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Nyquist WDM superchannel using offset-16QAM and receiver-side digital spectral shaping

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Abstract: The performance of Nyquist WDM superchannel using advanced modulation formats with coherent detection is degraded due to the existence of both inter-symbol interference (ISI) and inter-channel interference (ICI). Here, we propose and numerically investigate a Nyquist WDM superchannel using offset-16QAM and receiver-side digital spectral shaping (RS-DSS), achieving a spectral efficiency up to 7.44 bit/s/Hz with 7% hard-decision forward error correction (HD-FEC) overhead. Compared with Nyquist WDM superchannel using 16QAM and RS-DSS, the proposed system has 1.4 dB improvement of required OSNR at BER = 10−3 in the case of back-to-back (B2B) transmission. Furthermore, the range of launched optical power allowed beyond HD-FEC threshold is drastically increased from −6 dBm to 1.2 dBm, after 960 km SSMF transmission with EDFA-only. In particular, no more than 1.8 dB required OSNR penalty at BER = 10−3 is achieved for the proposed system even with the phase difference between channels varying from 0 to 360 degree.

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References and links
1. Introduction

The ever increasing bandwidth demand has driven fiber-optic communication system to target higher spectral efficiency (SE) transmission. In order to achieve higher SE, three major competitive technologies for forming spectrally-efficient wavelength division multiplexing (WDM) superchannels have been proposed so far instead of increasing serial interface rate [1]. One is the orthogonal frequency-division multiplexing (OFDM) technique [1–3], where frequency domain sinc-like subcarriers are spaced exactly at the symbol rate to obtain high SE. Another one is referred to Nyquist-WDM, which requires an ideal rectangular shaped spectrum with bandwidth equal to the symbol rate [4–6]. The last one is offset quadrature amplitude modulation (OQAM) based WDM superchannel with channel spacing equal to the symbol rate, where the tolerance of inter-channel interference (ICI) is improved by offsetting the in-phase and quadrature components of QAM-based carrier with half symbol period and controlling the phase difference (ΔΦ) between individual wavelength channels equal to either 90 or 270 degree [7–10]. For the OQAM based WDM superchannel, the deviation of optimal phase difference leads to severe performance degradation, and error-free transmission is impossible for offset-16QAM based WDM (16-OQAM-WDM) superchannel in case the deviation of phase difference from its optimal value is more than 60 degree [10]. Consequently, sensitivity of phase difference for the OQAM based WDM superchannel hinders its practical implementation due to the random environment perturbations, although such technique can relax the stringent requirements on devices and shows performance improvement with respect to that of OFDM and Nyquist-WDM. Recently, a practical receiver-side digital spectral shaping wavelength division multiplexing technique (RS-DSS WDM) has been proposed to build up multi-carrier superchannels as a supplementary to Nyquist-WDM [11–15]. In such superchannel, the RS-DSS technique can relax the stringent requirements on the transmitter-side filter, and permits the use of the conventional optical components. After receiver-side spectral shaping, the maximum likelihood sequence detection (MLSD) is applied to detect the shaped signal with optimum performance. It is well known that 16QAM exhibits low tolerance to the linear crosstalk. Consequently, RS-DSS WDM
superchannel suffers from large performance degradation using 16QAM with narrow channel spacing, due to the co-existence of both inter-symbol interference (ISI) and ICI, especially when the channel spacing is reduced to the symbol rate. Therefore, the symbol rate is commonly set below the channel spacing for 16QAM based RS-DSS WDM superchannel to avoid significant ISI and ICI, which is defined as quasi-Nyquist WDM [13, 15].

In this paper, we propose a Nyquist WDM superchannel using offset-16QAM and RS-DSS. The generation and transmission of 3-carrier 672 Gbit/s superchannel is numerically demonstrated with 28 GHz channel spacing over 12 × 80 km standard single-mode fiber (SSMF) with Erbium-doped fiber amplifiers (EDFAs) only, indicating a SE up to 7.44 bit/s/Hz assuming 7% hard-decision forward error correction (HD-FEC) overhead. Performance comparison between 16QAM based RS-DSS Nyquist WDM superchannel and the proposed Nyquist WDM superchannel is comprehensively investigated and significant performance improvement is secured. Furthermore, good tolerance of phase difference deviation is also achieved for our proposed Nyquist WDM superchannel, indicating of the potential towards practical implementation.

