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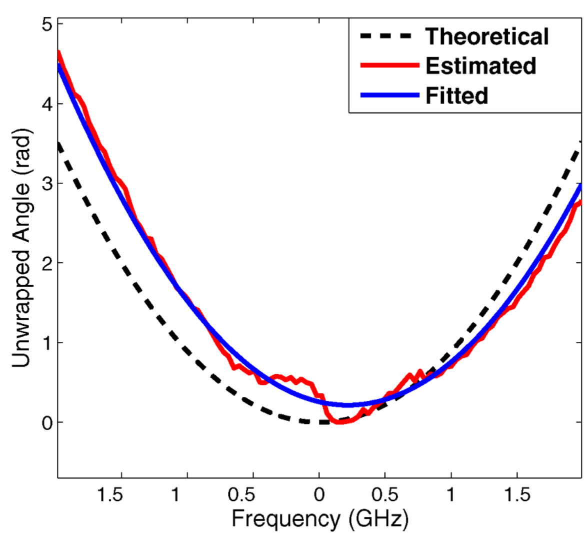

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Data-Aided Chromatic Dispersion Estimation for Polarization Multiplexed Optical Systems

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Abstract: We propose a full transmission link chromatic dispersion (CD) estimation technique for polarization-multiplexed coherent optical single carrier system using data-aided channel estimation and least square quadratic fit. New training sequences based on Chu sequence and Golay complementary pair are designed and compared for estimation performance against the ideal full-level Chu sequence for both QPSK and 16-QAM systems. The proposed technique is demonstrated in a 40-Gb/s coherent polarization multiplexed optical system over 2080-km fiber transmission for QPSK format and 80-Gb/s system over 1800-km fiber for 16-QAM format to verify its accurate and robust estimation performance.

Index Terms: Chromatic dispersion (CD), data aided, channel estimation.

1. Introduction

For next-generation optical networks, coherent receiver and digital signal equalization has been considered as the technology of choice. One of the most dominant impairment in optical transmission, namely, chromatic dispersion (CD), can now be fully equalized using frequency-domain equalization once the total dispersion in the transmission line is estimated. As CD is equalized using digital signal processing (DSP), there is a need to accurately estimate this parameter at the initialization stage of the receiver. This can be done by using either blind or data-aided method [1]–[5]. Blind estimation typically uses gradient algorithm and has been shown to be very slow on convergence speed and has singularity problem [3], [4] while data-aided method uses training sequences and is faster and more robust [2]–[5]. Since CD is a static channel impairment and only needs to be estimated once, it is more desirable to use data-aided method. Previous work on data-aided CD estimation used constant amplitude zero autocorrelation (CAZAC) Chu sequences [2], [3], which, while offering theoretically best performance, require high-resolution modulators especially for long sequences. Thus, short sequences are used in [2] and [3], which limit the solution space to a small amount of CD, and multiple estimations are used to find the best fit. We previously propose the use of Golay sequences for CD estimation in single polarization systems using autocorrelation property [6] and under space time block code scheme for polarization-multiplexed (PolMux) systems [5] using complementary spectral property, which also provide theoretically best estimation performance. By using Golay sequences, full transmission length channel estimation is possible, and single-stage estimation based on unwrapped phase response and least square quadratic fit can be used to estimate CD without prior knowledge of the transmission link. The method has been demonstrated in QPSK systems for over 2000-km transmission with good results. However, a comparison with standard Chu sequences in CD estimation, as well as estimation performance with different sequence lengths, has not been made, and the sequences used in [5] are only customized for QPSK modulator. As the trend for designing next-generation network is now shifting to 16-QAM systems, it is desirable to develop data-aided channel estimation and monitoring methods with training sequences designed specifically for 16-QAM system and beyond.

In this paper, we present, using experiments and simulations, full transmission link data-aided CD estimation method for both QPSK and 16-QAM systems using new modulation-format specific training sequences, namely, Golay sequences and quantized Chu sequences aided by single-stage quadratic-fit interpolation. The new modulation-format specific sequences will ensure easy integration into QPSK and 16-QAM commercial modulators without the need for high-resolution digital-to-analog converter (DAC) unlike the case with the ideal full-level Chu sequence. Theory and simulations on different sequence type, their lengths, and their performances are presented. The method is demonstrated in experiments for QPSK system over 2080 km and 16-QAM system over 1800-km transmission length, and the experimental results are consistent with simulations, which verify the good performance of the proposed new training sequences against the traditional CAZAC Chu sequence.

2. Data-Aided Channel Estimation and CD Estimation

2.1. Channel Estimation

As proposed in [7], optical channel in PolMux systems can be modeled as a 2×2 MIMO transmission channel, and wireless techniques for estimation of the MIMO channel can be used. The channel transfer function $H(f)$ is modeled as the 2×2 matrix

$$H(f) = \begin{pmatrix} H_{xx}(f) & H_{yx}(f) \\ H_{xy}(f) & H_{yy}(f) \end{pmatrix} \tag{1}$$

where H_{xx} and H_{yy} correspond to the transfer function in the X and Y-polarization, respectively; and H_{xy} and H_{yx} correspond to the cross-coupling between them, respectively.

