Orthogonal Frequency Division Multiplexing for Spectrally Efficient Nyquist WDM Systems

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***Abstract*— In order to meet the increasing demand on high data rate in the backbone optical networks, we choose offset QAM Nyquist Wavelength Division Multiplexing (OQAM N-WDM) as the technique to increase the spectral efficiency (SE) of fiber-optic WDM transmission systems. To get intersymbol interference (ISI)-free transmission, root-raised-cosine (RRC) pulses are used in the transmitter. To get interchannel interference (ICI) free transmission, OQAM is employed as modulation scheme enabling the multiplexing of the users' channels with a spacing equal to the symbol rate and thus achieving the highest SE. The performance is evaluated for this system propagating over a linear chromatic dispersion (CD) channel. Simulation results show that the required optical SNR (ROSNR) at BER of 10^{-3} for back-to-back connection of the transmitter and receiver meets the theoretical value of OSNR for QPSK transmission i.e. ROSNR = 13.3 dB.**

***Index Terms*— Fiber optics communication, Nyquist WDM system, OQAM, Coherent communications.**

I. Introduction

To meet the increasing demand for high data rates, new technologies to support larger capacity and higher spectral efficiency (SE) are required. One of the techniques that have been investigated to increase SE including spectral shaping is the Nyquist wavelength division multiplexing (WDM) [1]. In this work, we focus on this technique to achieve high spectral efficiency in fiber-optic WDM transmission systems. The main advantage of using Nyquist WDM over orthogonal frequency division multiplexig (OFDM) with cyclic prefix [2] is that there is no loss in SE due to cyclic prefix in OFDM.

The basic idea behind Nyquist-WDM is to manage on one hand the transmitted spectrum to be as compact as possible while meeting the ISI-free Nyquist criterion. On another hand multiplexing of the channels of the different users is done with a channel spacing if possible close or equal to the symbol rate to achieve high SE. For intersymbol interference (ISI)-free transmission, we choose an almost rectangular shape in the spectral domain (i.e. Nyquist pulse in the time domain). The sharp filtering is done digitally in the frequency domain. For symbol-rate channel spacing, we investigate the possibility of using orthogonal signals namely by employing OQAM [3] as a modulation scheme to ensure the absence of interchannel linear crosstalk i.e. no interchannel interference (ICI).

The orthogonally multiplexed signal is sent over an optical fiber where we only consider the linear effects of the fiber and specifically the chromatic dispersion (CD) effect. In long haul transmission, the channel memory is largely dominated by CD in this case with an ISI spread of more than hundred symbol durations. In this case, the equalizer of the desired receiver should take into account the introduced ISI.

In what follows, we first present the model of the OQAM Nyquist WDM system showing the architecture of the transmitter and receiver. In the receiver, the design of the equalizer is presented. Finally, the system is simulated in the presence of CD channel to test the designed equalizer for the desired transmitter.

II. WDM Transmitter Model

We simulate a three-channel WDM QPSK transmission system as shown in Fig. 1. Both pulse shaping and frequency domain multiplexing of the users' channels are done in the transmitter. In what follows, we first treat the channel of each user independently to get the desired spectrum of a Nyquist pulse at its output. We investigate the choice of pulse shaper and the DAC model where some prefiltering is also needed to get the desired spectrum. Then, we multiplex the channels of the users to form the input signal to the optical fiber channel. For multiplexing, we aim at packing the channels of the users at symbol-rate spacing if possible without getting ICI.

A. Choice of Pulse shaping filter

Pulse shaping is performed at the transmitter according to the Nyquist criterion to generate ISI free signals. The raised-cosine (RC) pulse shaping filter satisfies the Nyquist ISI criterion. In order to get zero ISI, the most common solution for RC is to factor its transfer function into equal parts, i.e., to use the square-root of the desired raised cosine system response in both the transmitter and the receiver based on the matched filter principle. The resulting transmitter frequency response is commonly called a root-raised cosine (RRC) response.

