Joint Pre-emphasis and Partial-response Coding for Spectrum Narrowing Caused by Repeated Optical-node Traversal in Ultra-dense WDM Networks

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Abstract *We propose a novel pre-filtering scheme that combines pre-emphasis and partial-response coding to mitigate the spectrum narrowing caused by repeated optical-node traversal. Simulations show that our optimum pre-filtering scheme extends the maximum node-hop count and transmission distance by up to 13 and 1040 km, respectively.*

Introduction

To fulfil the demand for greater network capacity cost-effectively, ultra-dense wavelength-division multiplexing (WDM) must be adopted[1]. In such systems, however, the impact of the spectrum-narrowing impairment caused by wavelength-selective switches (WSSs) in optical nodes is significant[2]-[10]. Spectrum narrowing induces intersymbol interference (ISI) because the global transfer function of WSSs does not meet the Nyquist criterion. Furthermore, the optical amplifiers add amplified-spontaneous-emission (ASE) noise to the attenuated signal spectrum. In these filtering-and-amplification processes, the ISI and ASE noise impair the signal in an interactive manner. The ISI can be cancelled by linear post-compensation filters in digital coherent receivers[11],[12]. However, ISI compensation at the receiver side degrades signal-to-noise ratio (SNR) since the lower-power frequency components of the signal are inevitably magnified[13].

The SNR degradation due to ISI compensation can be alleviated by pre-emphasis filtering[14]-[16]. In this scheme, frequency components that will be attenuated by node traversal are partly emphasized before transmission so that noise enhancement by post-compensation filtering is suppressed. Unfortunately, excess power loss is induced at each node since pre-emphasis allocates larger power to more lossy frequency components. Consequently, excess SNR degradation increases with the node-hop count. Another possible solution, partial-response coding, alleviates noise enhancement at the receiver side since the partial-response filter can halve the 3-dB bandwidth of the signal spectrum by allowing deterministic ISI[17]-[20]. Then, maximum likelihood sequence estimation (MLSE) conducts symbol decision under the residual deterministic ISI[17]; nevertheless, the noise enhancement is still inevitable since the partial-response filter does not reduce the overall signal bandwidth[13].

This paper proposes a novel pre-filtering scheme for mitigating severe spectrum narrowing in ultra-dense WDM networks. The proposed scheme simultaneously utilizes a pre-emphasis filter that emphasizes the spectral edges and a partial-response filter that suppresses the spectral edges in the transmitter-side digital signal processing (DSP) circuit. The two filters, which have different features, can create the optimum pre-filter. We execute intensive simulations on 32-Gbaud dual-polarization (DP) 4-QAM signals for 37.5 GHz grid systems. The results show that our scheme can extend the maximum node-hop count and transmission distance by up to 13 and 1040 km, respectively, in the systems examined.

Proposed spectrum-shaping scheme to mitigate spectrum narrowing

Figure 1 compares four transmitter-side spectrum-shaping schemes: (a) conventional Nyquist filtering, (b) pre-emphasis filtering, (c) partial-response filtering, and (d) the proposed combination of pre-emphasis filtering and partial-response filtering. In most current systems, the signal spectrum is shaped by the Nyquist filter. The signal repeatedly experiences filtering by WSSs and contamination by ASE noise along the channel. A linear post-compensation filter in the receiver executes ISI compensation. This process amplifies the power of low-SNR frequency components and so degrades the overall SNR[13]. The pre-emphasis filter amplifies the power of lossy frequency components before transmission[14]-[16]. This counteracts the spectrum narrowing induced by WSS traversal. As a result, the noise enhancement caused by post-compensation filtering is suppressed. However, each WSS traversal causes excess power loss and thus pre-emphasis filtering must set larger power levels to attain larger node-hop counts. Since the signal input power is limited by fibre nonlinearity, the effectiveness of pre-emphasis filtering declines with higher hop counts. As for partial-response filtering, the impact of spectrum narrowing is small thanks to its originally narrow signal bandwidth[18]-[20]. However, the post-compensation filter in front of MLSE enhances the noise as in the conventional Nyquist-filtering systems. The proposed scheme combines pre-emphasis filtering and partial-response filtering. The former suppresses the noise enhancement caused by post-compensation filtering. In addition, the partial-response filtering suppresses excess node loss due to pre-emphasis filtering by reducing the emphasis power needed. In this way, the optimum pre-filter is created by synergistically combining a pre-emphasis filter and partial-response filter.

