Spectrally Efficient DPSK-OCDMA Coherent System Using Integrated Ring-Resonator-Based Coders

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Abstract: We demonstrate the highest spectral efficiency of 0.5 bit/s/Hz for a multi-user spectral phase encoded OCDMA system, which operates within an 80 GHz transparent optical window using DPSK format and programmable ring-resonator-based integrated coders.

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1. Introduction: Optical code-division multiple access (OCDMA) is a rapidly advancing area [1] due to its potential for increased network functionality and flexibility and more importantly the potential for an enhanced degree of confidentiality compared to wavelength division multiplexed (WDM) systems as first discussed in references [2] and [8]. Different approaches to implementing OCDMA are based on the working principle (coherent and incoherent), timing coordination for multi-user access (synchronous and asynchronous), and on the coding scheme (time and/or frequency domain and amplitude and/or phase). The OCDMA system described here is a coherent and synchronous spectral phase encoded system. *Spectral phase encoded* (SPE) OCDMA is based on the ability to modify the relative optical phase of the spectral components of a broadband signal according to a set of codes that define a unique choice of phase shifts. A significant advantage of coherent systems is the ability to use orthogonal codes in order to limit the multi-user interference noise [3].

Unlike wireless CDMA, optical CDMA systems that have been demonstrated so far have had low spectral efficiency. Here, we demonstrate an OCDMA system at data rates of 5 Gb/s with an improved spectral efficiency of 0.5 bit/s/Hz. The key enabling technologies we have employed to achieve the high spectral efficiency are integrated ring resonator coders and differential phase shift keying (DPSK) modulation format. Integrated ring resonators provide a powerful tool for stable, accurate phase encoding with ultra-high frequency resolution. The fine spectral resolution (here a channel spacing of 10 GHz) allows us to limit the coded signal's bandwidth. In addition to giving higher spectral efficiency, this lets us put the coded signals within a 100 GHz WDM window, and reduces transmission impairments. Further, this ensures compatibility with current dense WDM networks (and their components) operating on a 100 GHz ITU grid, thus giving our system the unique capability of an overlay technology [4].

DPSK modulation format has been successfully used in DWDM systems due to its ~3-dB improved receiver sensitivity/OSNR requirement, compared to direct detection on-off keying (OOK), when using a balanced receiver. More beneficial in the context of coherent OCDMA systems is that the improved tolerance of DPSK over OOK to coherent crosstalk [5] allows increasing the number of simultaneous users. DPSK has been applied to a *temporally phase encoded* asynchronous OCDMA system operating with a spectral efficiency of 0.3 bit/s/Hz over a 400 GHz grid [6].

Here, we present an eight-user polarization multiplexed *spectral phase encoded* synchronous OCDMA system using DPSK modulation format. The spectral efficiency of 0.5 bit/s/Hz is the highest achieved for spectral phase encoded OCDMA systems.

2. Impact of coherent crosstalk on DPSK vs. OOK: We first quantified the relative performance benefit of DPSK over OOK using conventional non-return to zero (NRZ) modulation and with the OCDM coders

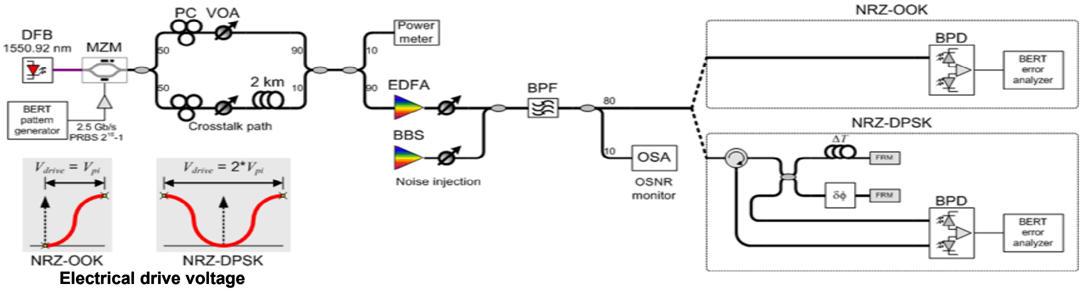

Fig. 1: Experimental setup for measuring the impact of coherentcrosstalk: DFB: Distributed feedback laser. MZM: Mach-Zehnder modulator. PC: Polarization controller. VOA: Variable optical attenuator. BBS: Broadband source. EDFA: Erbium doped fiber amplifier. BPF: Bandpass filter.