Thus, we choose as the pulse shaping filter an RRC filter $G_{\text{RRC}}(f) \in \mathbb{R}^{1\times M_p}, f \in [0, 2B]$ with roll-off factor ρ, $0 < \rho \leq 1$. B is the equivalent noise bandwidth of the receiver which is the inverse of the symbol spacing

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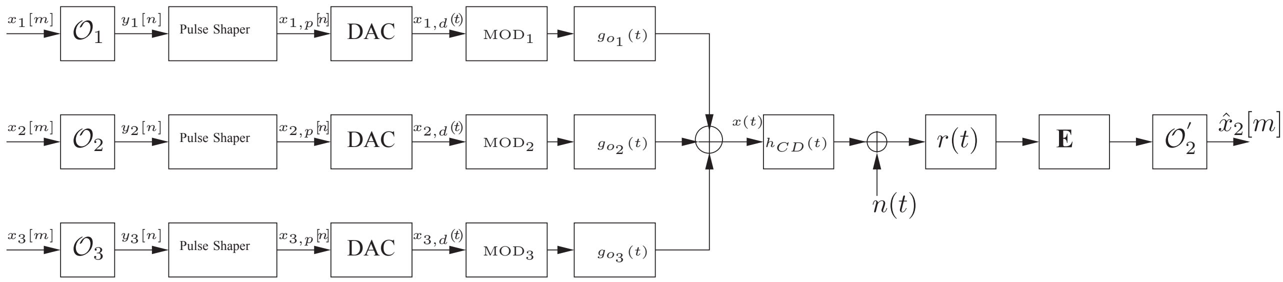

Fig. 1. WDM System model

T_s. The M_p coefficients of $G_{\text{RRC}}(f)$ are sampled directly in the frequency domain (FD) [4] having its coefficients given as:

$$G_{\text{RRC}}(f)=\begin{cases} 1, & 0 \leq |f| \leq \frac{1-\rho}{2T_s}, \\ \cos\left(\frac{\pi T_s}{2\rho}\left(|f|-\frac{1-\rho}{2T_s}\right)\right), & \frac{1-\rho}{2T_s} \leq |f| \leq \frac{1+\rho}{2T_s}, \\ 0, & |f| > \frac{1+\rho}{2T_s}. \end{cases}$$

The choice of ρ for the pulse shaper is important in case standard QAM is to be used in order to ensure orthogonality between users' channels. However, in case of OQAM, orthogonality is already guaranteed regardless of ρ, but other problems arise like for example peak to average power ratio (PAPR) for small values of ρ. In order to obtain the pulse shaped signal $x_{i,p}[n], i = 1,2,3$, the input signal $y_i[n]$ is first transformed into the frequency domain and then multiplied by the pulse shaper $G_{\text{RRC}}(f)$ (this is equivalent to only an approximate linear convolution due to filtering the input signal with the pulse shaper of length M_p. This method is explained in details in Section V).

B. DAC Model

To modulate the signal $x_{i,p}[n]$ onto an optical carrier, the signal is converted to the analog domain by a digital-to-analog (DAC) converter. We choose the following generic model for the DAC:

$$g_{\text{DAC}}(t) = \frac{1+\cos(2\pi t/T_s)}{2}, \quad -T_s/2 \leq t \leq T_s/2. \quad (1)$$

Because the DAC is supressing the preiodic repititons inherent to its input sequence, a Gaussian (optical) filter $g_o(t)$ is employed in each user's channel. The impulse response of it is found by taking the IFFT of its transfer function $G_o(f)$ given by:

$$G_o(f) = \exp\left(-\log(\sqrt{2})(2f/B_o)^4\right), \quad (2)$$

for an optical bandwidth of $B_o = 35$ GHz.

C. Precompensation of DAC and Optical Filter

The PSD of the signal $x_{i,d}(t)$ after being filtered with $g_{\text{DAC}(t)}$ and $g_o(t)$ does not resemble the response of an RRC filter in the passband region as can be seen in Fig. 2. Therefore, precompensation of the DAC and the optical filter has to be done.