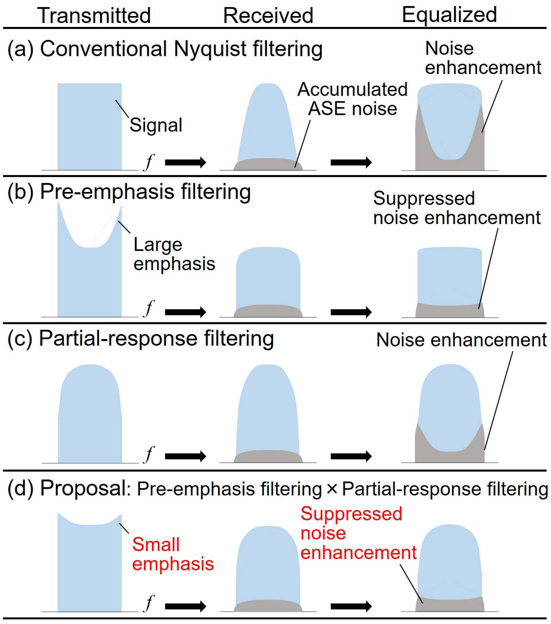

Fig. 1: Four candidates for spectrum shaping

Simulations

To assess the effectiveness of the proposed scheme, we conducted computer simulations. Figure 2 illustrates the simulation setup. A transmitter generates a 32-Gbaud DP 4-QAM signal whose spectrum is formed by a pre-emphasis filter and a partial-response filter. The pre-emphasis filter $C_t(f)$ is written as

$$C_t(f) = \lambda_t \left|\frac{N(f)}{T(f)}\right|^k ,$$

where λ_t is a power normalization factor at the transmitter side, $N(f)$ is accumulated ASE noise, $T(f)$ is the global transfer function of cascaded WSSs, and k is pre-emphasis strength[14]. Note that no pre-emphasis is applied if $k = 0$. Pre-emphasis strength, k, is optimized for each transmission system. The transmitter laser has a linewidth of 100 kHz. The signal is added to the network through a WSS and multiplexed with eight non-target signals that are closest to the target signal in the frequency domain. The cut-off slope of WSS passbands is defined by a Gaussian function with 10-GHz 3-dB bandwidth[21]. The port isolation of the WSS is 30 dB. After the erbium-doped fibre amplifier (EDFA), the signals enter a fibre link composed of an 80-km single-mode fibre (SMF) and an EDFA. The signal power launched into the fibre is optimized in each system. The loss coefficient, dispersion parameter, and nonlinear coefficient are 0.2 dB/km, 17 ps/nm/km, and 1.5 /W/km, respectively. The noise figure of the EDFA is 5 dB. The 8×8 optical nodes are configured in broadcast-and-select (B&S) or route-and-select (R&S) manner[22]. The node insertion loss is basically 16.5 dB for B&S configuration and 14 dB for R&S configuration. The signal spectrum is narrowed at each node traversal assuming the worst case. After multiple node hops, the target signal is dropped through a splitter in B&S nodes or through a WSS in R&S nodes. The target signal is then detected by a digital coherent receiver. The local oscillator has a 100 kHz linewidth. In the receiver DSP circuit, chromatic dispersion is cancelled by a fixed filter. The post compensation filter with 64 taps adapted by the least-mean-square (LMS) algorithm then performs polarization demultiplexing and signal-spectrum reshaping[11],[12]. Finally, conventional MLSE decodes partial-response-coded signals under the residual two-symbol-length ISI[17]. The target BER is 2.7×10^{-2} presupposing the use of forward-error correction (FEC)[23].

Figure 3 shows an example of the optimization of pre-emphasis strength k, where the transmitted signal is shaped by both a pre-emphasis filter and a partial-response filter. The nodes adopt the R&S configuration. In this example, the best performance is achieved when k is 3/6 (=1/2). The optimum pre-emphasis strength depends on the system.

Figure 4 illustrates an example of the proposed pre-filter that combines a pre-emphasis filter and a partial-response filter. Here, the pre-filter is optimized for a system with R&S node configuration and the node-hop count of 11. We observe that the optimum pre-filter includes a frequency-dependent emphasis portion and suppression portion.

Figure 5 depicts examples of the transfer functions of the pre-filter, cascaded WSSs, post-compensation filter, and entire system. The transmission condition of Fig. 4 is assumed. Figure 5(a) considers the use of only a pre-emphasis filter, whereas Fig. 5(b) uses our pre-filter shown in Fig. 4. We observe that our pre-filter offers small emphasis and hence excess loss due to pre-emphasis is suppressed. Moreover, noise enhancement due to the post-compensation filter is also suppressed.

Constellation maps after post-filtering are shown in Fig. 6. The use of R&S nodes is assumed. The transmission condition follows that of Fig. 4. Note that partial-response filtering increases the number of symbol states from 4 to 9 due to deterministic two-symbol ISI. We find that our proposed pre-filtering scheme achieves the highest SNR.

Figure 7 plots BER versus transmission hop count, for both B&S and R&S node configurations. The pre-emphasis strength of the pre-filter is optimized for each system. Our proposal substantially extends the maximum hop count; compared to conventional Nyquist filtering, the increments are 13 for the B&S configuration and 10 for the R&S configuration; the corresponding distance extensions are 1040 km and 800 km.

