Add-drop Multiplexing for Spectrally Overlapped Nonlinear Frequency Division Multiplexed Transmission Systems

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Abstract: We present an add-drop multiplexer for WDM nonlinear frequency division multiplexed transmission systems, capable of replacing channels in a modulated spectrum that uses spectral overlap to stitch the nonlinear spectrum to avoid guard bands. © 2024 The Author(s)

1. Introduction

The ever-growing global data traffic demands higher spectral efficiencies from optical transmission systems, which are, however, limited by the Kerr effect [1]. One promising candidate to overcome this limitation and to further increase the capacity per fiber core are modulation schemes based on the nonlinear Fourier transform (NFT). Applied to solutions of the nonlinear Schrödinger equation, it treats the third-order nonlinearity such that the resulting nonlinear spectrum propagates linearly along the optical fiber channel. The necessary equalization on the receiver side then reduces to a simple linear phase rotation [2]. In contrast to the well-known linear Fourier transform, the nonlinear spectrum of the NFT consists of two parts, the continuous (dispersive) part $q_c(\lambda) = b(\lambda)/a(\lambda)$, where λ is the nonlinear frequency, and the discrete (solitonic) part, which represents a discrete number of first order soliton pulses.

The nonlinear frequency division multiplexing (NFDM) scheme, as applied to modulate the continuous spectrum, uses a sum of orthogonal subcarriers, similar to the well-known OFDM scheme in the linear domain. Most of the work in this area focuses on single-channel transmissions and a guard interval has so far been necessary for WDM transmissions, since there are no nonlinear multiplexers available to handle the nonlinear inter-channel crosstalk (ICC) [3]. To solve this problem, we presented a new transmitter concept with a corresponding highly scalable photonic integrated circuit (PIC) design, in which we use spectral overlap between neighboring channels to mitigate ICC [4,5]: To create a nonlinear spectrum seamlessly covering several communication channels, the bandwidth (BW) of each channel is extended and the same data is modulated on the subcarriers in the overlapping regions between adjacent channels. To ensure proper superposition of the final optical signals of each channel, digital linear trapezoidal shaped filtering and active optical phase control are applied. With this solution, it is possible to efficiently use large frequency bands, such as the entire C-band, for data transmission, and approximate a coherent nonlinear spectrum across it. An important challenge that still remains is the ability to drop channels from this seamless spectrum during transmission and to add new channels. In this paper, we present for the first time an add-drop multiplexer concept for spectrally overlapped WDM NFDM transmission systems and propose a concrete realization.

2. Add-drop Multiplexer and System Setup

The design of the add-drop multiplexer is an extension of the idea introduced in [6], applied here to the nonlinear spectral domain. A potential PIC-based realization for adding and dropping one channel is shown in Fig. 1 and more details of the corresponding digital signal processing (DSP) flow are depicted in Fig. 2.

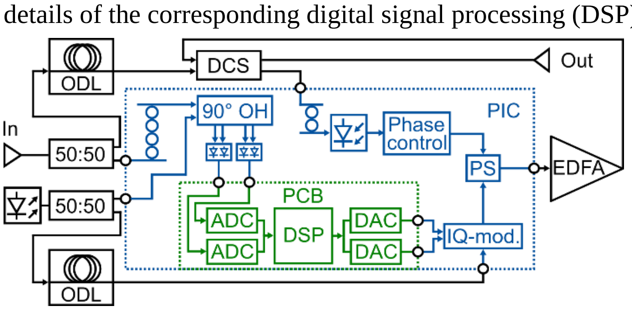

Fig. 1. Block diagram of the add-drop module. Blue: integrated in a PIC, green: placed on the corresponding PCB, black: discrete components.

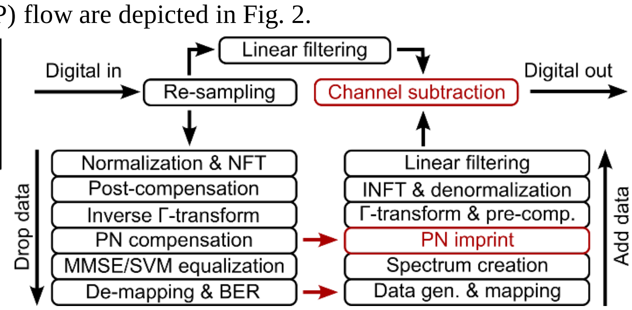

Fig. 2. Required steps in the digital signal procession block from Fig. 1.

First, the optical signal is split using a 3-dB coupler. One path is delayed using an optical delay line (ODL), e.g. a standard single mode fiber (SSMF), and the other path is coupled to the PIC, in which the target channel is dropped using a wideband coupled (ring-) resonator optical waveguide (CROW) filter. A laser used as local oscillator (LO) is also split and shared between a coherent Rx used to analyze the dropped signal and an IQ modulator later used to replace it. After digitization of the dropped channel, a DSP (Fig. 2) computes from it a signal that, if coherently added to the initial one, will both extinguish the initial spectrum of the target channel (dropping it) and replace it (adding the new channel). The optical signal generated by the IQ modulator is amplified with an EDFA to reach the needed launch power and combined with the delay-matched original signal using a 2x2 directional-coupler-splitter (DCS).

