

An Eight-User Time-Slotted SPECTS O-CDMA Network Testbed Incorporating a NOLM Time Gate

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Abstract: We incorporate time slotting into a 9 Gb/s/user SPECTS O-CDMA network testbed to achieve eight-user capacity. The system uses a NOLM time gate that selects between time-slotted users and suppresses multi-user interference.

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1. Introduction

Optical code division multiple access (O-CDMA) is of interest in local access networks since it provides flexible bandwidth access without being limited by the fixed wavelength or time-slot restrictions of WDM/TDM systems. The maximum number of users in a traditional O-CDMA system is determined by the cardinality of the code set, but demonstrations show that the multi-user interference (MUI) noise arising from incorrectly decoded signals limits the number of users long before the system capacity reaches the code set size [1]. For improved system performance, we have recently investigated synchronous O-CDMA [1-3]. These schemes employ specialized codes (such as Walsh codes) that temporally displace MUI away from the energy of the correctly decoded signal, thereby greatly reducing the impact of coherent interference. Since the signals do not occupy the entire bit time, synchronized O-CDMA additionally allows code sharing among users as long as they are placed in separate time slots within the bit time. This can effectively allow the system to support more users beyond the code set size. Thus, despite the added complexity, synchronous systems have the advantage over simpler asynchronous systems through improved performance and increased user capacity. This paper demonstrates the time-slotting concept, allowing a total of eight users to share the network while using only four codes. The testbed uses a nonlinear optical loop mirror (NOLM) to select between time slots, and we further show that the NOLM is effective in suppressing MUI.

2. Experimental Arrangement

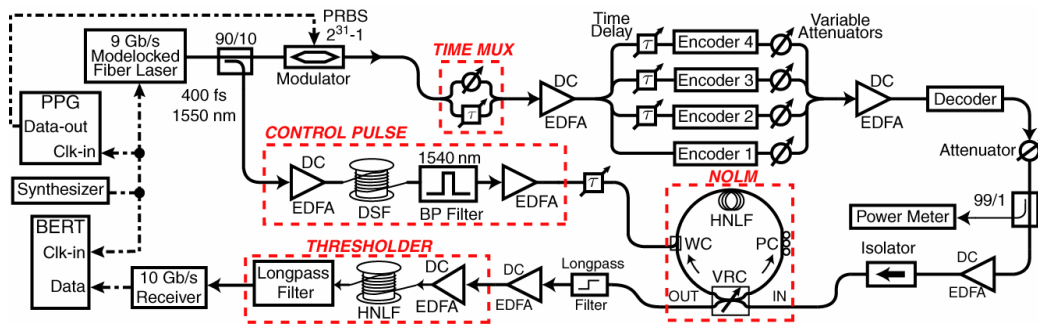


Fig. 1. Experimental arrangement for the time-slotted, eight-user SPECTS O-CDMA testbed. BP Filter: bandpass filter. DC-EDFA: dispersion-shifted EDFA. PC: polarization controller. WC: wavelength coupler. VRC: variable ratio coupler.

For the synchronous O-CDMA testbed, we use an encoding/decoding scheme called spectral phase-encoded time-spreading (SPECTS) [4]. In this scheme, encoding and decoding are performed in the spectral domain with zero-dispersion pulse shapers [5], using liquid crystal spatial light phase modulators (LC-SLPM) in the Fourier plane. In an encoder, the LC-SLPM applies a binary code to the spectrum by applying 0 or π phase shifts on individual spectrum components, causing coded pulses to spread in the time domain. A decoder can retrieve the signal by applying the conjugate phase code. The codes used by different encoders are orthogonal to each other, and thus the decoder can retrieve the signal pulse from the intended user while rejecting the pulses from the other users.

