Fibre nonlinearity mitigation of OOK signals with MLSE utilising MZ filter for diverse VSB filtering

L. Wu, M. Li, F. Zhang, Z.Y. Chen, L.-K. Chen and A.S. Xu

Fibre nonlinearity mitigation of non-return-to-zero on–off keying (NRZ-OOK) signals with diverse-vestigial-sideband (DVSB) filtering maximum likelihood sequence estimation (MLSE) is demonstrated by experiments and simulations, in which DVSB filtering is realised with a Mach-Zehnder (MZ) filter. In a 10.709 Gbit/s NRZ-OOK system, experimental results show that, at a fixed optical signal-to-noise ratio, the *Q*-factor is improved significantly with DVSB-MLSE compared to that with conventional MLSE. Simulations reveal that the performance of DVSB-MLSE can be further improved by optimising the parameters of DVSB filters for different launch powers.

Introduction: As electronic equalisation techniques have proven to be powerful tools for the compensation of signal distortions in optical communication systems, maximum likelihood sequence estimation (MLSE) has emerged as one of the most effective compensation technologies. It has shown to be effective in compensating for linear impairments such as chromatic dispersion (CD) and polarisation-mode dispersion [1, 2], as well as self-phase modulation (SPM) in the presence of large residual CD values [3]. However, the MLSE receiver shows little improvement in nonlinear tolerance compared to the standard receiver for small residual CD [3]. One of the approaches that can enhance the performance of MLSE is diverse-vestigial-sideband (DVSB) filtering and joint equalisation, which has proven to be effective through simulations in our previous works [4, 5]. In this Letter, we experimentally investigate the nonlinear mitigation capability of diverse-vestigial-sideband-filtering MLSE (DVSB-MLSE), in which DVSB filtering is realised with a Mach-Zehnder (MZ) filter. We also investigate the performance of DVSB-MLSE with optimal DVSB filters for different launch powers by simulation.

Configuration of DVSB-MLSE: Fig. 1 shows the configuration of DVSB-MLSE. The input optical signal is first split into two branches. The signals in the two branches are then filtered with optical bandpass filters (OBPFs) to upper and lower vestigial sideband (VSB) signals and optically-electrically (O/E) converted, respectively. Finally, the converted electrical signals are sampled by analogue-to-digital converters (ADCs) for joint MLSE equalisation. Since the inter-symbol interference brought about by fibre nonlinearity behaves differently in the upper and the lower VSB filtered signals, through jointly equalising them the nonlinearity can be better mitigated.

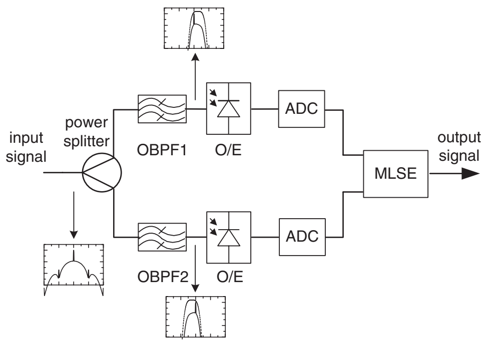

Fig. 1 *Configuration of DVSB-MLSE*

Experimental setup: Fig. 2 shows the schematic of our experimental setup. The 10.709 Gbit/s non-return-to-zero on–off keying (NRZ-OOK) signal with an extinction ratio of 7.8 dB is generated with $2^{15} - 1$ pseudorandom binary sequence. The OOK signal is then amplified and launched into the fibre link with a controlled power. The transmission link is composed of 100 km G.652 standard single-mode fibre (SSMF), the CD of which is fully compensated for by 14 km dispersion-compensating fibre (DCF). To adjust the optical signal-to-noise ratio (OSNR), after transmission the signal is first attenuated by a variable optical attenuator (VOA), then amplified by the erbium-doped fibre amplifiers (EDFAs). A 1.5 nm OBPF is used between these two EDFAs to remove outband amplified spontaneous emission (ASE) noise so that the amplified signal can have power high enough for photodetection. With part of the amplified optical signal tapped for the measurement of OSNR, the optical signal is then filtered with a 0.5 nm OBPF. For direct detection and conventional MLSE, the filtered signal is O/E converted by a photodiode and sampled by a Tektronix DSA 7200 digital serial analyser (DSA). For DVSB-MLSE, the filtered signal passes an MZ filter before the signals from its two output ports are O/E converted and sampled. The MZ filter has a free spectral range of 40 GHz, which corresponds to 20 GHz 3 dB passband bandwidth. The temperature of the MZ filter is carefully adjusted so that the attenuations of its two output ports for the input optical signal are both 3 dB. The bandwidth and sampling rate of the DSA are 18 GHz and 50 GS/s, respectively. Duration of the sampling process is 100 μs. The samples are then offline processed with a computer, and the bit error rate (BER) is evaluated and converted into *Q*-factor. The MLSE receivers take two samples per bit interval. Both conventional MLSE and DVSB-MLSE have four states.