In data-aided channel estimation, training sequences are sent through the channel using the space time block code scheduling scheme [8], [9] where the transmission matrix $S[k]$ is

$$S[k] = \begin{pmatrix} S_1[k] & -S_2^*[k] \\ S_2[k] & S_1^*[k] \end{pmatrix} \tag{2}$$

where $S1[k]$ and $S2[k]$ are the discrete Fourier transform (DFT) of two orthogonal sequences. After transmission, the received training sequences in frequency domain can be expressed as

$$\begin{pmatrix} R_1[k] & R_2[k] \\ R_3[k] & R_4[k] \end{pmatrix} = \begin{pmatrix} H_{xx}[k] & H_{yx}[k] \\ H_{xy}[k] & H_{yy}[k] \end{pmatrix} \begin{pmatrix} S_1[k] & -S_2[k]^* \\ S_2[k] & S_1[k]^* \end{pmatrix} + \begin{pmatrix} N_x[k] \\ N_y[k] \end{pmatrix} \tag{3}$$

where $R_1[k] - R_4[k]$ are the DFTs of the received signals; $N_x[k]$ and $N_y[k]$ are noise components; and $H_{xx}[k]$, $H_{yy}[k]$, $H_{yx}[k]$, and $\mathrm{H}_{xy}[k]$ are the frequency-domain channel transfer functions. Since the received signal is in frequency domain, assuming negligible noise components, the signal can be viewed as containing only the product of the channel transfer matrix $H(f)$ multiplied by the original training matrix in frequency domain. Therefore, an estimation of the channel transfer matrix can be obtained by multiplying the received signal with the inverse of the training matrix

$$H[k] = \begin{pmatrix} H_{xx}[k] & H_{yx}[k] \\ H_{xy}[k] & H_{yy}[k] \end{pmatrix} \approx \begin{pmatrix} R_1[k] & R_2[k] \\ R_3[k] & R_4[k] \end{pmatrix} \begin{pmatrix} S_1[k] & -S_2[k]^* \\ S_2[k] & S_1[k]^* \end{pmatrix}^{-1}. \tag{4}$$

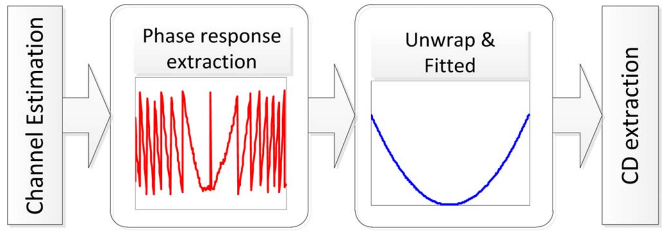


Fig. 1. Quadratic fit CD estimation block diagram.

2.2. CD Estimation

In systems with weak nonlinearities, a linear optical channel model mainly consists of polarization-independent component such as CD and polarization-dependent component such as polarization mode dispersion (PMD) resulting in a 2×2 channel transfer matrix as follows [10], [11]

$$\begin{pmatrix} H_{xx}(f) & H_{yx}(f) \\ H_{xy}(f) & H_{yy}(f) \end{pmatrix} = G(f) \begin{pmatrix} u(f) & v(f) \\ -v^*(f) & u^*(f) \end{pmatrix} \tag{5}$$

where PMD elements are 2×2 matrix with $|u(f)|2 + |v(f)|2 = 1$, and G(f) is the CD transfer function, which can be described as an all-pass filter in frequency domain characterized by

$$G(f) = \exp\left(-j\frac{\pi D\lambda^2 z}{c} f^2\right) \tag{6}$$

where D is the fiber dispersion parameter, z is the total fiber length, λ is the transmission wavelength, and c is the speed of light. Using (6), it can be seen that the phase response of the CD transfer function is a quadratic rotation, and CD can be estimated using quadratic fit.

The CD estimation method proposed in [3] is based on knowing approximately the total amount of CD, reconstructing multiple theoretical CD curves around this value, and choosing the curve that best fits the estimated value. This approach is limited to measuring a small amount of CD (residual CD) since large CD values require longer sequences and a large amount of estimation operations before the best fit is found. In our approach, by unwrapping the phase of the transfer function and using longer training sequences, the full CD transfer function can be estimated, which enables quadratic fit in one single step. Fig. 1 illustrates the steps of large CD estimation approach where the CD transfer function is first separated using the determinant method [3], [5] and phase response is extracted. Phase response samples are then unwrapped to remove the $\pi/2 \le \psi(f) \le \pi/2$ restriction where $\psi(f)$ is the sampled phase response of the CD transfer function and then a parabolic interpolation is fitted using least square method. CD parameter is then extracted from this quadratic fit.

In order to estimate CD using the above method, training sequence has to be sufficiently long for the intended transmission length. We derive an expression for the minimum required sequence length for CD estimation by first noting that, in the case of time domain CD compensation using FIR filter, the maximum number of taps is given by [12]

$$L_h = \frac{Dz\lambda^2}{cT^2} \tag{7}$$

where L_h represents the channel memory length or number of taps, λ is the laser wavelength, D is the dispersion factor, z is the transmission length, c is the speed of light, and T is the receiver sampling period. If S_p represents the samples per bit, then by extending the expression in [4] and combining with (7), the required sequence length is

$$L = \frac{L_h N_t}{S_p} = \frac{Dz\lambda^2 B N_t}{cT} \tag{8}$$

where B is the system baud rate and $N_t = 2$ for PolMux systems. Using (8), a training sequence with a minimum length of 64 symbols is required to accurately estimate CD for around 2000-km fiber

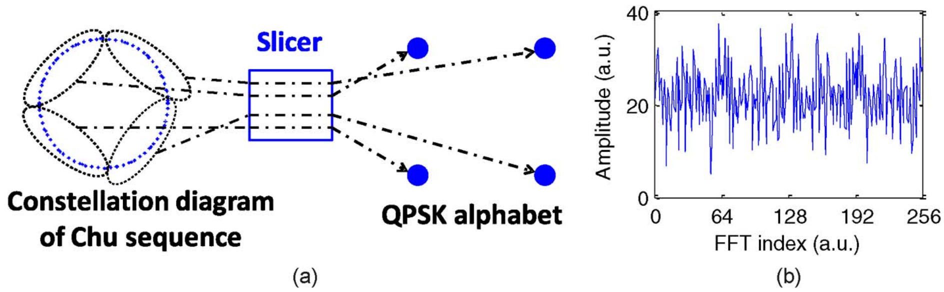


Fig. 2. (a) Generation of Q-Chu sequence and (b) frequency spectrum of Q-Chu-sequence.

transmission in a 40-Gbaud/s system, and it can be seen that a long training sequence will virtually eliminate the need to know the approximate CD value.

3. Training Sequences in PolMux System

For data-aided channel estimation in PolMux system, we propose the use of two new types of training sequences, both satisfy the orthogonal property and are designed for the specific system modulation formats such as QPSK and 16-QAM.

