlinearity Mitigation by a Simple DSP with Subcarrier-by-Subcarrier Frequency Flip in Multi-Subcarrier Wavelength Conversion Repeater

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***Abstract*— We have demonstrated Q-factor improvement from 1.6 to 1.8 dB due to inter-subcarrier nonlinearity mitigation in a 960 km-transmitted 1 Tbps multi-subcarrier signal by subcarrier-by-subcarrier frequency flip processing of a wavelength conversion repeater.**

Keywords*— *optical communication, optical network, wavelength division modulation, wavelength conversion, nonlinear compensation, phase conjugation

I. Introduction

In a high-capacity wavelength division multiplexing (WDM) network, a flexible carrier-unit wavelength conversion by an optical repeater in optical links is a promising approach for improving the efficiency of transmission bandwidth and preventing carrier collisions in the case of network failures and spot traffic demand for temporary events [1]. As a method of wavelength conversion, whole-band wavelength conversion [2] and carrier-by-carrier wavelength conversion have been reported [3,4]. While the former may enable to shift all signals in one wavelength band to another dark band with a single module [2], the latter is suitable for flexible carrier-unit wavelength conversion to avoid signal collision when all bands are lightened. Previous studies about the carrier-by-carrier wavelength conversion techniques proposed an optical/electrical/optical conversion, consisting of a coherent receiver, IQ modulation, and coherent transmitter [3,4]. Notably, conversion in the electrical domain is limited to analog signals, therefore avoiding additional power consumption and delay, which would be required by a complete demodulation.

Moreover, when a wavelength conversion repeater is used inside a transmission link, it offers new opportunities to improve signal quality, *i.e.,* to increase the transmittable distance or the capacity in the WDM network. Indeed, phase conjugation has been proposed and demonstrated in a wavelength converter for nonlinearity compensation NLC [4], as one of the dominant sources of signal distortion in WDM transmission systems is Kerr-induced nonlinearity [5]. Furthermore, we have recently demonstrated numerically a simple Digital Signal Processing (DSP) repeater using a combination of phase conjugation and optimal chromatic dispersion compensation (CDC) performed with phase conjugation for NLC [6]. Indeed, phase-conjugation, which is co-located with wavelength conversion, of the input signal in the electrical domain enables to mitigate nonlinearity distortions of the optical signal before wavelength conversion with the distortions after the wavelength conversion and co-located phase conjugation. Our method enhances this effect with optimal but limited CDC in the repeater, by improving the symmetry of the accumulated chromatic dispersion around the phase conjugation. Although it uses DSP, it still avoids full demodulation and decoding, therefore limiting power consumption and delay.

Our method is indeed effective for NLC of single carrier signal transmission, but one of its limit is the nonlinear distortions caused by surrounding carriers or subcarriers as NLC is performed on a single subcarrier basis. This is of particular concern for high capacity channels relying on subcarrier multiplexing, which have been researched for a high-capacity transmission [7]. Therefore, in this paper, we consider inter-subcarrier nonlinearity mitigation using the repeater DSP for multi-subcarrier transmission. As the inter-subcarrier nonlinearity is caused by the interaction between co-propagating subcarriers, a subcarrier walk-off can mitigate the temporal correlation between neighboring subcarriers and the inter-subcarrier nonlinearity [8]. Thus, we propose subcarrier-by-subcarrier "frequency flip" processing to add the subcarrier walk-off and mitigate the inter-subcarrier nonlinearity, in addition to the previously-proposed phase conjugation and optimal CDC methods. In this study, we show numerically the effectiveness of the proposed repeater DSP method in the context of wavelength conversion.

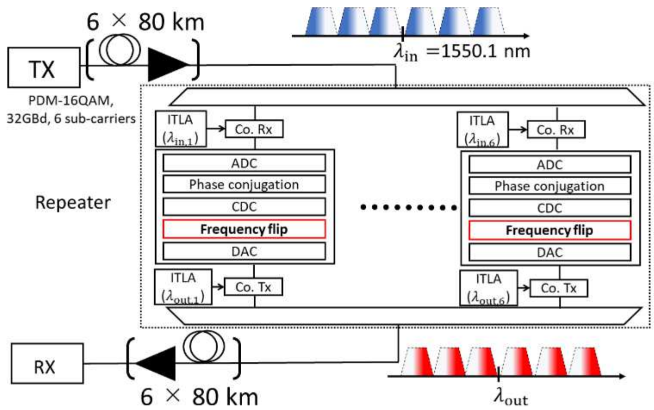

Fig. 1: Simulation setup and the concept of the proposed repeater.