For the testbed, a modelocked fiber laser generates pulses with a full-width at half-maximum of ~ 400 fs with a 9-GHz repetition rate. A 9-Gb/s 2^{31} -1 pseudo-random bit stream is added by on-off keying the pulse train with a

LiNbO₃ Mach-Zehnder modulator. The modulated data then proceeds to the time multiplexer (mux), which creates two time slots within the 110 ps bit period. The multiplexed signal is split into four streams and each of them goes into an encoder. The paths to each encoder vary by several bit shifts, decorrelating the PRBS between each encoder. The time mux likewise contains several bit shifts, decorrelating the PRBS between time slots. Each encoder in each time slot thus ends up seeing a different portion of the PRBS, effectively emulating eight separate users. Each encoder adds a different 64-chip Walsh code on the spread spectrum of the pulse streams. The coded signals are combined and go through the decoder, which reconstructs pulses for the two users from Encoder #1. The pulses from the other six users remain spread and low in amplitude. Finely adjustable time delays are used to bit align the outputs of the encoders with respect to one another. Each encoder path also contains attenuators (atten.) to equalize the power of the users.

After decoding, a NOLM selects one of the time slots for thresholding and detection. The NOLM employs 500 m of highly nonlinear fiber (HNLF) to serve as the nonlinear medium and a 3-ps, 9-GHz pulse train for the control. To generate the control pulses, we shift the wavelength of a tapped portion of the ~400 fs source pulse stream by sending it through 1 km of dispersion-shifted fiber (DSF). Self-phase modulation causes a significant portion of the pulse spectrum to shift to 1540 nm. Bandpass filtering this portion (1 nm FWHM) and amplifying it produces the 3-ps pulse train. The selected time slots proceed to the thresholder previously described in [2] to clean the signal of MUI leaking through the 3-ps gate. Operation is similar to the generation of the NOLM's control pulse. Essentially, the high peak power in a correctly decoded pulse drives self-phase modulation inside 500 m of highly nonlinear fiber (HNLF), causing the spectrum to shift to wavelengths above and below the center wavelength of the pulse. A longpass filter selects the red-shifted spectrum component and then passes it to the receiver. Incorrectly decoded pulses, with their low peak power, do not generate the shifted spectra and are thus suppressed. An O/E converter receives the thresholded signal for bit-error-rate measurements.

3. Results and Discussion

Cross-correlation measurements in Fig. 2 reveal that the NOLM is effective in suppressing MUI and can perform more than just simple time demultiplexing. Fig. 2a shows the cross-correlation at the input to the NOLM for eight users. A single time slot is centered at 0 ps, and spans from -27.5 ps to 27.5 ps. It contains a correctly decoded user that appears as a 940-fs pulse and three incorrectly decoded users that spread throughout the slot. The correlations also show the adjacent time slots containing the other four users, centered at approximately -55 ps and 55 ps. Since the slots share the same codes, they both contain a correctly decoded signal and three incorrectly decoded signals. The spreading of the correctly decoded pulses from the original input pulse originates from spectral filtering inside the encoders and decoders. Fig. 3b shows the NOLM output, having gated the desired correctly decoded signal at 0 ps. As expected, it completely removes the four users lying in the adjacent time slots, while careful dispersion compensation inside the NOLM allows the pulse to maintain its 940-fs pulse width. Additionally, the NOLM is shown to be effective at reducing MUI. It successfully blocks the incorrectly decoded signals which lie outside the gate.

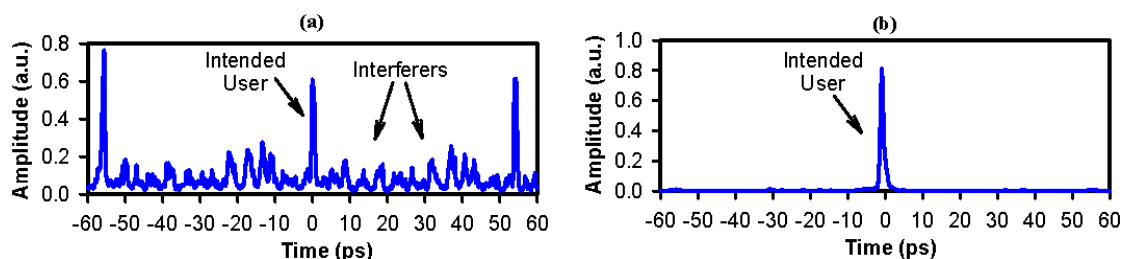


Fig. 2. Cross-correlation measurements (a) before and (b) after the NOLM with eight users distributed in two time slots. Reference pulse width is 400 fs.