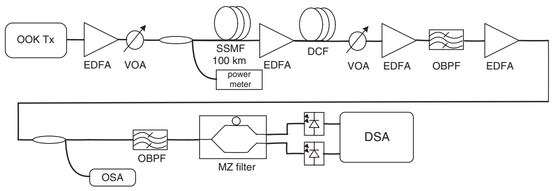

Fig. 2 *Experiment setup*

SSMF: standard singlemode fibre; EDFA: erbium-doped fibre amplifier; VOA: variable optical attenuator; OBPF: optical bandpass filter; OSA: optical spectrum analyser; MZ filter: Mach-Zehnder filter; DSA: digital serial analyser

Results and discussion: Fig. 3 shows the *Q*-factor against the launch power with different receivers. To ease comparisons, the OSNR at the receiver side is fixed to 14.0 dB for all measurements. For a standard receiver without equalisation, the *Q*-factor exhibits a drop of 2 dB when the launch power increases from 6 to 16 dBm. SPM is expected to be the dominant nonlinear effect for this case [6]. With conventional MLSE, the *Q*-factor shows a similar curve and the enhancement is less than 1 dB as the launch power is larger than 14 dBm, which demonstrates limited improvement of tolerance for SPM when CD is fully compensated. These results are in general agreement with the single-channel results [3]. In contrast, the *Q*-factor with DVSB-MLSE even increases when the launch power is more than 11 dBm, which is because the optimal parameters of DVSB filters vary with the power, and the parameters of the MZ filter used are closer to the optimal values for large launch power, as discussed in the following.

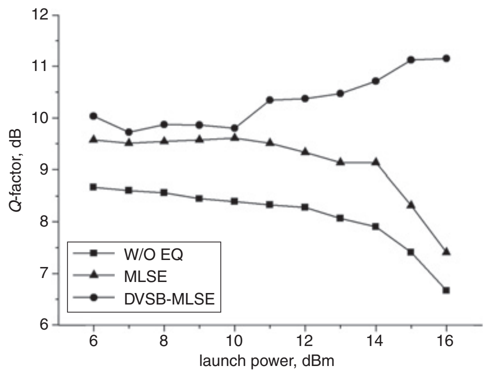

Fig. 3 *Q-factor against launch power*

We further simulated electronic equalisation with different equalisers using VPI transmissionMaker 7.5. The transmission system parameters were set to be the same as in the experimental setup shown in Fig. 2. All the OBPFs have second-order super Gaussian characteristics. For simplicity we assume the DVSB filters have the same bandwidths, and their detunings to the centre frequency of the OOK signal are symmetric. Fig. 4*a* shows the optimal parameters of the DVSB filters to obtain maximal *Q*-factor against the launch power. Both the optimal bandwidth *B* and the optimal detuning Δf increase with the launch power. The parameters of the MZ filter ($B = 20$ GHz, $\Delta f = 10$ GHz) used in the experiment are also shown in Fig. 4*a*. It can be seen that the parameters of the MZ filter are close to the optimal values for large launch power. Fig. 4*b* shows the simulated *Q*-factor against the launch power. Annotated with DVSB-MLSE is the curve when the OOK signal is DVSB filtered by an MZ filter, the parameters of which are fixed and equal to those in the experiment. It can be seen that the *Q*-factor increases with the launch power, in agreement with experimental results. The highest *Q*-factor is obtained at 18 dBm signal power, for the parameters of the MZ filter are mostly closed to the optimal values at this launch power. Using optimal DVSB filters indicated in Fig. 4*a*, the *Q*-factor curve is also given in Fig. 4*b*, annotated with DVSB-MLSEopt. It can be seen that the drop of the *Q*-factor is less than 0.8 dB when the launch power increases from 6 to 20 dBm. The optimised DVSB-MLSE outperforms the conventional MLSE significantly, especially for the case with large fibre nonlinearity.

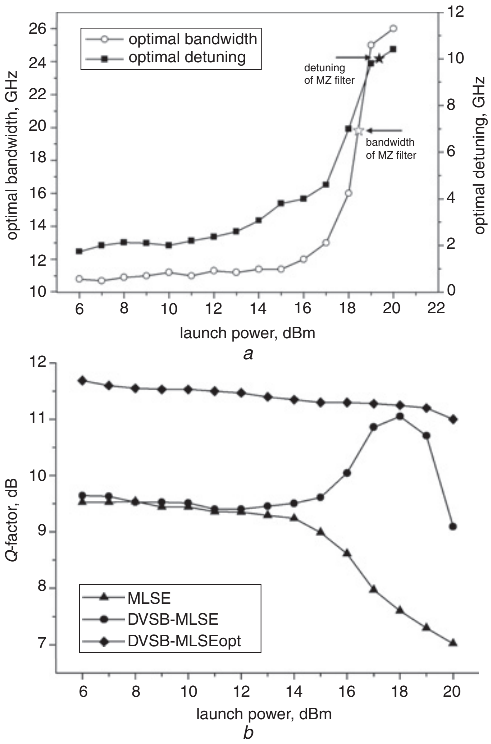

Fig. 4 *Simulation results*

a Optimal parameters of DVSB filters against launch power
b Simulated *Q*-factor for different equalisers against launch power

Conclusions: In a 10.709 Gbit/s NRZ-OOK optical transmission system, we have experimentally investigated the fibre nonlinearity mitigation capability of DVSB-MLSE, which utilises DVSB filtering and joint equalisation to enhance the performance of MLSE. In DVSB-MLSE, DVSB filtering is realised with an MZ filter. Both the experiments and the simulations show significant improvement of *Q*-factor using DVSB-MLSE compared to conventional MLSE. The optimal parameters of DVSB filters vary with the launch power. The performance of DVSB-MLSE with fixed DVSB filters can be further enhanced by utilising DVSB filters, the parameters of which are adjusted according to the launch power.

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