2. System configuration and offline DSP flow

System configuration of 16QAM based RS-DSS WDM superchannel together with digital signal processing (DSP) flow is schematically shown in Fig. 1(a). The multi-carrier is obtained from an optical comb generator (OCG). The linewidth of each carrier from OCG is 10 kHz. The signal data trains consist of 28 Gbit/s 2^{17}-1 pseudo-random binary sequences (PRBS) and differential coding is used to solve the phase ambiguity problem. These logic data trains are used to generate 4-level electrical signals. Then 3 carriers are, respectively, introduced to three parallel IQ modulators driven by these 4-level electrical signals. Polarization multiplexing is achieved through adding a delay of 180 symbols between two polarization tributaries. Then, each carrier is filtered by a 4th-order Gaussian optical filter, whose response is available in commercial products, in order to shape the optical spectrum for the purpose of achieving a trade-off between ICI and ISI. After spectrum shaping, all the carriers are launched into the 12 × 80 km EDFA-only SSMF link with launched optical power controlled by a variable optical attenuator (VOA). At the receiver-side, amplified spontaneous emission (ASE) noise loading is used to adjust the optical signal-to-noise-ratio (OSNR) for the back-to-back (B2B) measurement. Then, the signals are electrically amplified after the polarization-diverse and phase-diverse coherent detection. After amplification, four 5th electrical Bessel filters with 3dB bandwidth of 21GHz are applied to suppress the out-of-band noise. Finally, the received analog signals are sampled by ADCs with two samples per symbol and feed into the offline DSP module. The offline DSP flow is firstly started with I/Q imbalance compensation [16]. The electronic dispersion compensation (EDC) is next performed to compensate the accumulated dispersion in the SSMF link [16]. The adaptive equalization and polarization demultiplexing are performed by four butterfly L-tap T/2-spaced finite impulse-response (FIR) filters. These FIR filters are first adapted by the standard constant modulus algorithm (CMA) for pre-convergence. Final equalization is done by switching CMA to decision-directed least-mean-square (DD-LMS) algorithm. In the DD-LMS loop, the carrier recovery includes frequency offset compensation (FOC) using the fast Fourier transform (FFT) method [17] and the carrier phase recovery (CPR) using the blind phase search (BPS) method [18]. Instead of using hard decision after CPR, a simple two-tap FIR filter with a transfer function \( H(z) = 1 + \alpha z^{-1} \) is applied to each of the four quadrature components for post-filtering, where \( \alpha \) with a range of 0 to 1 is chosen as an optimized parameter [15]. Symbol decision is finally done by a 4-state MLSD algorithm with 16 branches. Note that no channel estimation after post-filtering is required for the implementation of MLSD [12–14]. As we can see, the post-filtering and MLSD can be easily
switched to hard decision by setting $\alpha$ equal to zero since no spectral shaping is done and the MLSD does not have any memory to use.

System configuration of offset-16QAM based RS-DSS WDM superchannel together with DSP flow is schematically shown in Fig. 1(b). The system configuration has two differences. First, there is half symbol period ($T_s/2$) delay between in-phase and quadrature tributaries before electronic-to-optical conversion. Secondly, the modulated carriers are phase shifted by $\Phi_k = (k-1) \times \Delta \Phi \ (k = 1, 2, 3)$ before transmitter-side spectrum shaping. Especially, $\Delta \Phi$ equaling to 90 degree is indispensable for optimal performance. The offline DSP flow is firstly started with I/Q imbalance compensation, followed by EDC to compensate for the accumulated dispersion in the fiber link. Then, a butterfly $T/2$ spaced finite impulse response (FIR) filters with only 1 tap is adapted to implement the CMA algorithm for the purpose of polarization demultiplexing [19], which is followed by the same FOC method. Next, the adaptive equalization is performed by four butterfly $L$-tap $T/2$-spaced finite impulse response (FIR) filters using modified LMS (M-LMS) algorithm for the sequences after FOC. The received signal after adaptive equalization at each polarization is obtained, as shown in Eqs. (1) and (2).

