Suppression of WDM Interference for Error-Free Detection of Ultrashort-Pulse CDMA Signals in Spectrally Overlaid Hybrid WDM-CDMA Operation

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***Abstract*—We demonstrated the complete suppression of wavelength division multiplexing (WDM) interference for the error-free detection of ultrashort-pulse code division multiple access (CDMA) signals in spectrally overlaid optical WDM-CDMA hybrid operation by the use of narrowband spectral notch filters in the CDMA decoder and a fiber nonlinear thresholder. Our experimental results show the feasibility of CDMA detection in a scheme where WDM channels are overlaid on CDMA channels in the same spectral region.**

***Index Terms*—Code division multiple access, femtosecond pulses, ultrashort pulses, wavelength division multiplexing.**

I. Introduction

RECENTLY, experiments on optical ultrashort-pulse code division multiple access (CDMA) communications have been reported by several groups using either bulk optic pulse shapers [1], integrated pulse shapers based on array waveguide grating (AWG) technology [2], or patterned fiber Bragg gratings [3]. The CDMA scheme promises high data-security asynchronous communications for local area networks and is well suited for a bursty environment such as the Internet, where a large number of users transmit data intermittently. Compared to wavelength division multiplexing (WDM), optical CDMA is technologically less mature. However, owing to its coherent broad-band nature, the ultrashort-pulse CDMA is complementary to WDM that uses narrow frequency channels. It may be possible to significantly increase the utilization of EDFA bandwidth in existing WDM systems through spectrally overlaying ultrashort-pulse CDMA on the WDM system. In such a novel hybrid WDM-CDMA system, broad-band CDMA signals utilize the spectral guard bands between WDM channels and may provide additional bandwidth to the WDM system without requiring costly expansion of EDFA bandwidth. The inherent difference between WDM and CDMA signals in the spectral domain (narrow-band versus broad-band) and in the time domain (low-intensity versus high peak power) implies that the crosstalk between two schemes can be suppressed allowing simultaneous error-free recovery of WDM and CDMA data. In the spectral domain (inset of Fig. 1), only a small fraction of the energy from broad-band CDMA spectra will fall within each narrow-band WDM channel while the WDM components can be also notched out of the CDMA spectra without degrading CDMA detection. In the time domain, compared to high-intensity CDMA signals, the WDM traffic is a low-intensity nonreturn to zero (NRZ) or RZ signal—it can be easily eliminated during CDMA detection by a nonlinear thresholder that rejects multiaccess interference based on signal peak power. This novel hybrid scheme draws advantages from both WDM and CDMA—the mature technology available for WDM and the high security and potential for larger spectral efficiency promised by overlaying CDMA on WDM.

In this letter, we report the first experiments demonstrating the feasibility of optical hybrid WDM-CDMA operation. Our experiments were performed using the ultrashort-pulse CDMA concept where subpicosecond laser pulses are used for spectral encoding/decoding; this approach offers the potential for higher performance compared to other CDMA alternatives [4] but also involves more complex technology. Our results should also be relevant to CDMA performed on longer time scales [3]. In this work, we focus on the complete suppression of WDM interference for error-free detection of CDMA signals by employing a narrow-band spectral notch filter in the CDMA decoder and by using a nonlinear fiber thresholder. As a result, we obtained error-free detection of a CDMA channel in the presence of a spectrally overlaid WDM channel. We address the scaling of these experiments to the hybrid operation with many closely spaced WDM users. To our knowledge, this is the first report of the bit error rate (BER) performance of a CDMA channel in hybrid WDM-CDMA operation.

II. Suppression of WDM Interference in a CDMA Detector

In a hybrid WDM-CDMA system, the network traffic consists of narrow-band WDM signals overlaid with broad-band CDMA signals in the same spectral region. Each user is equipped with two detectors—one for CDMA detection and the other for WDM detection. The WDM detector consists of a narrow-band pass filter followed by O/E conversion. The CDMA detector designed and constructed for the hybrid system consists of a spectral decoder, a fiber amplifier, a fiber nonlinear thresholder, and a receiver (here, an APD), as shown in Fig. 1. The complete pure CDMA system, including a spectral encoder/decoder pair and a fully dispersion-compensated fiber transmission link, has been investigated before [1]. Here, we focus on the suppression of WDM interference in

Manuscript received March 17, 2000; revised July 25, 2000. This work was supported in part by the National Science Foundation under grants ECS-9626967, ECS-9900369, and PHY-9722668.