Since the coherent receiver and the IQ modulator share the same laser, phase noise (PN) added at the receiver is in principle canceled again at the transmitter as far as the channel dropping scheme is concerned. For this to hold, the initial optical signal and the laser light sent to the IQ modulator are both delayed by the amount of time taken for the signals to be processed by the DSP. Moreover, the dynamic phase error incurred by propagation through the two optical fiber loops has to be corrected with a phase shifter (PS) [7]. To control the phase correction, the combined signal from the complementary port of the DCS is sent to a monitor photodiode. Since subtraction of the dropped signal in the main signal path corresponds to a coherent summation at the monitor, the power registered by the photodiode is maximized by the control system.

Up to here, the processing is in principle identical to that used in prior works in the linear domain [6,7]. There are, however, essential differences. First, the added channel is generated in the nonlinear domain, and combined with our spectral overlap approach to maintain a seamless nonlinear spectrum, approximating a nonlinear add-drop multiplexer. Second, additional steps are required in the DSP part when adding a new channel, as explained below.

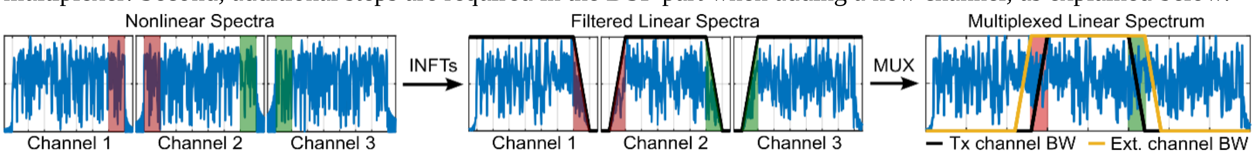

Fig. 3. Generation of a seamless nonlinear spectrum from three individual channels by using spectral overlap and linear trapezoidal shaped filtering for a proper superposition. The spectral part to be replaced by the add-drop multiplexer is shown for two different bandwidths.

Figure 3 summarizes how a seamless nonlinear spectrum is generated: After creation of the individual channels with spectral overlap (identical subcarrier regions are marked in red and green, respectively), inverse (I)NFTs are applied, followed by trapezoidal shaped linear filtering and final combination in the optical domain. In the case of our nonlinear add-drop multiplexer, the original spectrum, after channel subtraction, plays the role of channels 1 and 3, and the new channel that is to be added that of channel 2. This implies that in order to generate the added channel, the neighboring subcarriers of the other channels have to be known in the overlap region. Consequently, the entire NFDM processing stack has to be implemented in the Rx part of the add-drop before the new channel can be generated. A second requirement added to the processing stack is phase noise matching between the remaining part of the initial signal and the added one, as a prerequisite for implementing the spectral overlap. While the cancellation signal for the channel to be dropped automatically inherits the phase noise of the incoming signal, this does not hold for the added channel. Instead, this phase noise needs to be explicitly injected by the DSP, which is done by imprinting the phase noise factor computed during the phase noise compensation in the receiver part on the created spectrum. The trapezoidal shaped linear filtering is then applied to the newly created channel as well as to the cancellation signal, before electro-optic transduction and combination with the original one in the optical domain.

Another point to consider is the bandwidth of the channel to be add-dropped. Using the same bandwidth as on the transmitter side leads to a small part of the old channel remaining after the add-drop operation, as illustrated in the right panel of Fig. 3. To avoid this, the bandwidth can be slightly extended to remove the whole channel including the initial spectral overlap region from the Tx, and to create a new spectral overlap region (depicted in yellow).

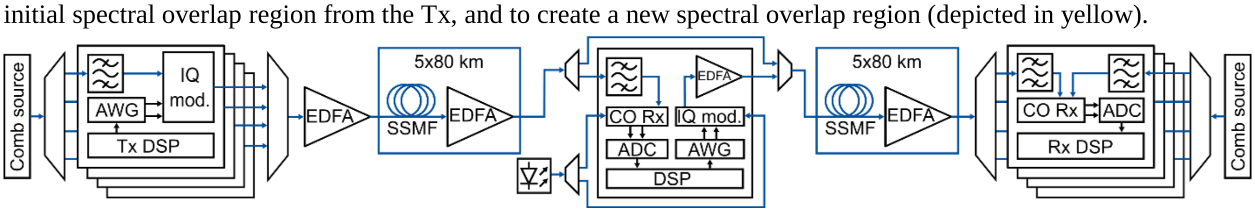

Fig. 4. Block diagram of the simulated transmission system.