3.1. Chu-Based QPSK and 16-QAM Sequences

Chu-based sequence is derived directly from the original Chu sequence [13] by first generating orthogonal Chu sequences at a desired length. Then, for the Chu-based QPSK sequences (Q-Chu), the sequences are passed through a QPSK slicer to obtain QPSK sequences with good frequency response comparable with the original Chu sequences, as shown in Fig. 2. The slicer can be mathematically formulated as

$$C_k = \text{sgn}(real(Z_k)) + j \times \text{sgn}(imag(Z_k)) \tag{9}$$

where Z_k is the Chu sequence which is given by

$$Z_k = \exp\left(\frac{\pi \times u \times n(n + \mathrm{mod}(L, 2))}{L}\right) \quad n = 0, 1, 2, \ldots, L \tag{10}$$

where sgn(x) is equal to 1 when $x > 0$ and is equal to -1 otherwise, u and L are prime integers, and L is the length of the sequence. This polyphase to quadriphase transformation offers a relatively flat frequency spectrum [shown in Fig. 2(b)] that is slightly worse than that of the ideal Chu sequence, which has a flat spectrum.

For 16-QAM systems, we propose the design of Chu-based 16-QAM sequence (16-QAM Chu) by modifying the method used to generate the Q-Chu sequence. The original Chu sequence is passed through an 8-PSK slicer with a design similar to the QPSK slicer above. After the polyphases to eight-phase transformation, an 8-PSK Chu sequence is obtained. The 8-PSK sequence is then adjusted to fill in the square 16-QAM constellation in order to form the final Chu-based 16-QAM sequence. The process of transforming a Chu sequence to a 16-QAM Chu sequence is shown in Fig. 3(a), while Fig. 3(b) shows the frequency spectrum of the 16-QAM Chu sequence compared with the Q-Chu sequence, and it can be seen that the 16-QAM Chu sequence has slightly better frequency spectrum compared with the Q-Chu sequence.

3.2. Golay Sequences

Golay sequences are pairs of "a" and "b" sequences that satisfy Golay property [14] such that: let $xcorr(a[n])$ denotes the autocorrelation function of sequence $a[n]$, then

$$xcorr(a[n]) + xcorr(b[n]) = 2L\delta(n) \tag{11}$$

where $\delta(n)$ is the Dirac delta function, and L is the sequence length.

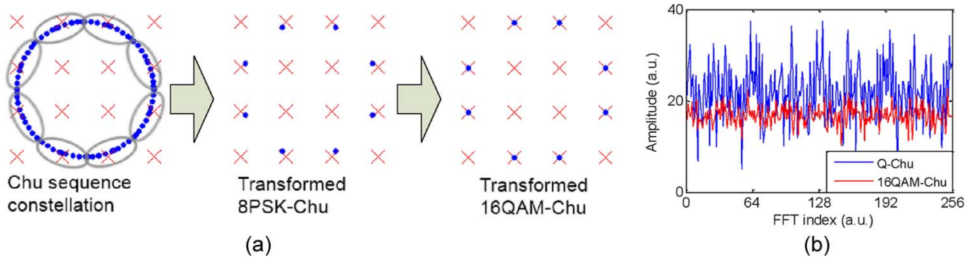


Fig. 3. (a) Generation of 16-QAM Chu sequences and (b) frequency spectrum of Q-Chu and 16-QAM Chu sequences.

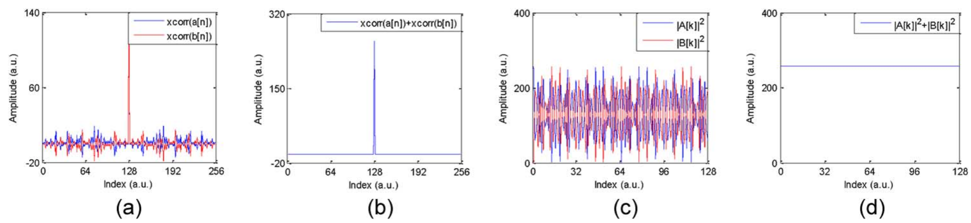


Fig. 4. (a) Autocorrelation of Golay "*a*" and "*b*" sequence. (b) Sum of their autocorrelation. (c) Power spectrum of Golay "*a*" and "*b*" sequence. (d) Sum of their power spectrum.

Equation (11) illustrates that the sum of the autocorrelation of "*a*" and "*b*" is an impulse as shown in Fig. 4(a) and (b). By taking the DFT of (11), Golay property can be derived in frequency domain as having complementary power spectra

$$|A[k]|^2+|B[k]|^2=2L \tag{12}$$

where $A[k]$ and $B[k]$ are the fast Fourier transforms (FFTs) of $a[n]$ and $b[n]$.

As shown in Fig. 4(c) and (d), the combination of the DFTs of "*a*" and "*b*" sequences results in a linear flat spectrum in frequency domain.

Golay sequences are orthogonal to each other and can be generated recursively using "seed sequences" that satisfy Golay property [14], and the constellation of the total sequence only depends on the seed sequences. We also notice that Golay sequences "*a*" and "*b*" are orthogonal to each other and can be fitted into the transmission matrix as follows:

$$S[k]=\begin{pmatrix} S_1[k] & -S_1^*[k] \\ S_2[k] & S_2^*[k] \end{pmatrix}=\begin{pmatrix} A[k] & -B^*[k] \\ B[k] & A^*[k] \end{pmatrix}. \tag{13}$$

The use of complex conjugate indicates the need for complex-valued sequences, while it can also be seen that systems with QPSK, 16-QAM, or higher order modulation formats will benefit from training signal that fits the modulated data constellation. Thus, instead of using real-valued binary phase-shift keying (BPSK) seed sequences [14], [15], we propose the use of complementary QPSK seed sequences: $a[n]=[1+j\ 1-j]$ and $b[n]=[1+j\ -1+j]$. It can be easily shown that the two seed sequences satisfy Golay property and sequences of 2^n length can be generated using the recursive construction method.