II. Proposed repeater DSP model

We first demonstrate the repeater DSP model to mitigate the nonlinearity distortion. The input signal of the repeater, which is converted to an electrical signal by a coherent receiver, is phase-conjugated by inverting the sign of the complex part for each polarization, mathematically expressed as $A(t) \rightarrow A^*(t)$, where $A(t)$ is the temporal signal. It has been reported that NLC with optical phase conjugation is enhanced by managing link dispersion mapping with dispersion compensation modules in standard optical links based on erbium-doped fiber amplifiers [9,10]. While such link management is possible with a pre-designed point-to-point link with mid-span optical conjugation, it is no longer possible in a network context and when wavelength conversion is performed simultaneously. Therefore, our wavelength conversion repeater performs additional CDC for managing link dispersion mapping using DSP. The optimal amount of dispersion compensation is determined to achieve the symmetry in power versus accumulated dispersion diagrams of front and rear optical links [6, 10].

In this paper, we consider the mitigation of the inter-subcarrier nonlinearity together with the above-mentioned intra-subcarrier NLC using phase conjugation. To mitigate the inter-subcarrier nonlinearity, we propose to perform subcarrier-by-subcarrier frequency flip processing, as illustrated in Fig. 1, which inverts the frequency response of the signal, mathematically expressed by $\tilde{A}(\omega) \rightarrow \tilde{A}(-\omega)$, where $\tilde{A}(\omega)$ is the frequency response of each subcarrier signal $A(t)$. The subcarrier-by-subcarrier frequency flip adds delay differences at the signal band edge for neighboring subcarriers, therefore reducing the temporal correlation between neighboring subcarriers and mitigating inter-subcarrier nonlinearity. The frequency flip processing can be simply implemented using a signal flip circuit in the frequency domain. Importantly, the frequency flip maintains the intra-subcarrier NLC effect from phase conjugation [11].

One may consider alternatives to frequency flip to create a walk-off between subcarriers, such as adding delay to the entire subcarrier [8] or exchanging the order of subcarriers [12]. However, adding delay to the entire subcarrier [8] loses the signal information to cancel out the nonlinearity generated in the first and second half of optical links for nonlinearity mitigation using the phase conjugation. Therefore, it is difficult to implement the adding delay and phase conjugation schemes in parallel. The subcarrier exchange method [12], which is expected to mitigate inter-subcarrier nonlinearity due to a similar principle to frequency flip, requires an additional management of the channels on a subcarrier base, to control the subcarrier order, and no longer at a channel level, which complexifies implement on a real network management system, especially in the context of an open network. Therefore, we focus on the frequency flip processing, which does not change the order of subcarriers and is easier to implement in a network system.

Therefore, we propose the simple repeater DSP consisting of three steps, phase conjugation, optimal CDC, and subcarrier-by-subcarrier frequency flip. The CDC circuit can be of modest size, sufficient to compensate for the accumulated dispersion in approximately one span, and not as large as circuits used to compensate for the dispersion accumulated through the whole link. The flip processing can be implemented using a simple sign reversal circuit. Notably, our DSP does not perform functions such as polarization demultiplexing, carrier phase recovery, symbol decision, or FEC decoding, which are necessary for large DSP used for signal demodulation. Therefore, comparatively, our DSP is simple, requires less power consumption and causes less delay.

III. Simulation setup

Figure 1 shows the simulation setup in this work, consisting of a transmitter, repeater, receiver, and optical fiber spans. At the transmitter, a 1 Tbps multi-subcarrier, consisting of PDM-16QAM 32 GBaud six subcarriers with a subcarrier spacing of 37.5 GHz, is launched to the optical fiber. The center wavelength of the launched multi-subcarrier, λ_{in}, is fixed at 1550.1 nm in this study. Bits of each subcarrier were generated independently using de-correlated pseudo random bit sequences (PRBS) patterns and were mapped onto complex 16-QAM symbols. They are shaped using a root-raised-cosine (RRC) filter with 0.15 roll-off factor and converted to the optical signal. The optical signal propagates over a total of 12×80 km spans of standard single mode fiber (SSMF) with a lumped amplifier, which compensates for the fiber attenuation. The numerical calculation of optical transmission in optical links is performed using a commercially available optical transmission simulator.

In the middle of the link, the multi-subcarrier signal passes through our proposed repeater, which digitally processes the signal and launches the processed signal to the last half of the optical links. In the repeater, the optical multi-subcarrier signal is first de-multiplexed into each subcarrier function with an optical filter. Alternatively, this can be performed with a coupler and filtered with local oscillator selection in digital domain. Each de-multiplexed subcarrier is individually converted into an electrical signal by a coherent receiver, sampled at two samples per symbol for DSP.