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removed. The experimental setup to measure the impact of coherent crosstalk on NRZ signals is shown in Fig. 1.

A CW laser is modulated at 2.5 Gb/s with $2^{15} - 1$ pseudorandom bit sequences (PRBS). Depending on the bias point and the electrical drive voltage to the modulator the modulation format is set to either NRZ-OOK or NRZ-DPSK, as shown in Fig. 1. The modulated signal is split between the signal and crosstalk paths, which are decorrelated by 2 km of standard single-mode fiber. Variable optical attenuators adjust their levels in order to vary the optical signal-to-crosstalk ratio (OSXR) and polarization controllers ensure that the two signals are co-polarized, which is the worst-case situation. The two signals are combined by using a 90:10 coupler. The NRZ-OOK signal is detected by a one input of a balanced photodetector, while the NRZ-DPSK signal is first demodulated and then detected using a balanced receiver. The received optical signal-to-noise ratio (OSNR) is degraded by loading noise from a broadband source immediately before the preamplifier to measure BERs in the range 1x10^{-4} to 1x10^{-11}.

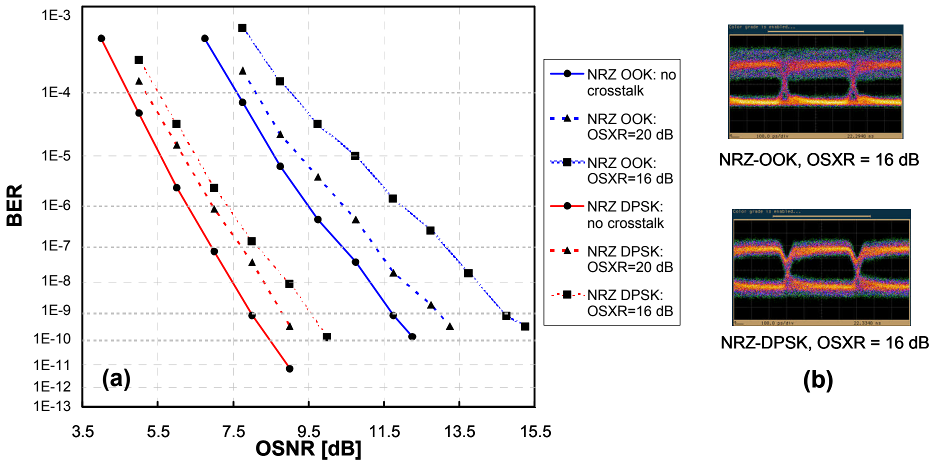

Fig. 2: (a) BER performance for NRZ-OOK and NRZ-DPSK as a function of OSNR for various OSXRs. (b) Electrical eye diagrams after detection.

Figure 2 shows the BER performance of NRZ-OOK and NRZ-DPSK as a function of the OSNR (measured in 0.1 nm noise bandwidth) for various OSXRs. Also, shown are the electrical eye diagrams after detection for NRZ-OOK and NRZ-DPSK at a crosstalk level of 16 dB. It is seen that the impact of coherent crosstalk is significantly smaller for DPSK compared to OOK. For example, at an OSXR level of 16 dB, the OSNR penalty at a BER of 1x10^{-9} for NRZ-OOK is ~3 dB while it is only ~1.5 dB for NRZ-DPSK. Although these results were taken for NRZ modulated signals, the improved tolerance of DPSK to coherent crosstalk also applies to RZ modulated signals, which is the signal format used in our OCDMA system.

3. Eight-user spectral phase encoded DPSK-OCDMA system: The experimental setup for the eight-user spectral phase encoded OCDMA system is shown in Fig. 3.