For 16-QAM systems, seed 16-QAM Golay sequences can be constructed from seed QPSK sequences as [15]

$$s[n]=2a[n]+b[n] \qquad \text{and} \qquad t[n]=-2b[n]+a[n] \tag{14}$$

where $s[n]$ and $t[n]$ are the 16-QAM Golay pair, and $a[n]$ and $b[n]$ are the QPSK Golay pair, respectively. The constellation of the original QPSK Golay sequences and normalized 16-QAM Golay sequences is shown in Fig. 5, and it can be seen that both the QPSK and 16-QAM Golay

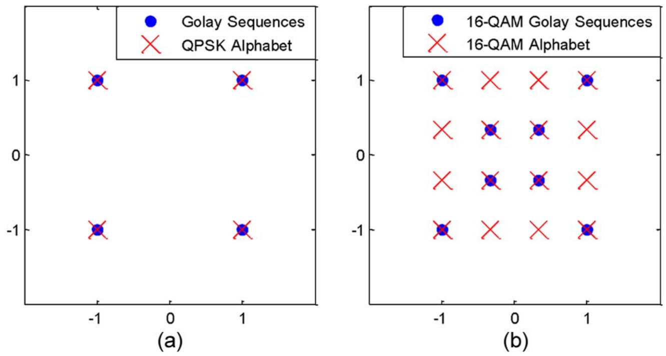


Fig. 5. Constellation of (a) QPSK Golay sequences and (b) 16-QAM Golay sequences.

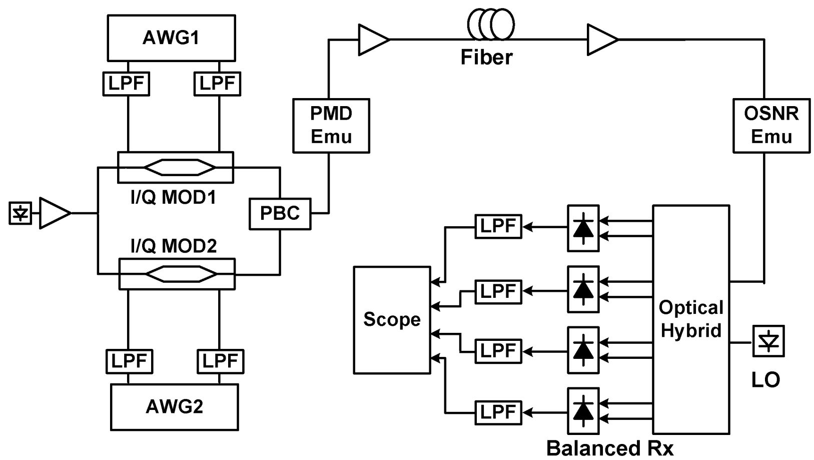


Fig. 6. Simulation setup.

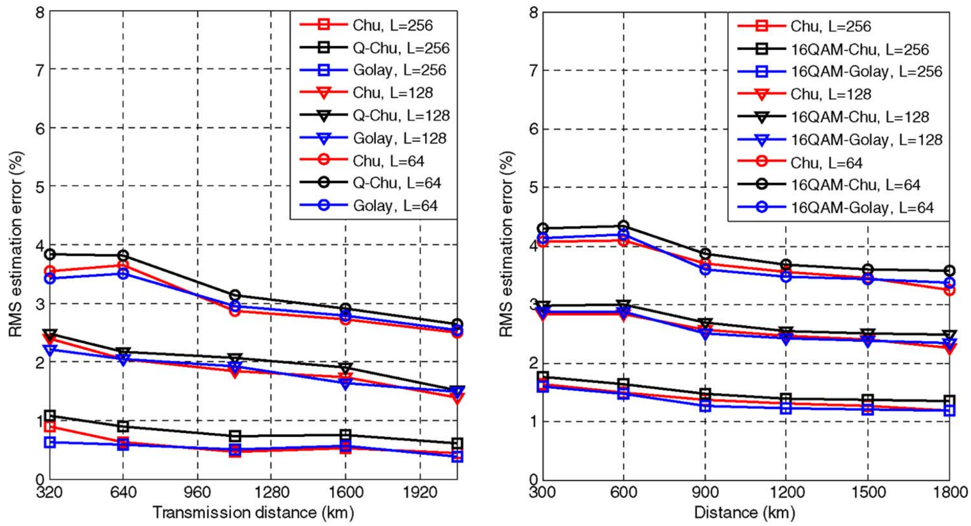
sequences fit their corresponding constellations. It is also clear from (14) that the 16-QAM Golay sequences have average power similar to that of a 16-QAM data signal.

4. Experimental and Simulation Demonstrations

4.1. Simulation Results

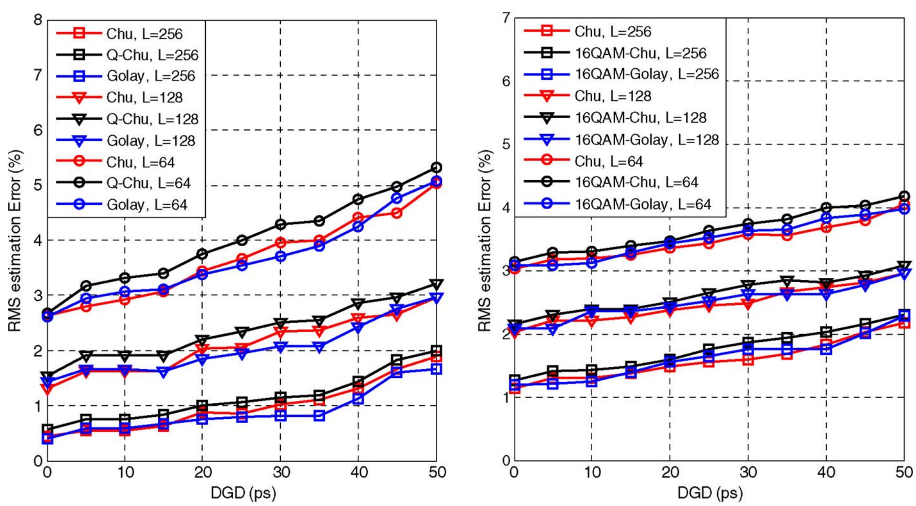
Simulations are carried out with *VPI TransmissionMaker* 8.6, and the simulation setup is shown in Fig. 6. Training sequences are sent through the arbitrary waveform generator (AWG) model to convert data into electrical signal and then to I/Q modulators to convert into optical signal. Data on X- and Y-polarization are then combined using polarization beam combiner (PBC). As described in (8), a sequence length of only 64 symbols is required for 2000-km transmission, and we also use longer length of 128 symbols and 256 symbols to investigate performance comparison. Fiber model consists of multiple spans of fiber with amplifiers to compensate for fiber loss. A second-order PMD emulator and optical-signal-to-noise ratio (OSNR) emulator are added at the beginning and end of the fiber model to investigate the estimation performance against various levels of PMD and OSNR.

