High performance 70 Gbit/s SPECTS optical-CDMA network testbed

W. Cong, R.P. Scott, V.J. Hernandez, K. Li, J.P. Heritage, B.H. Kolner and S.J.B. Yoo

Error-free operation of an optical code division multiple access (O-CDMA) network testbed with seven simultaneous users at 10 Gbit/s/user distributed in two time slots is demonstrated. The O-CDMA network testbed overcomes the key challenge of multi-user interference by adopting a highly nonlinear fibre-based thresholder and by careful system engineering.

Introduction: Remarkable increases in the internet traffic have recently propelled upgrades in the wide-area and metropolitan-area networks employing advanced wavelength-division-multiplexing (WDM) and time-division-multiplexing (TDM) communication systems. Modern local-area networks (LANs) on the other hand, require less processing at the centre nodes but more flexible high-speed access at the edges. Optical code division multiple access(O-CDMA) has promising advantages in LAN applications because of the high bandwidth capacity and the flexibility inherited from code-based reconfigurability without involving WDM or TDM switching components. While various O-CDMA schemes have been proposed and demonstrated in the past two decades [1, 2], they indicate that multi-user interference (MUI) is the primary hurdle in achieving a high capacity O-CDMA network.

In this Letter we discuss an O-CDMA networking testbed adopting the spectral phase encoded time spreading (SPECTS) technique. In this scheme, short optical pulses are phase modulated with a unique code in the spectral domain which spreads them in time [1]. The receiver reconstructs the original short pulses by using the conjugate code. Codes are chosen so that the signal pulses from other users remain spread in time. It is important to note that the integrated pulse energy of a time-spread pulse is the same as that of a compressed pulse making it difficult for traditional bandwidth-limited detectors to differentiate between them. In SPECTS O-CDMA, discrimination is achieved through nonlinear thresholding and detection. The thresholder is based on optical fibre nonlinearity, which was first proposed by Sardesai and Weiner [3]. Utilising highly-nonlinear fibre (HNLF) instead of dispersion-shifted fibre (DSF) in the thresholder significantly improved the sensitivity and suppressed MUI. Recently, we reported bit error rate (BER) measurement results of a smaller SPECTS O-CDMA testbed using the HNLF thresholder for one and two users [4, 5]. In this Letter, we demonstrate a time slotted O-CDMA network operating at 10 Gbit/s/user with a total of seven simultaneous users.

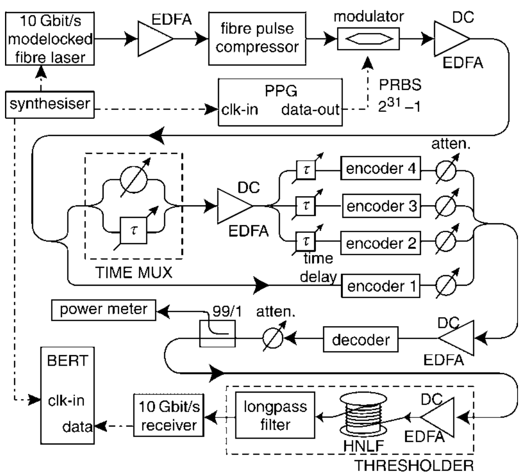

Fig. 1 *Experimental setup for seven-user SPECTS O-CDMA network testbed*

Experimental setup: Fig. 1 shows the experimental setup for the synchronous seven-user O-CDMA network testbed. The testbed includes four encoders and one decoder operating in two time slots to emulate a seven-user O-CDMA network (70 Gbit/s O-CDMA LAN) as described below. A modelocked fibre laser, followed by a pulse compressor, generates stable 500 fs pulses at 9.95328 GHz with a 1550 nm centre wavelength. Pseudorandom bit sequence (PRBS) modulated pulses are amplified by a dispersion-compensated erbium-doped fibre amplifier (DC-EDFA), and then split into two bit streams. One goes through encoder 1 directly, and the other is time multiplexed (MUX) into a 2 × 10 Gbit/s bit sequence occupying two 50 ps-wide time slots.

Each encoder and decoder consists of a fibre-pigtailed, zero-dispersion pulse shaper with a liquid-crystal spatial light phase modulator (LC-SLPM) in the Fourier (spectral) plane [4, 5]. Each LC-SLPM impresses a unique 64-chip Walsh phase-code (codes 5, 54, 52 and 32, respectively) on the pulse spectrum. The code on the decoder is conjugate to that on encoder 1. Thus, encoder 1 and the decoder are the *intended* user and encoders 2 to 4 act as *interfering* users. The time multiplexed output is amplified and split into three separate bit streams before being encoded. In this way, encoders 2 to 4 apply their respective codes to both time slots in the multiplexed channels. The variable time delays are used to slot align the interfering channels in time to the intended user channel and the attenuators are used to equalise each interferer's power to the intended user's power. The encoded pulse streams are combined, amplified and passed through the decoder. The output of the decoder goes to the thresholder (lower dashed box), which is composed of a preamplifier, 500 m of HNLF (Sumitomo, HNLF 1322AA-2), and a longpass filter ($\lambda > 1568$ nm). Spread pulses from the interferers are suppressed and short pulses from the intended user are passed by the thresholder, whose output feeds the optical receiver. The BER of the O-CDMA testbed is taken against the total received power at the thresholder input.