Fig. 3 shows the BER performance of this eight-user testbed. For the measurement, we define the receiver of the system to include the preamplifier of the NOLM, the NOLM, the thresholder, and the O/E converter. The horizontal axis of the plot indicates the total amount of optical power at the input to this receiver. The arrows at the end of BER curves indicate the power where we obtained error-free performance while collecting more than 3×10^{13} bits ($\text{BER} < 10^{-12}$). The back-to-back case shown in trace A corresponds to the testbed without the encoders and decoder. The two-user case (trace B) adds a single encoder and decoder, and thus “two users” refers to two 9-Gb/s streams placed

55 ps apart and sharing the same code. The four-user (trace C), six-user (trace D), and eight-user (trace E) cases each add an encoder to the system, and thus each encoder adds another pair of 9-Gb/s streams that share codes. The synchronous time-slotted O-CDMA network testbed performs error-free for up to six simultaneous users, while for eight users, a BER below 10^{-9} is achieved. The penalty occurring between the back-to-back and 2-user BER curves results from spectral filtering due to the encoder and decoder. A 4.5-dB penalty occurs at 10^{-9} BER between the two- and four-user curves. Since the BER curves are taken versus the total input power to the preamplifier of the NOLM, we would expect a 3 dB power penalty with each doubling of the number of users. The remaining 1.5 dB penalty is presumably caused by MUI. Between the four- and six- user curves, we see the expected 1.8-dB penalty due to the increase of number of users, but we do not see any penalty due to MUI. However when adding the last two users, we see a 5-dB power penalty, 3.8 dB of which must be due to MUI.

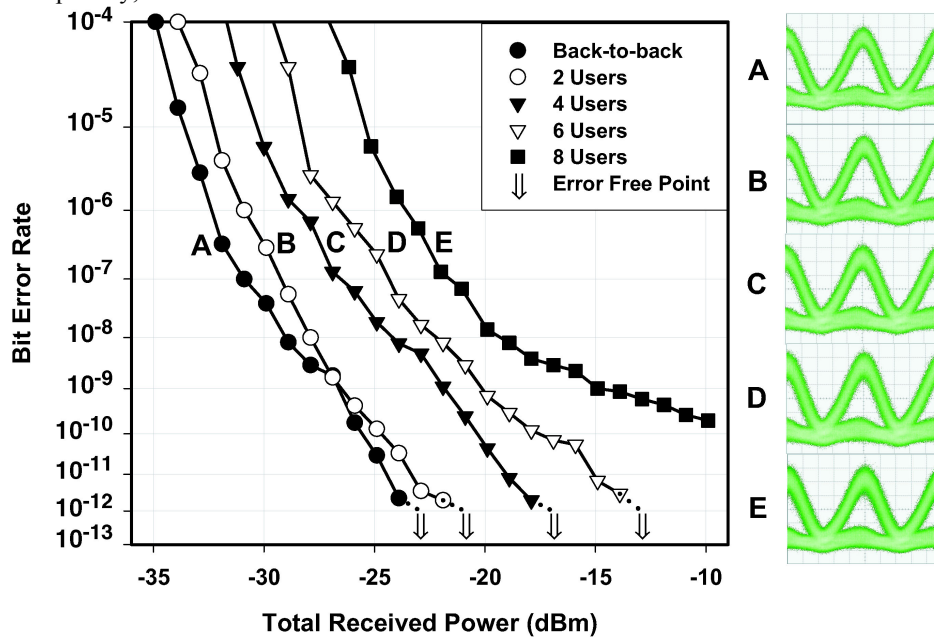


Fig. 3. Bit-error-rate and eye diagrams obtained for the 9-Gb/s/user, time-slotted, SPECTS O-CDMA testbed.

4. Conclusion

We have demonstrated a synchronous SPECTS O-CDMA network testbed incorporating time slotting, thereby increasing its capacity to eight users while using only four codes. For a synchronous system using Walsh codes, we show that the NOLM works successfully as a demultiplexer that suppresses multi-user interference. The combination of the NOLM with a thresholder allows us to achieve a BER below 10^{-9} for eight synchronous users distributed in two time slots and error-free performance for up to six users.

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