The simulation setup modeled to demonstrate the complete system is shown in Fig. 4. It has 4 WDM channels with a bandwidth of 28 GHz each, including a spectral overlap of 4 GHz on either side, resulting in an overall bandwidth of 100 GHz. In the transmitter DSP (similar to the right side of Fig. 2), data are generated and mapped to 32-QAM symbols, a b-modulated spectrum is generated as a sum of weighted sinc-functions, a Γ-transform is applied to overcome the power limitation of the b-modulation scheme [8] and dispersion pre-compensation is applied. After an INFT, denormalization, and trapezoidal shaped linear filtering that ensures the proper superposition of the spectrally overlapping WDM channels, the electrical signals are generated with an arbitrary waveform generator (AWG) with a sampling rate of 88 GSa/s. For each of the channels, the optical modulation is then applied to a line filtered out of the comb source using an IQ modulator. All channels are multiplexed together, amplified to -0.5 dBm launch power and sent over 5 spans of 80 km SSMF, centered at 1550 nm. The signal is then split up and in one path channel two is filtered out, coherently received, and sampled with an ADC with 80 GSa/s. After the DSP part (Fig. 2), the new optical signal is generated again with an AWG with 88 GSa/s and an IQ modulator with the laser also used as the LO in the coherent reception, after applying a delay matched to that of the DSP processing. Before combining with the original signal, a matched delay is also applied to the latter and an EDFA is used to boost the newly generated signal to the needed power. After another transmission over 5 spans, the channels are demultiplexed and filtered, all 4 channels are coherently received and again converted in the digital domain with 80 GSa/s. In the receiver DSP block (Fig. 2, left), each channel is re-sampled to the original 88 GSa/s, normalization is applied and the NFT is computed, followed by the remaining dispersion compensation, an inverse Γ-transform, and phase noise compensation, using 5 of the subcarriers in each channel as pilot tones. Before de-mapping and BER calculation, either a minimum mean square error (MMSE) equalizer or a support vector machine (SVM) is applied. The fiber in this setup is modeled as having an attenuation of 0.2 dB/km, a mean dispersion β_2 of -21.68x10^{-27} s^2/m, a nonlinearity coefficient γ of 1.3 W^{-1}km^{-1}, the EDFAs to have a noise figure of 5 dB, and the optical sources to have a linewidth of 100 kHz.

3. Results and Discussion

The PN imprint is an essential feature for obtaining good performance in the overlap region, since proper superposition of the channels with phase matching is required. As shown in Fig. 5(a), the error vector magnitude (EVM) otherwise increases drastically, making the subcarriers in these regions useless for data transmission. Furthermore, using the same channel bandwidth in the add-drop multiplexer as in the transmitter also results in a performance degradation, but by using the extended bandwidth, the degradation is fixed and the performance matches that of other channels as seen in Fig. 5(b).

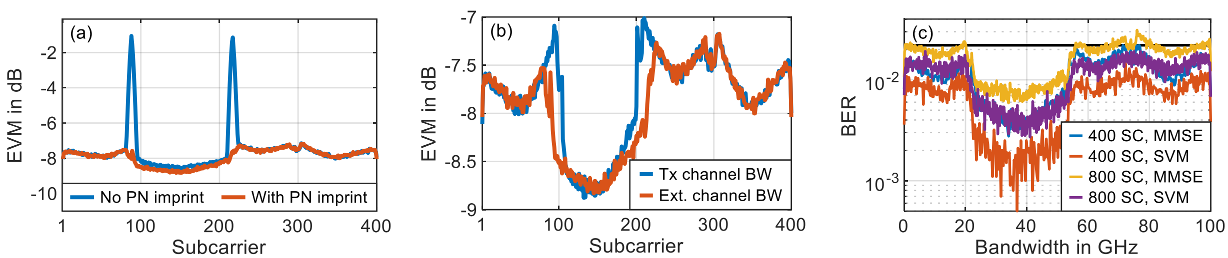

Fig. 5. (a) EVM per subcarrier without and with PN imprint. (b) EVM per subcarrier for different add-drop channel bandwidths. (c) BER over bandwidth for different numbers of subcarriers with MMSE or SVM equalization. The SD-FEC limit is shown in black.

Figure 5(c) shows the BER over the system bandwidth for transmissions using a total of 400 or 800 subcarriers (SC) and a block length of 6 or 10 ns, resulting in data rates of 333 and 400 Gbps and in spectral efficiencies (SE) of 3.3 and 4 b/s/Hz, respectively. MMSE or a simple SVM with a linear kernel is used for equalization. An increase of the subcarriers and therefore in SE comes at a cost of a decreased signal quality [8], so that the MMSE equalizer is only able to maintain a BER below the 2.2x10^{-2} SD-FEC limit for all subcarriers for the scenario with 400 subcarriers. Using an SVM improves the performance, so that the transmission with 800 subcarriers then also stays below the limit. The SE of the system can be further improved by using dual polarization (double SE), different constellation shapings [9], or joint modulation with the discrete spectrum [10]. It would also be possible to further increase the data rate in the channels that are dropped and added due to the shorter transmission distances.

4. Conclusions

We have presented for the first time an add-drop multiplexer for spectrally overlapped WDM NFDM transmission systems, opening the way to realize flexible system architectures with high spectral efficiencies, since no guard bands are required. Additionally, a PIC-based module has been proposed to realize such a system.

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5. References

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