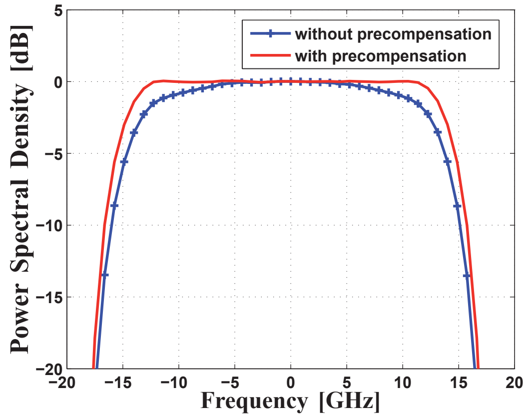

Fig. 2. PSD of the signal: with and without precompensation

The precompensation is done digitally in the frequency domain combined with pulse shaping. The transfer function of the precompensated DAC is:

$$G_{\text{DAC}}(f) = \text{sinc}(\pi f T)\frac{\cos(\pi f T)}{1-(2fT)^2}, \quad (3)$$

with $G_{\text{DAC}}(f = B) = 0.5$ and $T = T_s/2$. The transfer function of the precompensated optical filter is given in (2). The precompensated signal obtained is shown in Fig. 2.

D. Frequency Division Multiplexing

For multiplexing the channels of the users and in order to achieve simultaneously the highest spectral efficiency (overlapping spectra of the adjacent channels) and ICI free transmission, OQAM modulation scheme is employed. With OQAM, the spacing between the center of users' channels is reduced to symbol rate spacing without any penalty from ICI by orthogonally multiplexing the transmitted signals. This is done by introducing half-symbol delay between the in-phase and quadrature components of $x_i[m]$ that alternate for even and odd channels given by $\mathcal{O}_i$ shown in Fig. 3(a).

III. Chromatic Dispersion Channel Model

The orthogonally multiplexed signal $x(t)$ then propagates over the optical fiber. In this paper, we only consider the linear distortions of the fiber especially CD. Thus an

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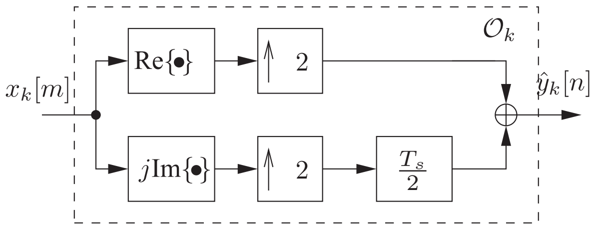
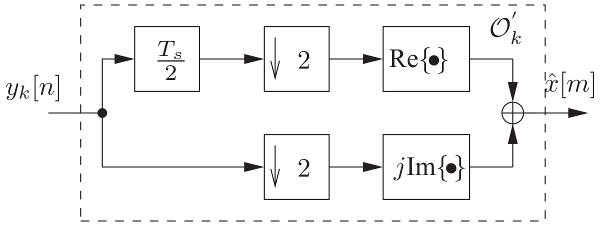


(a) Staggering Operation for even k



(b) Destaggering Operation for even k

Fig. 3. Staggering $\mathcal{O}_k$ and destaggering $\mathcal{O}_k^{'}$ for even k

equivalent base band transfer function of any linear fiber with CD can be described by:

$$H_{\text{CD}}(f) = \exp\{-j\alpha f^2\}, \tag{4}$$

where $\alpha = \frac{\pi\lambda^2\text{CD}}{c}$. The value of chromatic dispersion CD is expressed in ps/nm, the wavelength λ is in nm and the speed of light in vacuum c in m/s. Typical fiber parameter values for λ is $\lambda = 1550$ nm.

The impulse response $h_{CD}(t)$ of the channel is found by taking the IFFT of $H_{\text{CD}}(f)$. Note that CD is a time-invariant effect i.e. the coefficients of the channel are static and do not change over time.

IV. Receiver Model

In the receiver, we consider that the wavelength channels are first demultiplexed before being further processed. Thus, each channel is processed separately. We choose the second channel to be the main channel as shown in Fig. 1.

