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Published in:
Proceedings of European Conference on Optical Communications 2016

Publication date:
2016

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):

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Temporal Probabilistic Constellation Shaping for WDM Optical
Communication Systems

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Abstract Finite state machine sources transmitting QPSK are studied as input to WDM optical fiber
systems with ideal distributed Raman amplification. The probabilities of successive constellation sym-
bols are shaped for nonlinear transmission and gains of around 500km (5-10%) are demonstrated.

Introduction
Nonlinear interference (NLI) is currently one of the major factors limiting the reach of wavelength di-
vision multiplexed (WDM) optical fiber systems. Furthermore, the NLI introduces memory in the
channel, which makes the information theoretic analysis into channel capacity and achievable in-
formation rates (AIRs) difficult. The standard approach for estimating AIRs is to employ the split-
step Fourier method (SSFM) for solving the Man-
akov equation for fiber propagation 1. The result
is usually an AIR estimate, which decreases with
launch power after a certain optimal point for a
fixed distance due to the dominant nonlinear ef-
facts. Recently, the concept of probabilistic shap-
ing has been investigated 2,3 for increasing the
AIR of fiber links. These techniques usually oper-
ate on a memoryless assumption and their gains
are therefore limited to within the linear region of
transmission, or at best - the weakly-nonlinear re-
region, where the channel can also be considered
memoryless. In such cases, large modulation for-
mats are required for achieving significant shap-
ing gain, e.g. 64-quadrature amplitude modula-
tion (QAM), which is difficult for implementation in
transceivers with limited processing capabilities.
The memory in the optical channel can be taken
into account by using a finite state machine (FSM)
approach at the receiver 4, which allows for in-
creased AIRs by using the BCJR algorithm for es-
timating the mutual information (MI) between the
input and output sequences of a certain length,
generally longer than 1.

In this paper, a finite state machine source
(FSMS) is considered as input to the fiber optic
channel. A FSM model is also adopted for the
fiber channel, which allows for computing of MI
with memory, but also for optimizing the transition
probabilities of the FSMS. This optimization re-
sults in improved performance particularly in the
highly-nonlinear region of transmission.

Probabilistic optimization of FSMS
As mentioned, the nonlinearities introduce mem-
ory in the channel, or dependencies between
the received symbols in time. The idea behind
using FSMSs is to introduce dependencies be-
tween the transmitted symbols, thereby suppress-
ing (assigning lower probabilities to) sequences,
which result in strong NLI and poor performance.
We refer to this process as temporal probabilistic
shaping (TPS). TPS allows for optimizing the in-
put for channels with memory, which for the opti-
cal channel can be much more effective than sim-
ply optimizing the probability mass function (PMF)
of the constellation under the constraint of inde-
pendent, identically distributed (i.i.d.) symbols in
the transmit sequence. TPS was studied previ-
ously 7 with the target of ensuring a constant am-
pitude multi-dimensional input, however, no de-
sign rules were described for how to achieve the
shaping gain in practice.

In this work, an FSMS is constructed by defin-
ing the state at time \( k \) to be the previous \( N \) trans-
mitted symbols, \( s_k \triangleq (x_k-N, x_k-N+1, \ldots, x_k-1) \),
where \( N \) is the order of the FSMS. The current
transmitted symbol \( x_k \) governs the state transi-
tion. Optimizing the stationary distribution of the
transition probabilities can be done for e.g. lin-
ear impulse response channels by the general-
ized Blahut-Arimoto algorithm (GBAA) 5.

The GBAA is applied in this work with a few
modifications. The algorithm requires knowledge
of the likelihoods \( p(y_k|s_{k-N}^k, x_k) \), where \( y_k \) is the
received symbol at time \( k \), and \( s_{k-N}^k \) is the state
sequence from time \( k-N \) to \( k \). Since the likeli-
hoods are not available in closed form for the opti-
cal channel, we model them as Gaussians for
each possible state transition \( (|X|^{N+1}) \) transitions
in total, where \( X \) is the set of symbols in the con-
The optimization process is given in Fig. 1. The FSMS is initialized with uniform transition probabilities, and thereby uniform and independent probabilities of the constellation symbols. A long sequence is generated by the source for each polarization and WDM channel separately, which are then combined and passed through the fiber via the SSFM. A standard, single mode fiber is assumed with a loss of $\alpha$ via the SSFM. A square root raised cosine filter is applied with roll-off factor 0.01, and the guardband between channels is set to 2 GHz. Ideal distributed Raman amplification is assumed.

At the receiver, the central channel is acquired and chromatic dispersion is performed in the frequency domain. We also estimate the received $\gamma$ and chromatic dispersion is performed in the frequency domain. The parameters of the likelihood w.r.t. the transition probabilities of these Gaussians are estimated from training data.