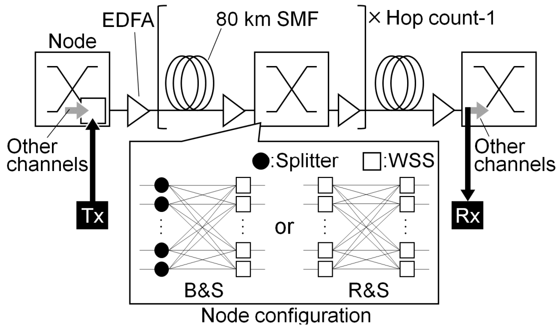

Fig. 2: Simulation setup

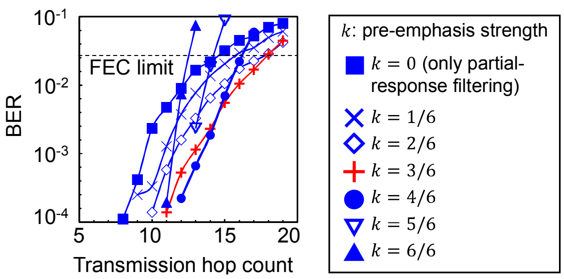

Fig. 3: Optimization of pre-emphasis strength

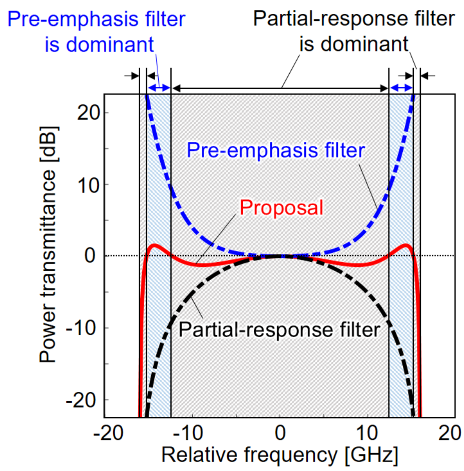

Fig. 4: Example of the proposed pre-filter

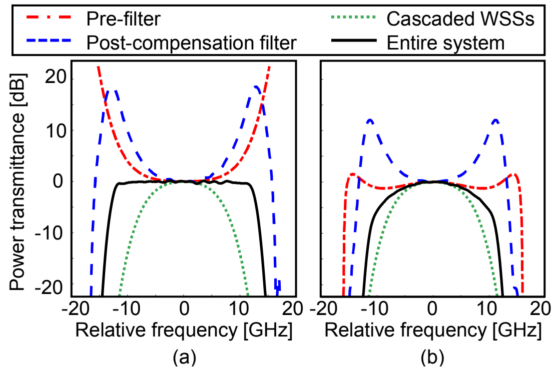

Fig. 5: Transfer functions including (a) pre-filter without partial-response filtering and (b) proposed pre-filter created by pre-emphasis filtering and partial-response filtering

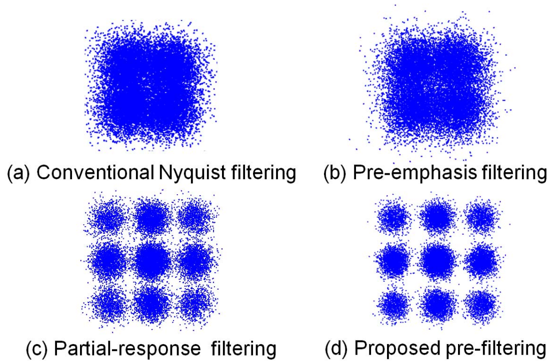

Fig. 6: Constellation maps after post-compensation filtering

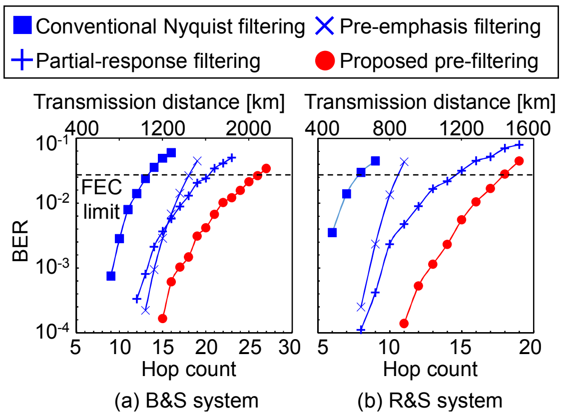

Fig. 7: BER versus hop count

Conclusions

We proposed a novel pre-filter that combines pre-emphasis filtering and partial-response filtering to mitigate the spectrum narrowing caused by repeated optical node traversal in ultra-dense WDM networks. The proposed pre-filter can yield significant SNR enhancement. Simulations showed that the proposed pre-filtering scheme can increase the maximum attainable hop counts of a 32-Gbaud DP 4-QAM signal by 13 in B&S-node systems and 10 in R&S node systems; the distance extensions are 1040 km and 800 km.

Acknowledgements

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