A. Receive filter

The received signal is filtered by a receive filter $r(t)$ which consists of an optical (Gaussian) filter whose transfer function is given in (2) and an electrical (Bessel) filter of the fifth-order whose transfer function is given as follows:

$$H_e(f) = \frac{945}{jF^5 + 15F^4 - j105F^3 - 420F^2 + j945F + 945}, \tag{5}$$

where $F = \frac{K}{B_e} f$, $B_e = 0.7 \times B$ is the 3 dB bandwidth and $K = 2.4274$ is the 3 dB normalization constant.

The impulse response of $r(t)$ is obtained by taking the IFFT of the product of $G_e(f_k)$ and $G_o(f_k)$.

B. Equalizer Design

After that, the equalization of the signal is done digitally in the frequency domain at a rate double that of the symbol rate i.e. a fractionally spaced equalizer $E(f) \in \mathbb{C}^{1\times M_e}$. The equalizer consists of an CD equalizer, an RRC filter so that an overall RC response is obtained and precompensation of the optical and electrical filters. It has M_e coefficients and it reads as:

$$E(f) = \frac{H_{\text{CD}}^{-1}(f) G_{\text{RRC}}(f)}{G_e(f) G_o(f)}, \tag{6}$$

Since we adopt the zero-forcing design for the equalizer, Eq. (6) will be evaluated at discrete frequency points i.e at $f = f_k, k = 0, \cdots M_e - 1$. Moreover, equalization is done in the FD where M_e degrees of freedom are used to design the equalizer and again with an approximate linear convolution (see Section V). Moreover, since the channel's coefficients are static, the equalizer's coefficients are also static.

Finally, destaggering $\mathcal{O}_2^{'}$ of the equalized signal is performed to get $\hat{x}_2[m]$ by applying flow reversal of $\mathcal{O}_2$ shown in Fig 3(b).

V. Filtering with an Approximate Linear Convolution

The filtering (either pulse shaping in the transmitter or equalization in the receiver) is performed in the frequency domain with an approximate linear convolution described as follows:

- The input signal $i[n]$ is transformed into the frequency domain by an FFT of size M which is M_p or M_e for pulse shaping and equalization, respectively. The consecutive input blocks to the FFT overlap with a factor of 50%.
- The input blocks are then multiplied by the coefficients of the corresponding filter $F_k(z)$ (pulse shaping filter or equalizer) with $z = e^{j2\pi f}$. The filter $F(z) \in \mathbb{C}^{1\times M}$ in this case should be given in the frequency domain with M coefficients.
- Finally each block is transformed back into the time domain by an IFFT of size M. The output signal $\hat{i}[n]$ is formed by discarding 50% of each of the filtered block.

In the literature [5], this method is misconceptually referred to as overlap-save method with 50% overlap, but it is only an approximately linear convolution since all M degrees of freedom have been used for the design of the filter/equalizer.

VI. Simulation Results

We simulated the Nyquist WDM system model presented for $B = 28$ GHz bandwidth. For the FD RRC pulse shaper in the transmitter, the FFT size is chosen as $M_p = 128$. The FFT size in receiver for channel equalization is $M_e = 512$. In Fig. 5, we plot the required OSNR at BER of 10^{-3} for different CD values and for

