Coherent Detected Temporal Optical Code Division Multiplexing System with High Spectral Efficiency Using Nyquist Pulse Shaping

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Abstract— We propose a high spectral efficiency temporal coded OCDM system using Nyquist pulse shaping and coherent detection (Nyquist-OCDM). The proposed system is compared with conventional OCDM system in terms of spectral efficiency and error vector magnitude. The system performance under different number of codes and different length of code is investigated by simulation.

1. INTRODUCTION

By employing dedicated orthogonal codes for each channel, optical code division multiplexing (OCDM) system offers several attracting features [1], e.g., asynchronous access, soft-capacity and high security, etc.. However, the spectral efficiency (SE) of OCDM system is decreased in the spectrum spreading process if the number of codes N_c employed is less than the spreading length N_l. In traditional OCDM systems, the spectral efficiency is further limited by the large carrier spacing (> baud rate) in spectral coded systems [2] or non-ideal pulse shaping (not Nyquist) in temporal coded systems [3]. In [4], we have proposed a high SE spectral coded system based on orthogonal frequency multiplexing (OFDM) with carrier spacing equals to baud rate.

In this paper, we present a coherent detected temporal coded OCDM system in which Nyquist pulse shaping is employed to improve the SE. By Nyquist pulse shaping of temporal coded signal, the spread spectrum width of signal can be reduced to chip-rate. Therefore, the SE of proposed system is improved compared with conventional temporal coded OCDM system [3] whose spectrum width could be several times of the encoding/decoding chip rate. Furthermore, the OCDM encoding/decoding and Nyquist pulse shaping are conducted in electrical domain, which can share the existing facilities with other digital signal processing (DSP) functions in the coherent optical communication system.

2. PRINCIPLE AND SIMULATION SETUP

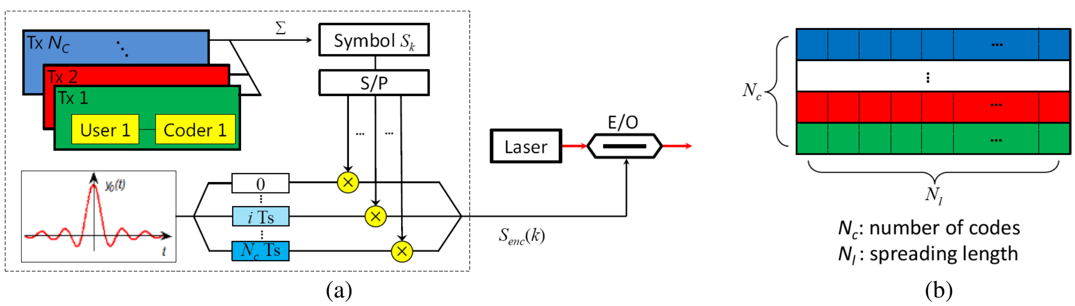

Figure 1: (a) Generation of Nyquist-OCDM signal and (b) the structure of codes.

Figure 1 depicts the generation of Nyquist-OCDM signal. In encoding step, specific code from the same orthogonal code set (e.g., Walsh code) with code length N_l is assigned to one of the N_c user for spreading. The spread signal from all users are then converged. The i_{th} block S_i of the sum of N_c encoded data can be described as:

$$S_i = \{C_{im}\} \quad (m = 1, 2, 3, \ldots, N_l)$$

where C_{im} is the mth chip in ith block. Without loss of generality, all users are assumed to transmit data with identical symbol rate R and modulation format (M bits per symbol). Thus, the chip rate

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of temporal encoding is $R_s = RN_l$ The spread signal is then pulse shaped by a Nyquist filter. The Nyquist shaped temporal coded signal is a finite sequence of N temporal symbols S^i_{enc} [5], which can be expressed as:

$$y(t) = \sum_{i=0}^{N-1} S^i_{enc}(t) \quad S^i_{enc}(t) = \sum_k C_{ik} \sin c\left(\frac{t-t_k}{T_s}\right) e^{j2\pi i F_s t} \quad |t_{k+1} - t_k| = T_s = \frac{1}{F_s}$$

By sampling $S^i_{enc}(t)$ with sample rate $R_s = N_l/T_s(iT_s < t < iT_s + T_s)$, the sampled signal is:

$$S^i_{enc}(m) = \sum_k C_{ik} \sin c\left(\frac{mT_s - t_k}{T_s}\right) e^{j2\pi i F_s m T_s} = \sum_k C_{ik} \sin c\,(m-k)\, e^{j2\pi i F_s m T_s} = C_{im}$$