Fig. 7(a) shows the estimation performance in root-mean-square (RMS) error percentage for different transmission distances with no PMD at an OSNR value of 26 dB for the QPSK system for all three types of sequence (Chu, Q-Chu, and Golay) with different sequence lengths L. It can be seen that the Golay sequences perform similarly to the Chu sequence for all transmission distances and both achieve high accuracy with low error percentage, while the Q-Chu sequence has slightly worse performance. Also, it can be seen that the error percentage decreases as the transmission



(a) (b)

Fig. 7. RMS error at different fiber length for (a) QPSK system and (b) 16-QAM system.



(a) (b)

Fig. 8. RMS error against PMD for (a) QPSK system and (b) 16-QAM system.

distance increases since the total CD increases linearly with distance but the estimation error does not, which, in most cases, results in slightly higher accuracy at longer distances. Finally, longer sequence improves the estimation performance since this increases the resolution of the estimated channel information and provides the quadratic interpolation with more data for more accurate results. Results for the 16-QAM system are shown in Fig. 7(b) with similar trends compared with the QPSK system but with slightly higher overall error since, compared with the QPSK systems, the 16-QAM system has been scaled down to fit inside the modulator range. Also, since the 16-QAM Chu sequence has a much improved frequency spectrum, performance gap among the 16-QAM Chu, Golay, and ideal Chu sequences is smaller. Simulation results for both QPSK and 16-QAM systems show that both Golay and quantized-Chu sequences attain similar estimation performances compared with the ideal Chu sequence.

Fig. 8(a) shows the CD estimation error for the QPSK system using Chu, Q-Chu, and Golay sequences at 2080-km transmission against different PMD values [represented by mean differential

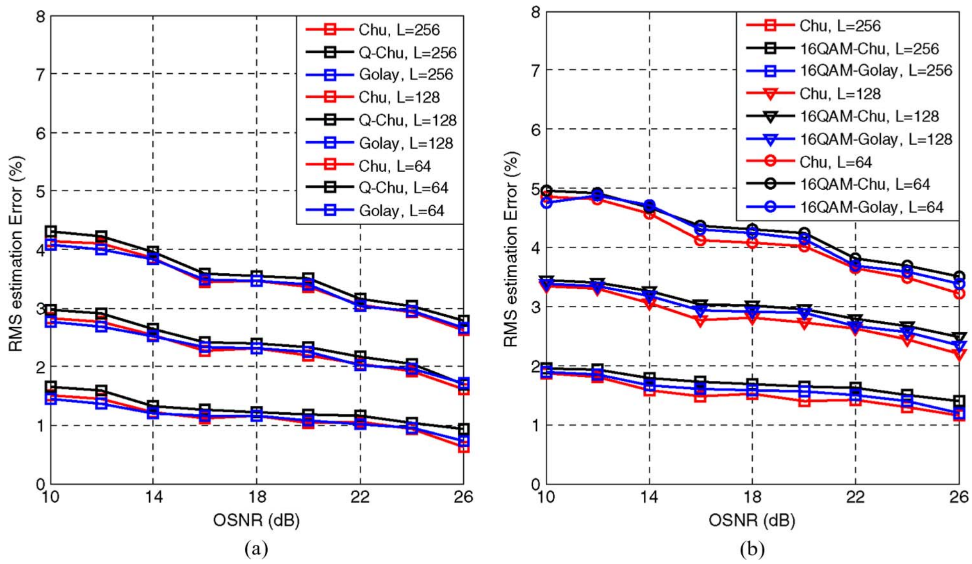


Fig. 9. RMS error against OSNR for (a) QPSK system and (b) 16-QAM system.