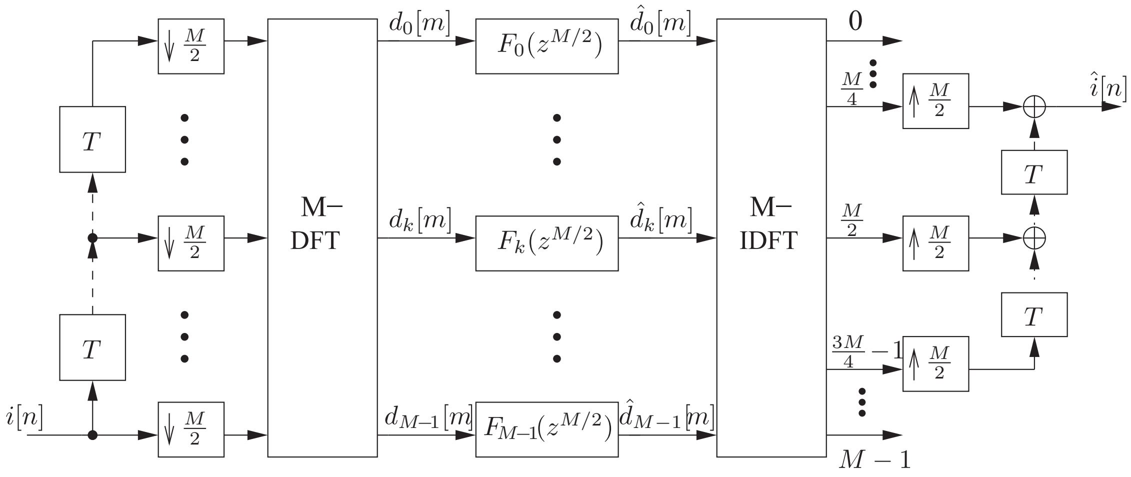


Fig. 4. Only an approximate linear convolution of the input signal and the filter $F(z = e^{j2\pi f})$ with 50% overlap of the input blocks and 50% discard/save of the output blocks.

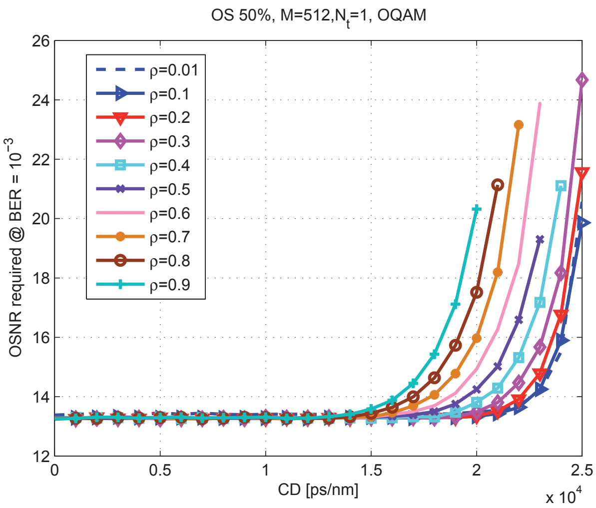


Fig. 5. Required OSNR for different CD values and for different roll-off factors

different roll-off factors and we consider that the equalizer in each subband of Fig. 4 has only one tap.

The first result that can be observed in the figure is that the required OSNR for back-to-back connection (CD = 0 ps/nm) is 13.3 dB for $\rho \geq 0.1$ and 13.4 dB for $\rho < 0.1$. The fact that there is a 0.1 dB penalty in the WDM system is because of the FFT limitation at the transmitter i.e. the size of M_p. In other words, decreasing ρ requires increasing M_p to avoid degradation in performance. A second result that can be seen in the figure is that higher CD values can be compensated when decreasing the roll-off factor ρ.

VII. Conclusions and Future Work

For ISI- and ICI-free transmission in a Nyquist WDM transmission system, RRC pulses and offset QAM modulation scheme were employed, respectively. OQAM modulation has enabled a symbol-rate channel spacing for multiplexing the users' channels without crosstalk between them and thus achieving the highest spectral efficiency. A 3-channel system was simulated propagating over a CD channel. Thus, the equalizer of the desired receiver should take into account the introduced ISI due to CD.The results show that ROSNR for back-to-back connection of the transmitter and receiver meets the theoretical value of OSNR for QPSK transmission i.e. ROSNR = 13.3 dB and that higher CD values are tolerated with low ρ.

However, crosstalk from inphase and quadrature components and from overlapping subchannels completely cancels out just in case of ideal sampling phase if the carrier spacing matches the symbol rate and if the orthogonal pulse shapes are used (in the absence of channel impairment). A phase mismatch in a multicarrier O-QAM system results in crosstalk. As a future work, the design of the equalizer taking into account the existance of ICI in case of phase mismatch shall be considered.

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