A Combination of Eigenvalue and Spectral Function Modulation in Nonlinear Frequency Division Multiplexing

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Abstract: We propose a combination of eigenvalue and spectral function modulation as a new method of nonlinear frequency division multiplexing, which provides higher capacity and fault-tolerance.

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Eigenvalue communication has been repeatedly proved significant in data communication for nonlinearity removal. This process is mainly based on the integrability of Nonlinear Schrödinger Equation (NLSE) with no loss and no higher-order dispersion. Normalized NLSE is given by:

$$\frac{\partial q(t,z)}{\partial z} = -j\left(\frac{\partial^2 q(t,z)}{\partial t^2} + 2q(t,z)|q(t,z)|^2\right). \tag{1}$$

where $q(t,z)$ is the normalized signal along the fiber. Eigenvalue communication indicates that even though the signal suffers serious distortion in time domain due to fiber nonlinearity, its eigenvalues remain almost the same in transmission [1]. By using eigenvalues and nonlinear Fourier transformation supported in the interval $[T_1, T_2]$(Eq. 2),

$$\frac{dv}{dt} = \begin{pmatrix} -j\lambda & q(t) \\ -q^*(t) & j\lambda \end{pmatrix} v,\ v(T_1,\lambda) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-j\lambda T_1}. \tag{2}$$

we can transform the signal to nonlinear Fourier spectrum, where nonlinear distortion presents itself as a simple phase rotation [2]. Thus the original signal can be easily recovered. In order to improve the capacity, researchers are using nonlinear frequency division multiplexing (NFDM). There are two degrees of freedom, namely eigenvalue and spectral function. Several papers about eigenvalue modulation [3,4] have been reported and some groups claim interest in spectral function modulation. But there have been no reported results about using both degrees of freedom. Here we explicitly introduce the combination of eigenvalue and spectral function modulation.

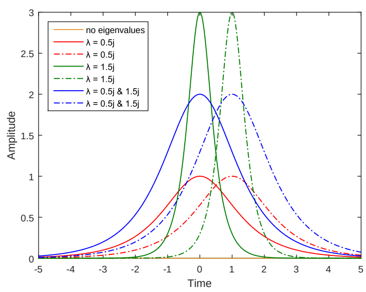

Fig. 1. Transmitted signals produced by INFT and time shift. Both signals with no eigenvalues equal zero in the time domain (orange line), so there are seven diverse signals shown in this figure. For other six signals, line patterns and dashed patterns respectively present signals with the same spectral amplitudes. To indicate three bits, we need to additionally assign another signal.

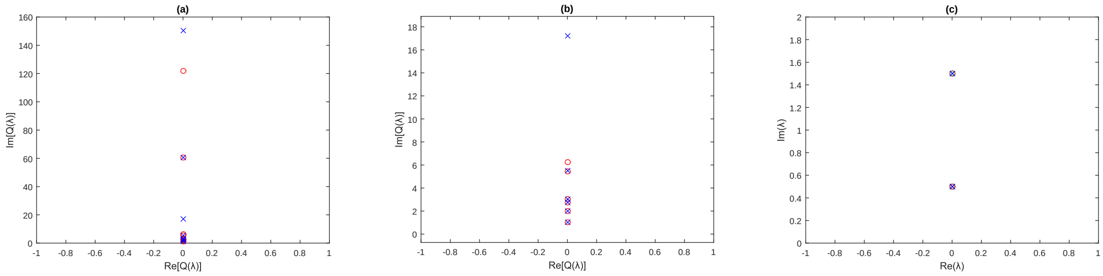

Fig. 2. (a)Nonlinear spectral functions at the transmitter (circle marks) and at the receiver (cross marks). Different signals vary in their spectral amplitudes. (b)Enlarged view of (a). Lower spectral amplitudes suffer less distortion in nonlinear frequency domain. (c)Original eigenvalues at the transmitter (circle marks) and corresponding eigenvalues at the receiver(cross marks).

Both eigenvalue modulation and spectral function modulation are efficient methods of multiplexing by enabling more signals on limited nonlinear bandwidth. After the coherent receiver, in DSP module, NFT is used to convert the distorted signal to nonlinear frequency domain where nonlinearity removal is conducted. Then we can judge from both eigenvalues and spectrum functions to decide transmitted signals.

Before transmission, signals need to be carefully designed at the transmitter in nonlinear spectral domain to ensure easy decision at the receiver. Desired signals in time domain can be produced by inverse nonlinear Fourier transformation (INFT). Different signals are mapped as different bit sequence. For example, N waveforms are mapped into $log_2 N$ bits. For signals with the same eigenvalue, scaling the amplitude means a shift of center in time domain. So it simplifies the process of signal production. Here we show a combination of two different schemes of modulation. Two eigenvalues and two spectral function amplitudes are adopted, which can form 7 diverse signals. Then we additionally assign the eighth signal, with which all signals indicate three bits. The transmitted signals are shown in Fig. 1. We only need to generate 4 of them with the same spectral amplitude and produce the other 4 with a time shift so that they present changed spectral amplitudes correspondingly. In Fig. 2.(a), we demonstrate received signals in the nonlinear spectrum as recovered spectral functions. Fig. 2.(b) illustrates the enlarged view of Fig. 2.(a). Fig. 2.(c) shows the eigenvalues at the receiver compared to those at the transmitter. It shows that eigenvalues suffer little distortion along the fiber. When a signal is obtained after nonlinearity removal, we first check its eigenvalue so we can narrow the possibility down to two signals with different amplitudes, then we check the spectral amplitude to make the final decision. Using the above method, dual-multiplexing can be realized.

There are still two points to be highlighted. For signals with no eigenvalue, namely zero, we need another designed signal to indicate a different amplitude. Even so, this combination of modulation still greatly improves capacity and fault-tolerance. Eigenvalue and spectrum provides double ways of accurate signal decision. Even if one of them suffers huge distortion, it is possible to distinguish signals from the other degree of freedom.

In conclusion, a combination of eigenvalue and spectral function modulation provides a new method of nonlinear frequency division multiplexing. It exceeds the original single scheme of modulation by improving capacity as well as fault-tolerance.

References

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