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Pseudo-Random Sequences for Modeling of Quaternary Modulation Formats

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Abstract

We discuss the influence of pseudo-random quaternary sequences on DQPSK transmission performance and present an efficient method to generate such sequences.

1 Introduction

Multi-level modulation formats are considered for next-generation optical transmission systems. In particular differential quadrature phase shift keying (DQPSK) is attractive as it encodes 2 bits/symbol and as such offers a combination of high spectral efficiency and large chromatic and polarization-mode dispersion tolerance [1, 2]. To asses the linear and nonlinear transmission properties of such modulation formats, inter-symbol interference as occurs along the transmission line should be properly modeled [3]. Binary modulation formats are routinely modeled using pseudo-random binary sequences (PRBS), but for quaternary modulation formats no such standard exists. Hence, to generate a quaternary sequence typically two PRBS are multiplexed with a cyclic shift for de-correlation. However, such a sequence does not necessarily include all possible combinations of symbols up to a given length, which can result in inaccurate modeling of system penalties. This can be avoided by using pseudo-random quaternary sequences (PRQS).

In this paper we discuss the influence of pseudo-random sequences on 42.8-Gbit/s NRZ-DQPSK transmission. In addition, we present an efficient method for PRQS generation by multiplexing two PRBS with a suitably chosen cyclic shift.

2 Pseudo-random quaternary sequences

Assume a sequence to have length k^n, where k is the alphabet size and n an integer value. A pseudo random sequence can then be defined as a sequence that contains all possible combinations of symbols up to length n (subsequences) exactly once. Such sequences are known as *de Bruijn* sequences and are considered in the remainder of this paper. Note that *de Bruijn* sequences are equal to standard PRBS with length k^n-1 with the exception that PRBS lack the subsequence with n consecutive zeros. It is evident that for $k \geq 4$ the required sequence length to consider all possible subsequences of a given length n grows very rapidly. For example, consider subsequences of length $n = 7$. For binary sequences this results in a sequence length of $2^7 = 128$ symbols, whereas for quaternary sequences $4^7 = 16384$ symbols are required. Hence, the subsequence length n for $k \geq 4$ is restricted by simulation complexity. This underlines the need for a properly chosen PRQS to correctly model system penalties.

A simple method to generate PRQS is to multiplex two PRBS (u and v) with a cyclic shift for de-correlation. A figure of merit for the de-correlation in the resulting sequence can be obtained by computing,

$$correlation = \sum_r \left| \Pr(r) - \frac{1}{k^n} \right| ,$$

where $Pr(r)$ is the probability of each possible subsequence r for a pseudo-random sequence with alphabet size k and subsequence length n. Fig. 1 shows the correlation as function of the cyclic shift between two PRBS of length 2^6, normalized with respect to the correlation value obtained when there is no cyclic shift between u and v. As evident from Fig. 1 the relative correlation is zero when v is cyclically shifted over +/-3 symbols. It can be shown that for a 2^n PRBS and a cyclic shift of +/-$n/2$ symbols (for n is even) always a PRQS with length $4^{n/2}$ is obtained. Shifting v over -$n/2$ symbols is equal to shifting v over +$n/2$ symbols and inverting it.

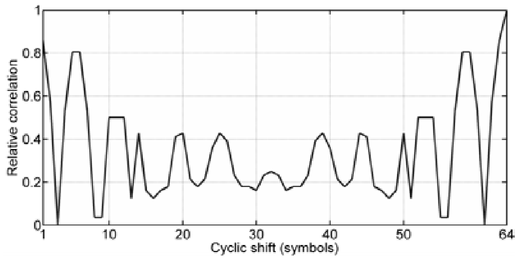

Fig. 1: Correlation as a function of the cyclic shift.