Therefore, the original data can be recovered by decoding the sampled signal ($S^i_{enc}(m) = C_{im}$) at the receiver. Since the bandwidth of Nyquist-shaped baseband signal equals to chip rate R_s when the roll-off factor $\alpha = 0$ [6] the theoretical spectral efficiency of above system is:

$$SE = M\frac{N_c R}{R_s} = M\frac{N_c}{N_l}\ \text{bit/s/Hz}$$

The maximum $SE_{\max}(= M\ \text{bit/s/Hz})$ is achieved when $N_c = N_l$, which is at least two times of SE of the traditional OCDM system [2] and equals to SE of the spectral efficient OFDM-OCDM system [4] The encoded signal is sent to modulator for electrical-optical (E-O) coversion.

Figure 2 shows the simulation setup for the transmission of Nyquist-CDM signal over 400 km standard single mode fiber (SSMF) link with coherent detection. The pseudo-random binary sequences (PRBS) of order 15 is generated at an aggregate bit rate of 40 Gbps. The QPSK mapped data is serial to parallel (S/P) converted to emulate data streams for different users ($N_c = 256$). Data from all users are encoded in parallel using orthogonal Walsh codes ($N_l = 256$). The sum of all encoded signal is filtered by a Nyquist filter to get an inter-symbol-interference (ISI)-free narrow band signal. Then the complex Nyquist shaped temporal coded signal sample is converted to electrical signals by two digital-to-analog converters (DACs) and modulated on optical carrier from the laser (central wavelength = 1552.52 nm, i.e., central frequency = 193.1 THz) with an optical I/Q modulator. The laser power and linewidth are set to 1 mW and 100 kHz, respectively. The optical spectrum of the modulated signal is shown in the inset of Fig. 2 whose bandwidth is equal to chip rate (20 Gchip/s) as the roll-off factor is 0.

The signal is transmitted over four spans, each of which consists of 100 km SSMF and an Erbium Doped Fiber Amplifier (EDFA) with a noise figure of 5 dB. The transmitted optical signals is detected by a coherent receiver. The optical-electrical (O-E) converted signal is sampled and digitalized by two analog-to-digital converters (ADCs). The outputs from ADCs are feed to the DSP blocks for signal recovery. Firstly, the chromatic dispersion is compensated in frequency domain and carrier phase is then estimated using Viterbi-Viterbi algorithm. The phase corrected signal is sent to the CDM decoder. Finally, the decoded signal is sliced and demapped to bits.

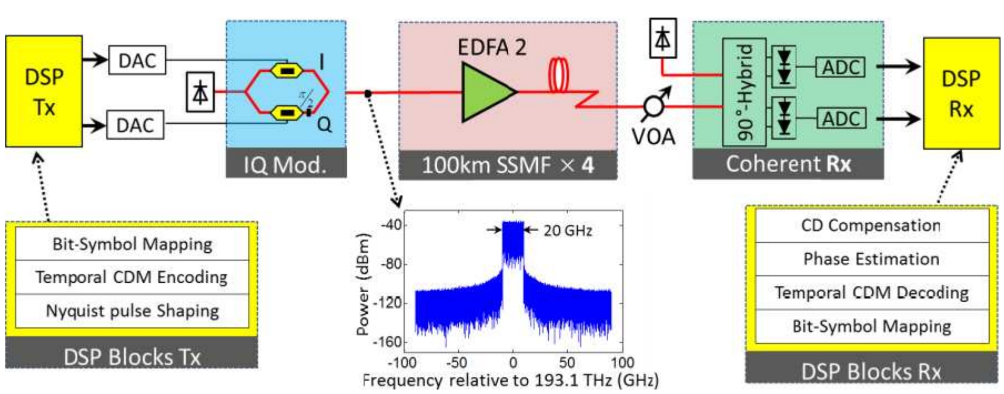

Figure 2: Simulation setup (inset: optical spectrum after Nyquist shaping).

3. RESULTS

Figure 3(a) shows the error vector magnitude (EVM) [7] of proposed Nyquist-OCDM system with respect to received OSNR (green triangle) in the back-to-back configuration The OSNR is measured with a spectral resolution of 0.1 nm. Compared with OCDM only system (red circle), no OSNR penalty is found due to Nyquist pulse shaping, which can be explained by the ISI free feature of Nyquist pulses in time-domain.