$$Z_x(k) = \Re\{ [S_{xx}(k)S_{yx}(k)]^T [W_{xx}(k)W_{xy}(k)] + j\Im\{ [S_{xx}(k)S_{yx}(k)]^T [W_{xx}(k)W_{xy}(k)] \} \} \tag{1}$$

$$Z_y(k) = \Re\{ [S_{yx}(k)S_{yy}(k)]^T [W_{yx}(k)W_{yy}(k)] + j\Im\{ [S_{yx}(k)S_{yy}(k)]^T [W_{yx}(k)W_{yy}(k)] \} \} \tag{2}$$

where $W_{xx}, W_{xy}, W_{yx}, W_{yy}$ are adaptive filters, $S_{xy} \ (M = X, Y; N = O, Y)$ represents the $L$ element vectors of the sequences after FOC. Subscript $M$ indicates the vector’s polarization state ($X/Y$ polarization). Subscript $N$ indicates vectors come with an odd ($N = O$) or an even ($N = E$) sample. There is one sample delay between $S_{xx}$ and $S_{yy}$. And the adaptive filters are updated according to Eqs. (3)–(6).

$$W_{xx}(k+1) = W_{xx}(k) + \mu [\Re\{e_x\} S_{xx}(k) + j\Im\{e_x\} S_{xy}(k)] \tag{3}$$

$$W_{xy}(k+1) = W_{xy}(k) + \mu [\Re\{e_x\} S_{xy}(k) + j\Im\{e_x\} S_{yy}(k)] \tag{4}$$

$$W_{yx}(k+1) = W_{yx}(k) + \mu [\Re\{e_y\} S_{yx}(k) + j\Im\{e_y\} S_{yy}(k)] \tag{5}$$

$$W_{yy}(k+1) = W_{yy}(k) + \mu [\Re\{e_y\} S_{yy}(k) + j\Im\{e_y\} S_{yx}(k)] \tag{6}$$
Where $e_x = d_x - Z_x$ and $e_y = d_y - Z_y$ is the constellation error with $d_x$ and $d_y$ being the symbols closest to $Z_x$ and $Z_y$, respectively. $\mu$ is the update coefficient. As we can see that the Ts/2 offset between in-phase and quadrature components can be eliminated during adaptive equalization [8]. The carrier phase is recovered based on the BPS method. After CPR, two-tap FIR filters with a transfer function $H(z) = 1 + \alpha z^{-1}$ is applied to each of the four quadrature components for post-filtering, which is followed by the symbol decision based on MLSD algorithm.

3. Simulation results and discussions

As shown in Fig. 1, numerical simulations are carried out with a 3-carrier setup, where the central carrier is chosen under investigation because of severe ICI an ISI in the central channel. 3 carriers out of an OCG based on external modulation technique are chosen as multi-carrier optical source at the transmitter-side [20]. Both the M-LMS equalization for the proposed WDM superchannel and CMA plus DD-LMS equalization for 16QAM based RS-DSS WDM superchannel are deployed with 21-tap $T/2$-spaced FIR filters. The FFT-size used in FOC is 8192 and the block size for BPS based CPR with 64 test angles is 100 in all cases of both superchannels for the ease of discussion.