Much effort went into system engineering to minimise the effects of MUI. An important consideration was O-CDMA code selection. Pulses spread with Walsh codes have a characteristic intensity minimum at their centre and thus provide superior MUI suppression in a synchronous system than would a code which produces maximally flat pulse spreading (e.g. M-sequences). Unwanted reflections, dispersion and polarisation effects are also important. The testbed incorporated careful optical engineering to reduce reflections, and used polarisation-maintaining, dispersion-shifted fibre (PM-DSF) around the encoders and decoder. However, we made no attempt at polarisation control within the HNLF thresholder.

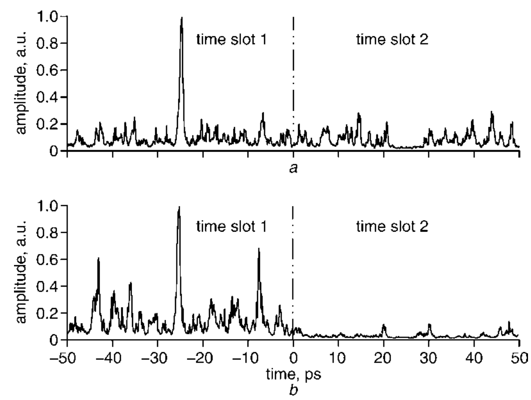

Fig. 2 *Cross-correlation traces of decoder output*

a Seven users in two time slots
b Four users in time slot 1

Results and discussion: Fig. 2 shows the decoder output signal in the time domain measured using a cross-correlator with a 400 fs reference pulse. Fig. 2*a* is a plot of the combined signals from all seven users. Time slot 1 contains the intended user and three interferers, and time slot 2 contains three more interferers. The tall peak at the centre of time slot 1 is from the intended user, and the noise-like signals along the bottom in both time slots are from the interferers. Time slot 2 demonstrates the centre intensity minimum associated with Walsh codes. Fig. 2*b* is the decoder output signal when one arm of the time MUX is blocked, yielding no users in time slot 2, and it shows why we can accommodate two time slots simultaneously. The interferers' signals in Fig. 2*b* are not equalised to the intended user because of gain sharing in the EDFA following the time MUX. In the HNLF of the thresholder, self-phase modulation and other nonlinear effects generate spectrum at longer and shorter wavelengths owing to the high peak power of the intended user, and at the same time, the output spectra for the spread pulses from the interferers remain nearly unchanged. After going through a longpass filter, MUI is suppressed and the power contrast ratio between the intended user and the sum of the six interferers is typically >20 dB. Additional details of HNLF thresholder operation are described in [5].

Fig. 3 shows the BER performance of the SPECTS O-CDMA system. The O-CDMA network testbed achieves error-free performance while accommodating up to seven users. At the bottom of each BER curve, an arrow indicates the minimum power in the network required for error-free operation, i.e. no detected errors while collecting more than 3×10^{12} bits (BER $< 10^{-12}$). Trace A is the back-to-back BER curve of the testbed without encoders and decoder. Trace B is the BER curve of one user only. For traces C–E, we add successive pairs of interferers. The power penalty between traces A and B is approximately 5 dB, due to spectral filtering and subsequent pulse broadening at the encoder and decoder stages. There is also power penalty associated with each additional pair of interferers. The BER plots show total power measured at the front of the DC-EDFA of the thresholder, which is increased while we add users to maintain the same input power to the thresholder from the intended user, thus showing apparent power penalty.

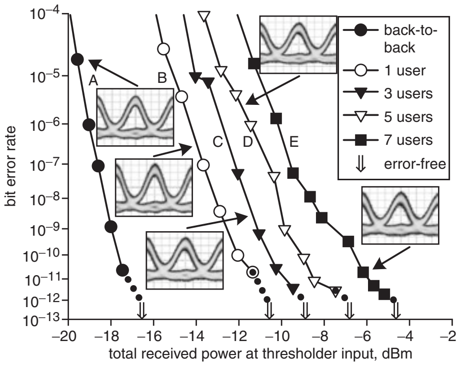

Fig. 3 *BER performance of SPECTS O-CDMA system*

Conclusion: This Letter describes error-free performance of a synchronous SPECTS O-CDMA network testbed with seven users, each operating at 10 Gbit/s, distributed in two time slots. The HNLF thresholder successfully differentiates the intended user from the six interferers leading to error-free 70 Gbit/s O-CDMA operation.

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