The repeater DSP consists of only three processes, phase conjugation, CDC, and frequency flip part. In the phase conjugation part, the complex temporal signal is converted to the conjugated signal so that the imaginary part of each polarized component, XQ and YQ, is inverted its sign. After the phase conjugation part, the temporal signal is converted to the frequency domain, and chromatic dispersion in the signal is partially compensated to maximize the NLC effect by phase conjugation. Then, the frequency response is inverted in frequency for flipping.

Finally, each subcarrier signal is modulated to the optical signal, multiplexed, and the repeater launches the multi-subcarrier signals to the second half of optical links, where the center wavelength of the output multi-subcarriers, λ_{out}, ranges in C-band wavelength. The repeater DSP can simultaneously include functions to compensate for the penalty of the repeater insertion, such as device-induced skew, imbalance between four sampling channels, and frequency offsets due to subcarrier frequency deviations between the optical signal and the LD-laser.

At the receiver, the signals are received with a standard coherent receiver followed by DSP, consisting of residual CDC, adaptive equalization, phase recovery, and estimated bit-error rate and Q-factor. We use the Q-factor of the center subcarrier to evaluate the system performance, as it has the worst performance due to the inter-subcarrier nonlinearity.

For simplification of the investigation, we neglect the degradation of performance due to the wavelength conversion devices in numerical evaluation. Detailed evaluation of this influence is for future experimental studies, but a previous hardware evaluation of such a conversion device [3] showed a Q-factor penalty of approximately 0.5 dB, to be compared with gains above 0.5 dB compared to the reference case without wavelength conversion device, as shown further in Figs. 3 and 4.

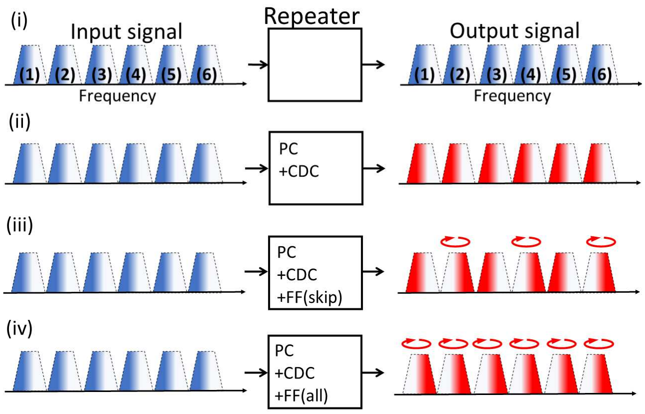

Fig. 2: Schematically illustration of four cases in our calculation simulation. PC, FF (skip), and FF (all) mean the phase conjugation processing, the frequency flip with one subcarrier skip, and all subcarrier frequency flip. (1)~(6) are the index of subcarriers.

IV. Simulation result and Discussion

A. Investigation of the performance

First, we consider that the repeater does not convert the subcarrier wavelength, *i.e.*, $\lambda_{\text{out}} = \lambda_{\text{in}}$ to simply evaluate the capability of the nonlinear mitigation by the proposed method. We investigate the proposed method performance for four significant cases: (i) the reference case, without the repeater DSP, (ii) our previous DSP proposal featuring phase conjugation and optimal CDC [6], (iii) our new DSP proposal featuring frequency skip applied to every two subcarriers (frequency flip with one subcarrier skip) and (iv) our new DSP proposal featuring frequency skip applied to all subcarriers (all subcarrier frequency flip). These cases are schematically illustrated in Fig. 2, where the number within parentheses represents the subcarrier index and the characteristic of the input signal is changed by phase conjugation and CDC. For clarification, in the third case of frequency flip with one subcarrier skip, the frequency responses of the even subcarriers, *i.e.,* 2, 4, and 6, are inverted, marked with a circular arrow. In the fourth case of all subcarrier frequency flip, the frequency responses of all subcarriers are inverted. Indeed, we investigate the influence on the relevant subcarrier due to the frequency flip to an adjacent subcarrier by comparing two cases of (iii) and (iv), where only the relevant or an adjacent subcarrier is frequency-flipped and where both the relevant and adjacent subcarrier are frequency-flipped.

Figure 3 shows the span input power dependence of the Q-factor for four cases, illustrated as black, red, orange, and blue lines, respectively. In the case without the repeater DSP, Q-factor is maximized at a span input power of 3 dBm/subcarrier as 7.7 dB, and the Q-factor decreases in the nonlinear regime above 3 dBm/subcarrier due to the nonlinearity. By adapting phase conjugation and optimal CDC in the repeater, the maximum Q-factor is improved to 8.7 dB, and the signal power for a high Q-factor is also expanded. Nonetheless, the performance is limited because this method cannot compensate for the inter-subcarrier nonlinearity generated in the multi-subcarrier transmission. The result of frequency flip processing, in addition to phase conjugation and optimal CDC, shows further improvement in Q-factor, up to 8.9 dB and the optimum signal launch power increases by 1dB to 4dBm, in case (3) of frequency flip with one subcarrier skip. Furthermore, applying the frequency flip to all subcarriers (case 4), enables to increase the maximum Q-factor to 9.4 dB as flipping both neighboring subcarriers adds more walk-off than flipping only one of them. This highlights the efficiency of increasing the walk-off among subcarriers through simple frequency flipping.