3.1 Effect of channel spacing

![Fig. 2. Required OSNR at BER = $10^{-3}$ with respect to the channel spacing. The transmitter-side optical filter bandwidth is optimized to maximize the performance for each channel spacing.](image)

The relationship between required OSNR to achieve the target of BER = $10^{-3}$ with respect to the channel spacing is shown in Fig. 2, under the scenario of B2B transmission. When the channel spacing is large than the symbol rate, namely the quasi-Nyquist WDM, both WDM superchannels suffer from performance degradation with gradually reduced channel spacing. In particular, the 16QAM based RS-DSS WDM superchannel outperforms over proposed offset-16QAM based RS-DSS WDM superchannel. When the channel spacing is equal to the symbol rate, namely the Nyquist WDM, the worst performance is achieved for 16QAM based RS-DSS WDM superchannel. However, the best performance is obtained for our proposed WDM superchannel due to nearly free ICI, by offsetting the in-phase and quadrature components of QAM-based carrier with half symbol period and controlling the phase difference between individual wavelength channels equal to 90 degree [8–10]. It is found that error-free transmission cannot be obtained for both WDM superchannels, because of
occurrence of severe ICI when the channel spacing is smaller than the symbol rate. Therefore, we only focus on the channel spacing equal to the symbol rate of 28 GHz in the following discussions, defined as Nyquist WDM superchannel.

3.2 Effect of transmitter-side optical filter bandwidth

![Graph](image.png)

Fig. 3. Required OSNR at BER = 10^{-3} with respect to the transmitter-side optical filter bandwidth.

We then investigate the impact of transmitter-side optical filter bandwidth (Opt-BW) on the proposed Nyquist WDM superchannel and 16QAM based RS-DSS Nyquist WDM superchannel. The performance is also evaluated in terms of required OSNR to achieve the target of BER = 10^{-3} under the scenario of B2B transmission. The Opt-BW is swept from 23 GHz to 34 GHz and the result is summarized in Fig. 3. As for the 16QAM based RS-DSS Nyquist WDM superchannel, narrow Opt-BW causes severe ISI, while wide Opt-BW over channel spacing introduces large amount of ICI due to the spectrum overlapping. In particular, when the Opt-BW is larger than 30 GHz, error free transmission cannot be obtained due to the diverging CMA-based adaptive equalizers in the presence of severe ICI. The optimal Opt-BW occurs around 25 GHz because of the compromise between the ICI and the ISI. However, in term of our proposed Nyquist WDM superchannel using offset-16QAM and RS-DSS, the system performance is mainly limited by narrow Opt-BW induced ISI, because the system is nearly ICI free even with severe spectrum overlapping. Thus, when the Opt-BW is larger than the channel spacing of 28 GHz, similar system performance can be obtained within 0.05 dB required OSNR variation. Meanwhile, when the Opt-BW decreases less than the channel spacing of 28 GHz, the system performance suffers from degradation due to the severe ISI arising from the narrow filtering effect. Fortunately, the proposed Nyquist WDM superchannel always shows impressive performance improvement compared to the 16QAM based RS-DSS Nyquist WDM superchannel, when the Opt-BW is larger than 25 GHz. Especially, 2.12 dB improvement of required OSNR at BER = 10^{-3} is obtained, when the Opt-BW is equal to the channel spacing of 28 GHz. If the Opt-BW further reduces less than 25GHz, both superchannel systems are ISI limited and similar performance is observed.

3.3 Optimization of RS-DSS

In principle, a full-response equalization before CPR is expected to exhibit an amplitude response roughly inverted to the channel response. As a result, the in-band noise, together with ICI, can be enhanced after full-response equalization [13]. With the RS-DSS, the enhanced noise and ICI are expected to be greatly suppressed, along with spectrum shaping
induced ISI into the signal at the same time. Therefore, RS-DSS needs to be optimized practically in order to achieve a compromise between residual ICI and ISI after digital spectrum shaping. The equivalent amplitude response of RS-DSS is shown in Fig. 4(a) for different values of $\alpha$. We can see that the larger $\alpha$ is, the sharper spectrum shaping is expected. In order to find the optimal $\alpha$ for minimizing the required OSNR at BER = $10^{-3}$, the optimization of RS-DSS is carried out on the condition of different Opt-BW. The relationship between optimal $\alpha$ and the Opt-BW is described in Fig. 4(b). As for the 16QAM based RS-DSS Nyquist WDM superchannel, the system suffers from severe enhanced ICI after full-response equalization. Thus, large $\alpha$ is preferred to perform sharp spectral shaping for the sake of enhanced ICI mitigation. On the other hand, rather large $\alpha$ (i.e., $\alpha = 1$) is also undesirable due to the severe post-filtering generated ISI. We can see that the variance of $\alpha$ is within the range of 0.7-0.8, minimum $\alpha$ is obtained when the Opt-BW is 25 GHz, because there exists an optimal trade-off between the ISI and the ICI. However, as for the proposed Nyquist WDM superchannel, the system performance is mainly limited to the ISI owning to nearly free ICI even with severe spectrum overlapping. On such condition, the optimal $\alpha$ is chosen with respect to the Opt-BW in order to match the response of RS-DSS with actual channel response as much as possible. Consequently, narrower Opt-BW always leads to the selection of larger $\alpha$.