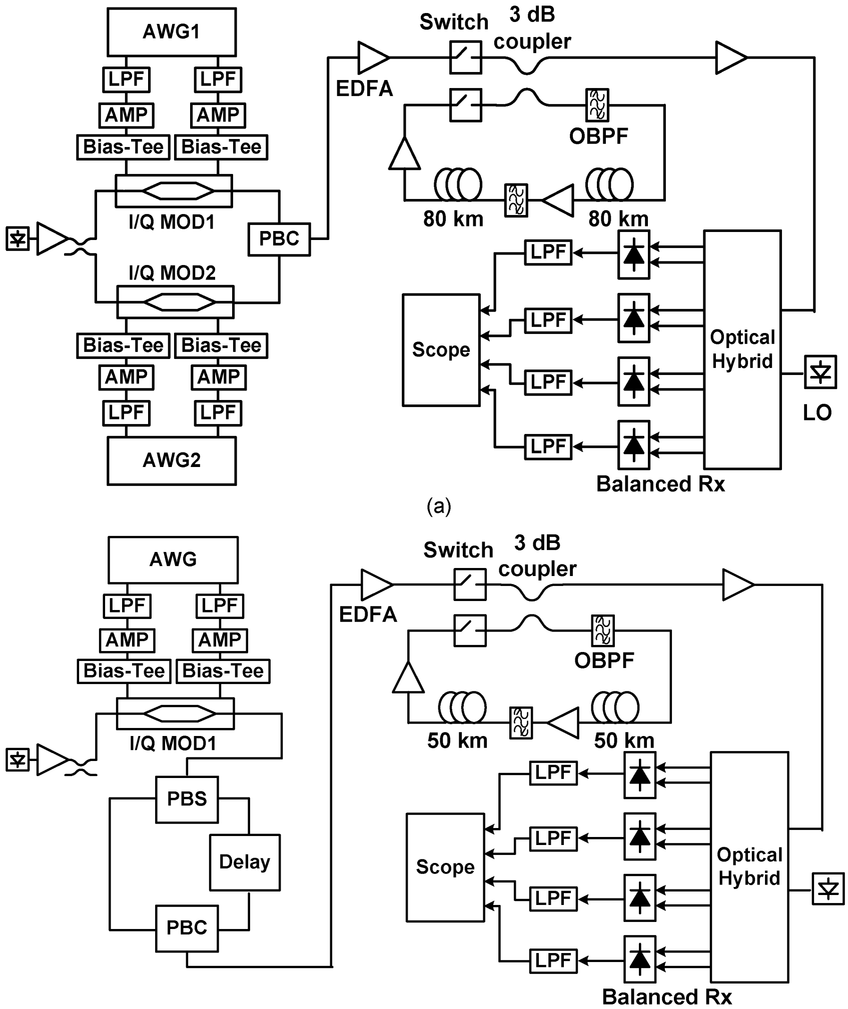
group delay (DGD)] using the PMD emulator with second-order PMD. It can be seen that, with the addition of PMD, the estimation performance degrades slightly at very high DGD values and overall still achieves very high accuracy of less than 5.5% RMS error. Sequences with longer symbol length L have better performance and are slightly more robust against higher PMD values. In all cases, both the Chu and Golay sequences perform similarly. The Q-Chu sequences have slightly worse performance but still within 0.5% error of the Chu sequence. Overall, DGD does not have a significant impact on the estimation error. Results for the 16-QAM system are shown in Fig. 8(b) for Chu, 16-QAM Chu, and 16-QAM Golay sequences, and similar trends can be observed compared with those of the QPSK system.

Fig. 9 shows simulation results for CD estimation performance against different levels of OSNR for both QPSK and 16-QAM systems using the proposed training sequences. It can be seen that lower OSNR has slightly negative impact on the estimation performance. Longer sequences are slightly more robust against low level of OSNR, and thus, for full-channel CD estimation, choosing a longer sequence than required improves the overall performance.

Overall, it can be seen that the CD estimation performance using the proposed Golay and Chu-based training sequences is accurate and comparable with the ideal Chu sequence for both QPSK and 16-QAM systems. The use of longer sequences improves the estimation performance in all cases compared with the shorter sequences as expected for estimation using interpolation such as quadratic fit. While the constellation of the Chu sequence becomes much more complex at longer length, all other sequences have length-independent constellation and can be generated at longer length using QPSK/16-QAM system modulator. It can also be seen that both PMD and OSNR slightly affect the system performance, but the estimation is still accurate. Using the minimum required sequence length of 64 symbols results in the RMS estimation error around 5%, while increasing the length to 256 symbols reduces the estimation error to less than 2% for both QPSK and 16-QAM systems.

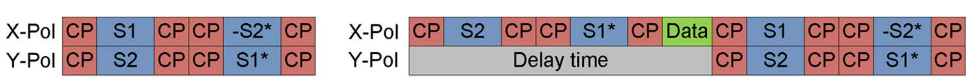
4.2. Experimental Demonstration

Fig. 10(a) shows the experimental setup to demonstrate the CD estimation technique using the proposed training sequences for the QPSK system. The training sequences are generated by two AWGs at 10 Gsymbol/s. Chu- and Q-Chu-sequence pair are generated using shift orthogonal method, and Golay sequences are generated using recursive construction and QPSK seed pairs. While sequences with minimal length of 64 symbols are required from (8), each training sequence in



(b)

Fig. 10. Experimental setup for (a) QPSK system and (b) 16-QAM system.



(a) (b)

Fig. 11. Structure of training frame for (a) QPSK system and (b) 16-QAM system.

the experimental demonstration has been chosen to have length $L = 256$ symbols in order to enhance the estimation accuracy with cyclic prefix (CP) $N_{cp} = 64$ as shown in Fig. 11(a). The sequences are then modulated and polarization multiplexed through the PBC. A 160-km-long recirculating loop with standard single-mode fiber (SSMF) is used as a fiber channel with loop timing determining the total transmission length. For 16-QAM experiments, due to the unavailability of the original setup, the transmitter side consists of only one AWG to generate data on X-polarization and a delay line to emulate the Y-polarization with delay time of 27.2 ns, as shown in Fig. 10(b). The recirculating loop is 100 km long, and due to the different setup, the structure of the training sequences is modified and shown in Fig. 11(b) for the 16-QAM system. The receiver setup for both QPSK and 16-QAM systems is the same, where the signals are first filtered by an optical bandpass filter (OBPF) before being fed into an optical hybrid followed by 18-GHz balanced receivers. The signals are then captured in a 20-GHz 50-Gsamples/s oscilloscope for offline processing.

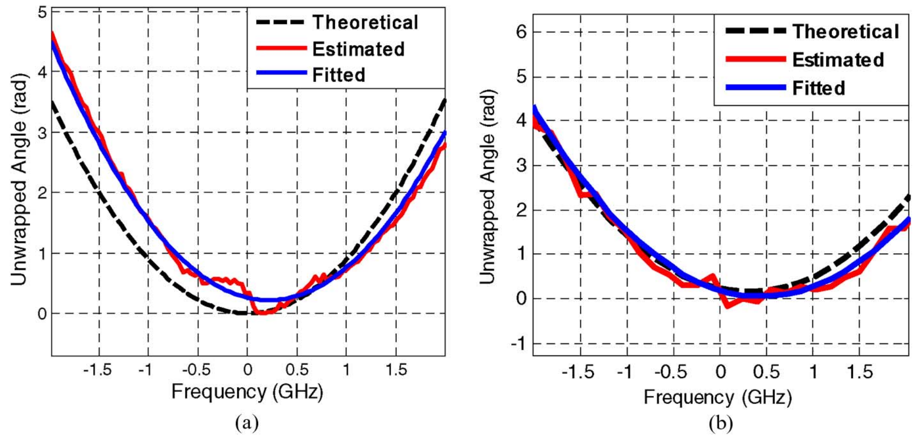


Fig. 12. CD estimation phase curves for (a) 40-Gb/s QPSK system after 2080 km and (b) 80-Gb/s 16-QAM system after 1800 km.