For OCDM based optical access networks the maximum number of users is limited by the power loss caused by power splitter in the remote node (RN). To emulate the such attenuation in simulation, a variable optical attenuator (VOA) is used after 400 km fiber but before the optical mixer at the receiver side to adjust the received optical power. The measured EVM versus additional attenuation is shown in Fig. 3(b). The measured EVM is 34.0% when the additional attenuation by VOA is 35 dB. The large link power budget mainly benefits from the coherent detection.

The impact of N_c and N_l is also studied. Three different scenarios: (i) $N_c = N_l = 128$; (ii) $N_c = 256$, $N_l = 128$; (iii) $N_c = 256$, $N_l = 256$ are evaluated. Fig. 4 shows the recovered signal constellations after transmission over 400 km SSMF Corresponding EVM (in percentage) is shown on the top of each constellation. Though orthogonal codes are employed in our system, the system's EVM is still slightly related to N_l and N_c. Although the SE achieves maximum when all orthogonal codes are used for coding ($N_l = N_c$) the system performs worst at the same time With the same code length (N_l) the peak to average power ratio of encoded signal increases for larger N_c, which degrades the system performance by interacting with fiber nonlinearity and component nonlinearity (e.g., nonlinear transfer function of optical modulator). With the same number of users (N_c), longer code length sacrifices the SE but helps to reduce the average power which relieves the fiber nonlinearity impact on the signal. These indicate that a tradeoff between SE and system performance has to be made when choosing N_l and N_c.

Our scheme also provides high secure transmission. The received data can only be recovered when the correct codes are provided for decoding. Furthermore, Nyquist-OCDM can combine with WDM technology to improve transmission capacity.

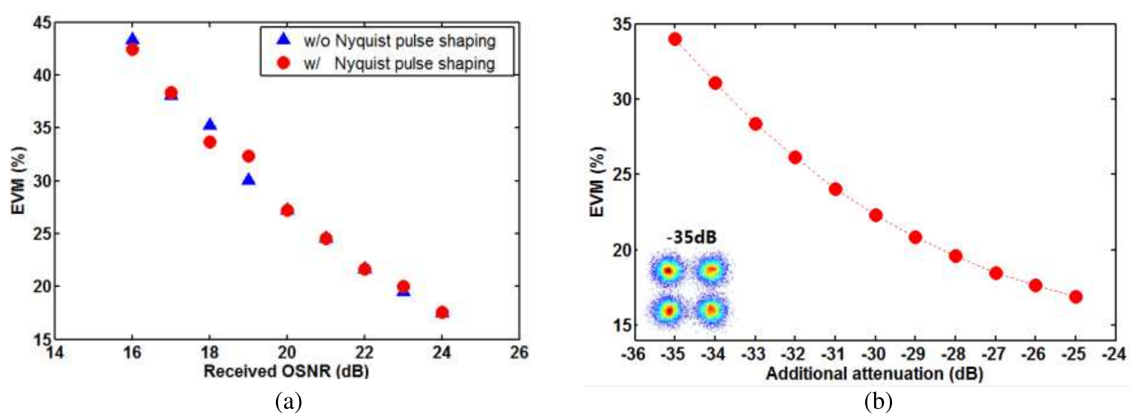

Figure 3: (a) EVM vs received OSNR for Nyquist-OCDM (red) and OCDM only system (blue). (b) EVM vs link attenuation for Nyquist-OCDM system.

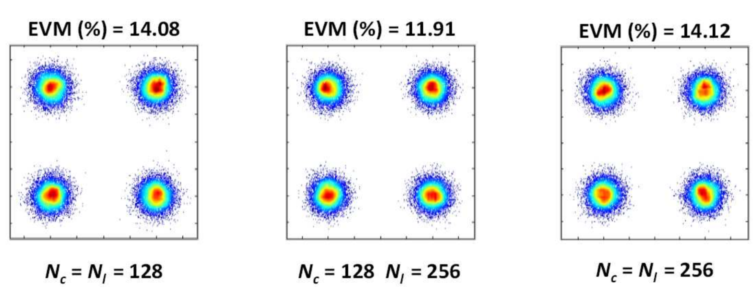

Figure 4: Recovered QPSK signal constellations after 400-km SSMF transmission.

4. CONCLUSION

In this paper, we proposed a high spectral efficiency temporal coded OCDM system using Nyquist pulse shaping and coherent detection. The maximal SE of Nyquist-OCDM system is at least two times of that of the traditional OCDM system. The transmission of Nyquist-OCDM system using Walsh codes over 400 km SSMF is evaluated by simulation. The system performance towards the number of users and code length are investigated, which showed that Nyquist-OCDM is a promising technology for optical access network.

ACKNOWLEDGMENT

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