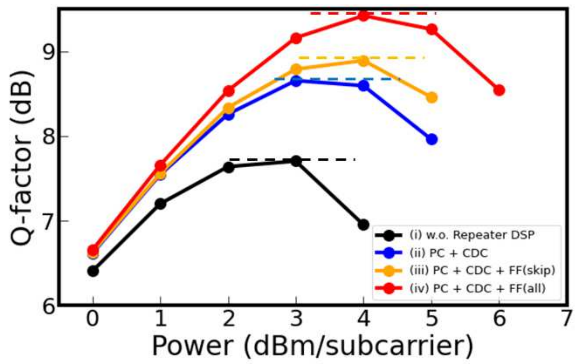

Fig. 3: Q-factor as a function of the span input power per subcarrier in the case without wavelength conversion, *i.e.* $\lambda_{\text{out}} = \lambda_{\text{in}}$.

B. Wavelength convesion

Finally, we evaluated the effectiveness of our proposed method in the case that the repeater converts the subcarrier wavelength for the second half of transmission. In this simulation setup, the center wavelength of the input multi-subcarrier signal to the repeater is fixed at 1550.1 nm. Through the repeater, each subcarrier wavelength of the multi-carrier is converted so that the center wavelength of the multi-subcarrier, λ_{out} , ranges from 1535.0 to 1565.1 nm, schematically shown in Fig. 4(a).

Figure 4(b) shows the conversion wavelength dependence of the Q-factor for three cases, without the repeater DSP (previous case 1) as a reference, with the repeater DSP of phase conjugation and optimal CDC [6] (previous case 2), and that of phase conjugation and CDC and frequency flipping to all subcarriers (previous case 4). Within the range of wavelength conversion in this simulation, the repeater DSP is efficient in mitigating nonlinearity and improving the Q-factor. The proposed method, including frequency flip processing, shows the highest performance, with Q-factor improvement from 1.6 to 1.8 dB compared to the case without the repeater DSP, as it efficiently mitigates inter-subcarrier nonlinear crosstalk adding walk-off between subcarriers. In the case of the repeater DSP containing frequency flip processing, Q-factor is slightly higher for shorter conversion wavelengths. Indeed, chromatic dispersion is lower for wavelengths shorter than the wavelength of the input signal, and the walk-off between neighboring subcarriers induced by frequency flipping is more effective during the optical links after the repeater on the low side of the conversion wavelength.

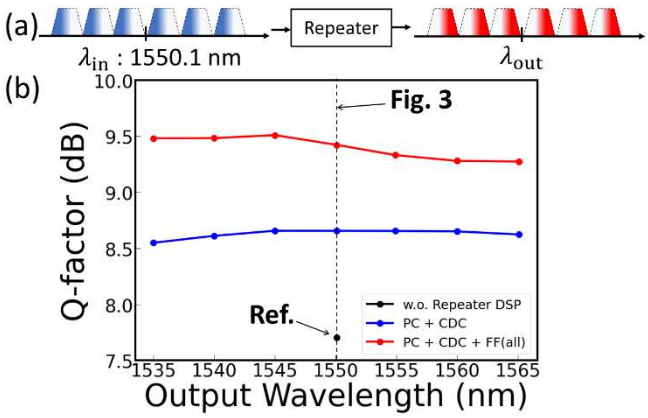

Fig. 4: (a) Schematic of wavelength conversion for the multi-subcarrier. (b) Q-factor as a function of the output wavelength.

V. CONCLUSION

We have demonstrated a wavelength converter repeater featuring a simple DSP method for nonlinear mitigation in multi-subcarrier transmission. Subcarrier-by-subcarrier frequency flip processing, combined with the previous method using phase conjugation and optimal CDC, improves the system performance due to mitigating the inter-subcarrier nonlinearity together with intra-subcarrier NLC by phase conjugation. The effect of subcarrier-by-subcarrier frequency flip is enhanced in the case of frequency flipping to all subcarriers, compared to the case of frequency flipping for every two subcarriers. In the wavelength conversion system where the repeater in the middle of links covert the subcarrier wavelength in the range of C-band, the proposed repeater DSP method shows from 1.6 to 1.8 dB Q-factor improvement in 960km 1 T bps multi-subcarrier signal consisting of PDM-16QAM 32GBaud six subcarriers.

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