![Fig. 4.](image_url) (a) The equivalent amplitude response of RS-DSS for different values of $\alpha$; (b) Relationship between optimal $\alpha$ and transmitter-side optical filter bandwidth.

### 3.4 B2B performance

The optical spectra of the generated 28 GHz-spaced three channel 224-Gb/s signals after transmitter-side optimal filtering for individual channels, together with the optimal response function of optical filters, are shown in Fig. 5. The optimal Opt-BW for 16QAM based RS-DSS and proposed Nyquist WDM superchannel is 25 GHz and 31 GHz, respectively, as shown in Fig. 3. We can see that 16QAM based RS-DSS Nyquist WDM superchannel is aggressively filtered in order to fit into the 28 GHz channel spacing with acceptable ICI. Yet, the proposed Nyquist WDM superchannel is just slightly filtered in order to avoid severe ISI. Then, the B2B performance is obtained in Fig. 6 on the condition of the optimal RS-DSS. The required OSNR at BER = $10^{-3}$ for the proposed Nyquist WDM superchannel is 21.1 dB, which shows about 1.4 dB improvement compared to the 16QAM based RS-DSS Nyquist WDM superchannel and only 1.1 dB penalty compared to the theoretical limit. The insets in Fig. 6 show typical recovered constellations at polarization Y before post-filtering for each Nyquist WDM superchannel on the condition of 22 dB OSNR and a clear constellation is observed for the proposed offset-16QAM based RS-DSS Nyquist WDM superchannel.
3.5 Fiber transmission performance

In order to investigate the transmission performance, the Q-factor after 960 km SSMF transmission and the corresponding received OSNR are calculated as a function of launched optical power per channel under the optimal Opt-BW together with optimized RS-DSS for both Nyquist WDM superchannels, as shown in Fig. 7. For the ease of comparison, the achieved Q-factors under different launched optical power per channel and the launched optical power range allowed beyond BER of $4.4 \times 10^{-3}$ ($Q = 8.37$), indicating of the HD-FEC threshold with 7% overhead [21], are presented in Table 1. It is observed from Fig. 7 and Table 1, that the optimum launched optical power per channel for both superchannels is approximately $-2$ dBm. At optimal launched optical power, the achieved Q-factor for the proposed Nyquist WDM superchannel is 10.66 dB, which shows 2.3 dB improvement compared to the 16QAM based RS-DSS Nyquist WDM superchannel. In particular, 1.5 dB and 1.7 dB Q-factor improvement are also obtained for the proposed Nyquist WDM superchannel on the condition of launched optical power per channel equaling to $-7$ dBm and $2$ dBm, where the system is ASE noise limited and nonlinearity limited, respectively. Furthermore, we can see that error-free transmission cannot be obtained for the 16QAM based RS-DSS Nyquist WDM superchannel whatever the launched optical power per channel is. However, the launched optical power range allowed beyond the HD-FEC threshold is from $-6$ dBm to $-2$ dBm.
dBm to 1.2 dBm for the proposed Nyquist WDM superchannel. Therefore, we can conclude that the proposed Nyquist WDM superchannel shows superior performance over the 16QAM based RS-DSS Nyquist WDM superchannel for the occurrence of both nonlinearity and ASE noise.