TABLE 1

Experimental results summary for QPSK system

Distance (km)	Real CD (ps/nm)	RMS error % (Golay)	RMS error % (Chu)	RMS error % (Q-Chu)	RMS error % (Random)
320	5376	0.4	1.5	1.7	1.2
640	10752	1.2	1.0	1.3	0.9
1120	18816	0.9	0.9	1.0	14.0
1600	26880	0.5	0.6	0.8	5.5
2080	34944	0.9	0.7	1.1	8.0

Both frequency offset compensation and timing synchronization are carried out by data-aided algorithm [16]. After frequency offset compensation and timing synchronization, CD transfer function is estimated using the method described in Section 2. The phase responses of the CD transfer function are shown in Fig. 12(a) for QPSK 2080-km transmission and Fig. 12(b) for 16-QAM 1800-km transmission, respectively, with the red curve being the extracted estimated phase response, the black curve being the theoretical value, and the blue curve being the least square quadratic fit. It can be seen that both the estimated- and quadratic-fit CD curves are shifted due to extra impairments in the systems. However, the CD estimate is extracted from the curvature of the phase plots and is immune to this shift.

Experimental results for QPSK system transmission are summarized in Table 1, which shows highly accurate estimation with low RMS error percentage with a maximum error of 1.5% for the Chu sequence and 1.2% for the Golay sequences, while it can also be seen that the Q-Chu sequence has slightly worse performance with maximum error of 1.7%. The real CD parameter for the fiber is measured using the baseband amplitude-modulation (AM) response method in [17] and is found to be 16.8 ps/(nm · km) with 0.1% accuracy. When random QPSK data sequences are used as training sequences, we obtain significant higher estimation error at long distances.

Fig. 13 shows the estimation error percentage using the Chu, Q-Chu, and Golay sequences at different transmission fiber lengths, while results using random QPSK sequence are omitted due to having much higher error (above 5% for transmission distance beyond 640 km). It can be seen that the Golay sequences achieve very similar performance compared with the full-level Chu sequence, whereas the Q-Chu sequence has slightly worse performance. However, the performance of the Q-Chu sequence is still within 0.5% error of the ideal Chu sequence. Overall, experimental results for QPSK systems are consistent with the simulation results presented in Section 4.1.

For 16-QAM system experiments, due to the unavailability of a second AWG, data on the Y-polarization are emulated by delaying data on the X-polarization with a delay time of 27.2 ns, which

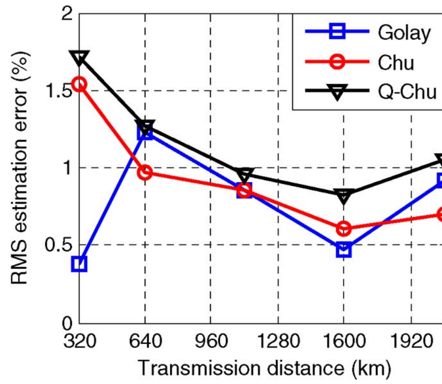


Fig. 13. RMS estimation error at different transmission distances for QPSK systems.

TABLE 2

Experimental results summary for 16-QAM system with $L = 128$

Distance (km)	Real CD (ps/nm)	RMS error % (16QAM-Golay)	RMS error % (Chu)	RMS error % (16QAM-Chu)
300	4800	2.76	2.96	2.65
600	9600	2.90	2.80	2.91
900	14400	2.84	3.04	3.05
1200	19200	2.70	2.64	2.60
1500	24000	2.60	2.47	2.79
1800	28800	2.63	2.80	2.74

TABLE 3

Experimental results summary for 16-QAM system with $L = 64$

Distance (km)	Real CD (ps/nm)	RMS error % (16QAM-Golay)	RMS error % (Chu)	RMS error % (16QAM-Chu)
300	4800	4.35	4.25	4.46
600	9600	4.15	4.15	4.45
900	14400	4.29	4.01	4.25
1200	19200	4.20	4.25	4.4
1500	24000	3.96	4.28	4.36
1800	28800	4.05	3.98	4.05

corresponds to 272 symbols for our 10-Gbaud systems. This delay time setup limits the maximum length of the training sequences to 128 symbols per sequence. While this length is enough for channel memory requirements according to Equation (8) and as shown in the simulation, the estimation performance is less accurate compared with using 256-symbol sequences. Tables 2 and 3 shows the experimental results for the 16-QAM system with both sequence lengths of $L = 128$ and $L = 64$, respectively. The CD parameter of the fiber used in this experiment had been independently measured using the method in [17] to be 16 ps/(nm · km) with 0.1% accuracy.

Table 2 shows the estimation error for the 16-QAM system using Chu, 16-QAM Golay, and 16QAM-Chu sequences with $L = 128$ and it can be seen that maximum error for these sequences are 3%, 2.9%, and 3%, respectively. For $L = 64$, maximum errors for Chu, 16-QAM Golay, and 16-QAM Chu sequences are 4.3%, 4.4%, and 4.5%, respectively. Fig. 14 shows the combined data from Tables 2 and 3, and it can be seen that all three types of sequences perform very similarly to each other, and the maximum errors are consistent with the simulation results. While 256-symbol sequences are not used, the relationship between sequence length and their performance for 128-symbol and 64-symbol sequences is verified and is consistent with the simulation results.