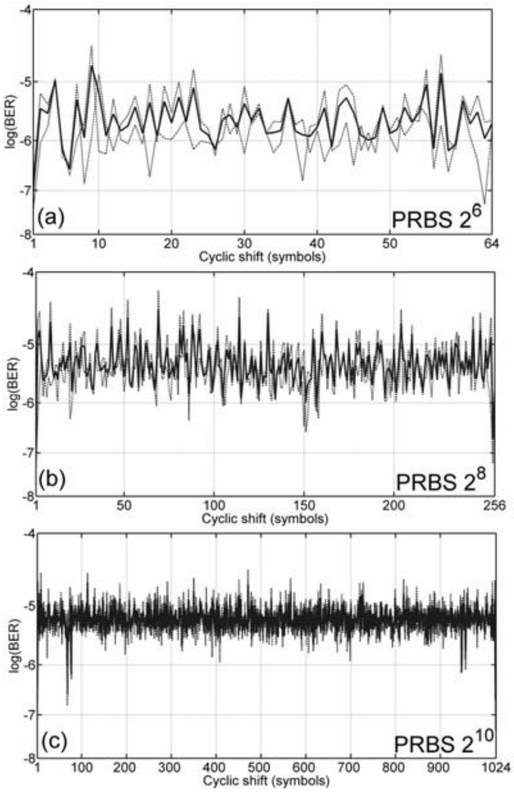

Fig. 2: BER for 42.8-Gbit/s NRZ-DQPSK over 1140 km for different pattern length and cyclic shift, doted lines denote in-phase and quadrature tributaries.

3 Simulation results

We now simulated the influence of different 4-level sequences on 42.8-Gbit/s NRZ-DQPSK transmission. Single channel transmission over 12x95-km (1140 km) of standard single mode fiber (SSMF) is simulated with a pre-compensation of 680-ps/nm, 85-ps/nm/span in-line under-compensation and zero residual dispersion. The launch power is 4 dBm per channel into the SSMF and -1 dBm into the DCF. At the receiver the OSNR is set to 18.3 dB (0.1 nm res.) which results in a back-to-back bit-error ratio (BER) of 10^{-9}. The BER is computed using a Karhunen-Loeve series expansion [4].

Fig. 2 shows clearly that the performance is strongly dependent on the cyclic shift between *u* and *v*. Short PRBS result on average in a lower BER, thereby incorrectly modeling the transmission penalties. For longer PRBS (1024 symbols) the variation in BER as a function of the cyclic shift is reduced, but differences of more than an order of magnitude are still apparent. This shows that even for long sequences an arbitrary cyclic shift can potentially result in inaccurate modeling of transmission penalties.

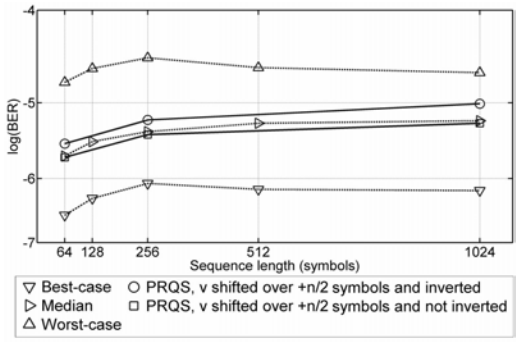

Fig. 3: Worst-case, median and best-case BERs for all cyclic shifts and the BER obtained with PRQS.

Fig. 3 shows the worst-case, median and best-case obtained BER for all possible cyclic shifts between *u* and *v* larger than two (to ensure all symbol transitions exist). For a sequence length longer than 256 symbols the median value is relatively constant, indicating this is sufficient to properly determine transmission penalties. It furthermore shows that the BER obtained with the proposed PRQS is close to the median value over all possible cyclic shifts which indicates that these sequences are suitable for modeling of DQPSK transmission impairments.

The proposed method can also be used to generate multi-level sequences for modulation formats with >2 bits/symbol. This can be helpful to explore modulation formats such as polarization-multiplexed DQPSK (with 4 bits/symbol) [5], which are likely to be used in future optical transmission systems.

4 References

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