Fig. 7. Performance after 960 km SSMF transmission as a function of launched optical power per channel along with the calculated OSNR at the receiver-side.

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<th>Q-factor of launched power per channel of</th>
<th>Power range</th>
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<td>16QAM based RS-DSS Nyquist WDM</td>
<td>−7 dBm  8.36 dB  3.87 dB</td>
<td>−6 dBm - 1.2 dBm</td>
</tr>
<tr>
<td>Offset-16QAM based RS-DSS Nyquist WDM</td>
<td>7.36 dB  10.66 dB  5.57 dB</td>
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### 3.6 Performance sensitivity to phase difference between channels

In practical implementation of the proposed Nyquist WDM superchannel, the precise phase difference (ΔΦ) between channels is hard to realize due to random environment perturbations. Thus, it is essential to investigate the effect of phase difference deviation between channels for the proposed Nyquist WDM superchannel. As a comparison, we also take traditional 16-QAM-WDM superchannel into account by switching post-filtering and MLSD into hard decision. Figure 8 shows the performance versus the phase difference between channels for different superchannels, when the Opt-BW is fixed to the channel spacing of 28 GHz. The best performance of both superchannels can be secured, when ΔΦ is either 90 or 270 degree. Furthermore, the proposed Nyquist WDM superchannel using offset-16QAM and RS-DSS shows about 0.47 dB performance improvement of required OSNR at BER = 10⁻³ compared to the 16-QQAM-WDM superchannel, owning to the post-filtering and MLSD for enhanced noised suppression and ISI equalization. Meanwhile, 16-QQAM-WDM superchannel suffers from severer performance degradation with a deviation of optimal ΔΦ compared to the proposed Nyquist WDM superchannel. Within 1 dB required OSNR penalty, ΔΦ tolerance range is around ± 25 degree for the 16-QQAM-WDM superchannel. However, ± 15 degree improvement of tolerance range can be secured for the proposed Nyquist WDM superchannel. In particular, when ΔΦ tolerance range is large than ±
60 degree, error-free transmission cannot be obtained for the 16-QAM-WDM superchannel in the presence of severe ICI after full-response equalization. On the contrary, owning to spectrum shaping by the two-tap post-filter, the enhanced ICI is greatly suppressed for the proposed Nyquist WDM superchannel. Furthermore, a compromise between residual ICI and ISI is obtained with optimal Opt-BW of 28 GHz. As a result, similar performance can be acquired when $\Delta \Phi$ tolerance range is beyond $\pm$ 60 degree and the proposed Nyquist WDM superchannel suffers from only about 1.8 dB required OSNR penalty at those deviations. Therefore, we can conclude that the variance of required OSNR at BER = $10^{-3}$ is within 1.8 dB in case $\Delta \Phi$ is varied from 0 to 360 degree for the proposed Nyquist WDM superchannel.

![Fig. 8. Performance as a function of phase difference between channels.](image)

4. Conclusion

We have proposed a Nyquist WDM superchannel using offset-16QAM and RS-DSS, achieving a SE up to 7.44 bit/s/Hz with 7% HD-FEC overhead. Through a comprehensive investigation, our proposed Nyquist WDM superchannel shows great performance improvement compared with the 16QAM based RS-DSS Nyquist WDM superchannel. 1.4 dB improvement of required OSNR at BER = $10^{-3}$ is acquired under the scenario of B2B transmission. In addition, launched optical power range allowed beyond the HD-FEC threshold from $-6$ dBm to 1.2 dBm is obtained for the proposed Nyquist WDM superchannel after 960 km SSMF transmission with EDFA-only. Moreover, practical implementation of the proposed Nyquist WDM superchannel is secured through investigating the performance sensitivity to the phase difference deviation between channels. No more than 1.8 dB required OSNR penalty at BER = $10^{-3}$ is obtained even with a varying phase difference between channels from 0 to 360 degree.

Acknowledgments

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