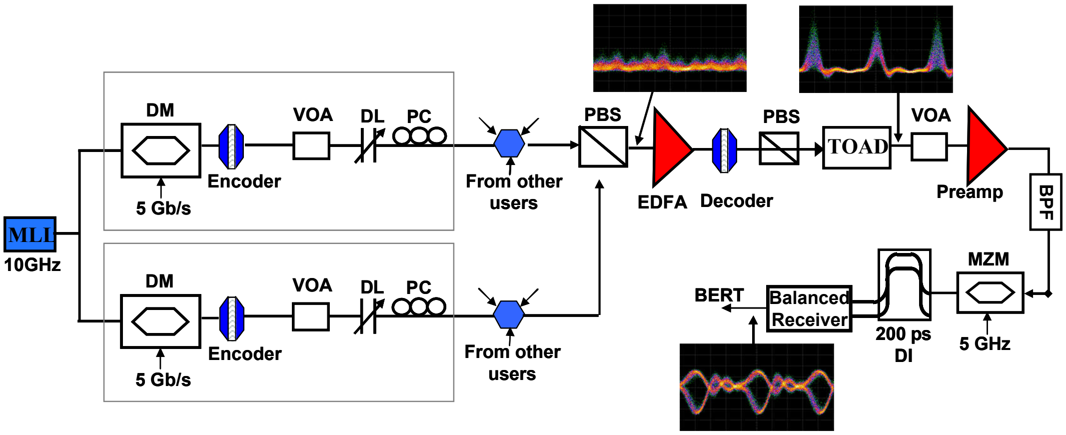

Fig. 3: DPSK-OCDMA experimental setup: MLL: Mode-locked laser. DM: Data modulator. VOA: Variable optical attenuator. DL: Delay line. PC: Polarization controller. PBS: Polarization beam splitter. EDFA: Erbium doped fiber amplifier. BPF: Bandpass filter. MZM: Mach-Zehnder modulator. DI: Delay interferometer.

The output of a 10 GHz mode-locked laser (MLL) is split and the outputs are independently modulated by 5 Gb/s data streams (two laser pulses are used per bit) consisting of 2^{15}-1 PRBS. These modulated data streams are further split and then encoded in four separate programmable ring resonator based spectral phase encoders, described in detail in reference [7]. The coders select and demultiplex eight frequency components from the modulated MLL signal and apply a phase shift of 0 or π to each component depending on the particular user's *Hadamard code*, before recombining the shifted components. We use codes H_1, H_2, H_3, and H_4 from the conventional orthogonal Hadamard-8 code set. The output after each encoder is split using a 1x2 splitter for polarization multiplexing in order to emulate eight simultaneous users. The output of each user is equalized in power, and then passively and synchronously combined with all other users. A polarization beam splitter (PBS) is used to combine users in orthogonal polarizations. All eight users occupy the same 80-GHz spectral bandwidth (8 frequency bins x 10 GHz), thus providing compatibility with existing DWDM systems.

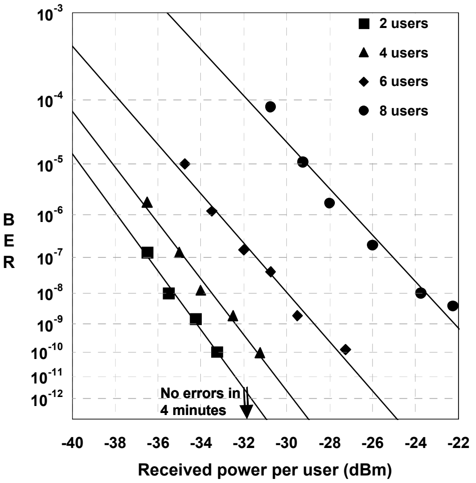

Fig. 4: BER performance for code H_4 with two, four, six and eight simultaneous OCDMA users.

At the receiver, polarization demultiplexing is followed by a phase conjugate decoder, which realigns the phase of the individual frequency components to reconstruct the original pulse for the selected code, while incorrectly decoded signals remain temporally broadened. Optical time-gating provides multi-user interference rejection by extracting the desired decoded channel from the remaining incorrectly decoded signals. This is followed by another time gate implemented with a Mach-Zehnder modulator driven with a 5 GHz clock to select one pulse out of the two that represent a data bit in order to reduce inter-symbol interference (ISI). The signal is received by a DPSK receiver comprising of a 1-bit delay interferometer and a balanced detector.

The uncorrected BER performance is shown for code H_4 as a function of the received power (per user) in Fig. 4 for the cases of two, four, six, and eight simultaneous polarization multiplexed OCDMA users. As the number of simultaneous users is increased the power penalty increases due to increased coherent crosstalk from interfering users.

4. Conclusions: A significant challenge in OCDMA systems is maximizing the spectral efficiency. Higher spectral efficiency can be realized through advances in devices for optical en/decoding, multi-user interference (MUI) reduction, and new coding designs and modulation formats. We have demonstrated an eight-user spectral phase encoded OCDMA system with a spectral efficiency of 0.5 bit/s/Hz through the use of DPSK format and ring resonator based integrated coders with ultra-fine frequency resolution. Future work is focused at increasing the spectral efficiency further, with a goal of 1 bit/s/Hz by increasing the data rate per user. With forward error correction (FEC) the system can be operated with higher number of simultaneous users, further increasing the spectral efficiency.

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