The optimization process is given in Fig. 1. The FSMS is initialized with uniform transition probabilities, and thereby uniform and independent probabilities of the constellation symbols. A long sequence is generated by the source for each polarization and WDM channel separately, which are then combined and passed through the fiber via the SSFM. A standard, single mode fiber is assumed with a loss of $\alpha = 0.2\ dB/km$, dispersion $D = 17\ ps/(nm \cdot km)$ and nonlinear coefficient $\gamma = 1.3(W \cdot km)^{-1}$. A square root raised cosine filter is applied with roll-off factor 0.01, and the guardband between channels is set to 2 GHz. Ideal distributed Raman amplification is assumed.

At the receiver, the central channel is acquired and chromatic dispersion is performed in the frequency domain. The parameters of the likelihoods are then estimated, and the MI is maximized w.r.t. the transition probabilities $p(s_k|s_{k-1})$ of each state. The MI is then calculated separately, and the process is repeated with the updated FSMS until convergence or a certain predefined number of iterations. We note that the channel, i.e. the likelihoods, depend strongly on the input itself. The process is therefore not guaranteed to converge. However, in our simulations, convergence was usually observed before the 10-th iteration. We note that the optimization is performed in one polarization only due to the increased complexity of joint processing.

While the MI calculation and the MI optimization require similar processing steps (a BCJR algorithm is used for both), the memory $M$ assumed for MI calculation is not necessarily the same as the order of the FSMS $N$. Longer $M$ is always beneficial, however, the complexity of the BCJR is linear with the number of transitions in the receiver trellis, which is exponential with $M$. We note that if a receiver is to be built for such models, the same complexity is generally required for demodulation. Operating a system with highly specialized FSMS of high order which can be detected by a low-complexity trellis is therefore of interest.

Results

We demonstrate the benefits of the method for QPSK input constellation, which is chosen due to its small complexity and implementation penalty. While probabilistic shaping gain with the i.i.d. symbol assumption is not possible with QPSK due to the constant amplitude, the gains from TPS are of interest in this paper. We measure the received MI in bits per symbol per polarization (bits/symbol for simplicity), as calculated by a BCJR processing assuming $M$ symbols of memory. The MI in this case also represents AIR.

We also estimate the received effective SNR as $SNR = 10 \cdot \log_{10}\frac{E_k[|x_k|^2]}{E_k[|n_k|^2]}$, where $E_k[\cdot]$ is the expectation w.r.t. $k$. The SNR thus includes the NLI noise.

We start by analyzing the potential benefits of optimized FSMSs as channel input in the highly non-linear region of transmission. To that end, 200 km single channel, single polarization transmission at 10 GBaud is simulated. We keep the distance short so that the major impairment is the NLI.

In Fig. 2(a), the MI is given as a function of the launch power for FSMS order of up to 3. We see increasing gains with the order of up to 0.25 bits/symbol at the highest launch power. Fig. 2(b) shows the received SNR for each $N$. We see that not only the MI is increased, but also the effective SNR at the receiver side. The reason is that sequences, resulting in severe NLI are suppressed by the FSMS. The impact of the increased SNR can be seen in Fig. 2(c), where the MI is given for different values of the memory $M$. When independent, uniformly distributed QPSK symbols are input to the channel, processing with memory 3 provides around 0.1 bits/symbol of gain. When the FSMS state transition probabilities are optimized, the gain is increased to the above mentioned 0.25 bits/symbol. The same gain is achieved with memoryless processing at the receiver with complexity which is orders of magnitude smaller than that of the BCJR, at the cost of negligible complexity increase at the transmitter.

In Fig. 3, the optimized PMF of the states in the FSMS is shown for the highest considered launch power $P_{ln} = 7\ dBm$. The state is represented by the previous two QPSK symbols (the QPSK symbol numbering is also given). We see that the optimization process favors states with close neighbors, and suppresses states, for which the two symbols are at longer Euclidean distance. The rest of the states have rather similar optimized
provides even higher gains at negligible complexity increase. Furthermore, as we saw in Fig. 3, the optimized state PMF has a symmetric structure. Generalizing this symmetry and imposing it on the optimization process will improve the accuracy and speed of the optimization, which is especially relevant for high-order constellations.

**Conclusions**

In this paper, the transition probabilities of a finite state machine source (FSMS) were optimized for nonlinear WDM transmission. We demonstrated that the resulting temporal probabilistic shaping gains can be achieved with minimal receiver effort by shifting complexity to the transmitter side. Up to 500 km of reach increase were achieved with a FSMS of third order with standard receiver processing and QPSK input for a long-haul WDM system.

**Acknowledgements**

This work was supported by the DNRF Research Centre of Excellence, SPOC, ref. DNRF123.

**References**