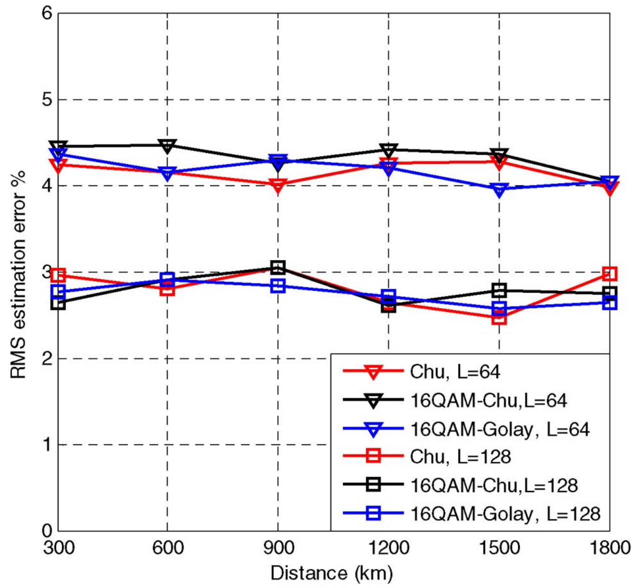


Fig. 14. Estimation performance of Golay, 16-QAM Golay, Chu and 16-QAM Chu sequences for 16-QAM system.

Overall, it can be seen that, for both QPSK and 16-QAM systems, Golay pairs and Chu-based sequences provide very similar performance compared with the ideal Chu sequence, while offering advantage of length-independent constellation, which makes them suitable for large CD estimation using data-aided channel estimation aided by quadratic-fit curve interpolation.

5. Conclusion

We have proposed a new CD estimation technique using training sequences and a quadratic fit to the phase response. The use of long binary sequences enables full transmission link CD estimation, while it can also be seen that the proposed Golay and Chu-based sequences perform similarly to the ideal multilevel Chu sequence. Moreover, both the Golay sequences and Chu-based sequences can be customized in QPSK and 16-QAM format, which allows easy integration into commercial 100-Gb/s QPSK system and also those that employ higher order modulators. Through simulation, we confirm that the proposed CD estimation method is robust against various levels of PMD and OSNR, and longer sequences give more accurate results. The combined techniques are experimentally demonstrated through 40-Gb/s coherent PolMux QPSK system for up to 2080-km transmission distance and 80-Gb/s PolMux 16-QAM system for up to 1800-km distance to achieve highly accurate CD estimation.

References

[1] M. Kuschnerov, F. N. Hause, K. Piyawanno, B. Spinnler, M. S. Alfiad, A. Napoli, and B. Lankl, "DSP for coherent single-carrier receivers," *J. Lightwave Technol.*, vol. 27, no. 16, pp. 3614–3622, Aug. 2009.

[2] F. N. Hauske, Y. Ye, I. T. Monroy, F. Pittala, and N. G. Gonzalez, "Combined CD and DGD monitoring based on data-aided channel estimation," presented at the Signal Proc. in Photon. Comm., Toronto, Canada, 2011, Paper SPTuC3.

[3] F. Pittala, F. N. Hauske, Y. Yabin, N. G. Gonzalez, and I. T. Monroy, "Fast and robust CD and DGD estimation based on data-aided channel estimation," in *Proc. ICTON*, Jun. 26–30, 2011, pp. 1–4.

[4] M. Kuschnerov, M. Chouayakh, K. Piyawanno, B. Spinnler, E. de Man, P. Kainzmaier, M. S. Alfiad, A. Napoli, and B. Lankl, "Data-aided versus blind single-carrier coherent receivers," *IEEE Photon. J.*, vol. 2, no. 3, pp. 386–403, Jun. 2010.

[5] C. C. Do, C. Zhu, A. V. Tran, S. Chen, T. Anderson, D. Hewitt, and E. Skafidas, "Chromatic dispersion estimation in 40 Gb/s coherent polarization-multiplexed single carrier system using complementary Golay sequences," presented at the Proc. OFC, Los Angeles, CA, 2012, Paper OW4G.1.

[6] C. Do, A. V. Tran, and D. F. Hewitt, "Chromatic dispersion estimation based on complementary Golay sequences for 80 Gb/s QPSK single-carrier system with frequency domain equalization," in *Proc. ATNAC*, Jun. 2011, pp. 1–4.

[7] Y. Han and G. Li, "Coherent optical communication using polarization multiple-input-multiple-output," *Opt. Exp.*, vol. 13, no. 19, pp. 7527–7534, Sep. 2005.

[8] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[9] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space–time block codes from orthogonal designs," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999.

[10] J. C. Geyer, F. N. Hauske, C. R. S. Fludger, T. Duthel, C. Schulien, M. Kuschnerov, K. Piyawanno, D. van den Borne, E.-D. Schmidt, B. Spinnler, H. de Waardt, B. Lankl, and B. Schmauss, "Channel parameter estimation for polarization diverse coherent receivers," *IEEE Photon. Technol. Lett.*, vol. 20, no. 10, pp. 776–778, May 2008.

[11] R. A. Soriano, "Chromatic dispersion estimation in digital coherent receivers," *J. Lightwave Technol.*, vol. 29, no. 11, pp. 1627–1637, Jun. 2011.

[12] S. Savory, "Compensation of fiber impairments in digital coherent systems," in *Proc. ECOC*, 2008, pp. 1–4.

[13] D. Chu, "Polyphase codes with good periodic correlation properties," *IEEE Trans. Inf. Theory*, vol. IT-18, pp. 531–532, Jul. 1972.

[14] M. Golay, "Complementary series," *IRE Trans. Inf. Theory*, vol. IT-7, no. 2, pp. 82–87, Apr. 1961.

[15] C. Chong and V. Tarokh, "Two construction of 16-QAM Golay complementary sequences," in *Proc. IEEE ISIT*, 2002, p. 240.

[16] H. Minn, V. Bhargava, and K. Letaief, "A robust timing and frequency synchronization for OFDM systems," *IEEE Trans Wireless Commun.*, vol. 2, no. 4, pp. 822–839, Jul. 2003.

[17] D. Derickson, *Fiber Optic Test and Measurement*. Englewood Cliffs, NJ: Prentice-Hall, 1998, pp. 486–487.