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Publisher Item Identifier S 1041-1135(01)00505-5.

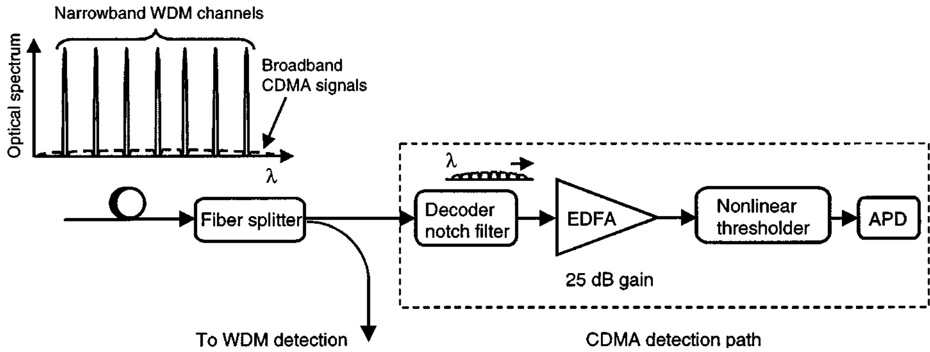


Fig. 1. Schematic diagram of a CDMA detector constructed for optical WDM-CDMA hybrid operation. Incoming network traffic consists of broad-band CDMA signals (dashed line) and spectrally overlaid narrow-band WDM channels (solid line).

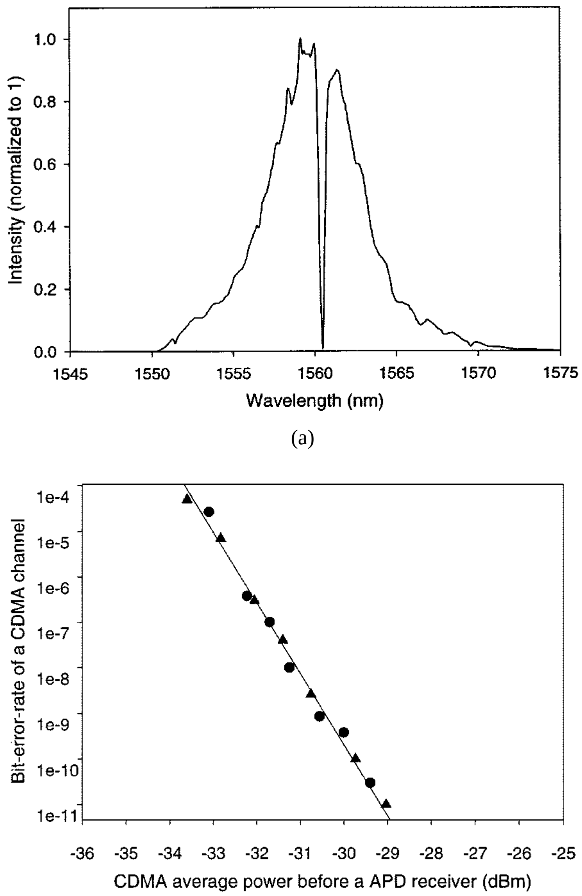
the CDMA detector to ensure error-free CDMA detection for the hybrid operation. The spectral decoder used here is made from a programmable fiber-pigtailed femtosecond pulse shaper equipped with a liquid-crystal phase-modulator array (LCM) [5]. Its function is to demultiplex CDMA users in the networks through matching the spectral phase code applied in the encoder [4]. Since the wavelength components of both CDMA and WDM data are spatially dispersed across the Fourier plane of the pulse shaper, we can easily install narrow-band notch filters at the Fourier plane to remove most (>99.5%) of the WDM power. The hybrid WDM-CDMA principle proposed here could also be implemented using other encoder-decoder technology such as AWG [2] or fiber Bragg grating [3] based approaches. Then, after an EDFA with 25-dB gain, we launched the CDMA data and the surviving WDM interference into a nonlinear thresholder based on self-phase modulation (SPM) in a dispersion-shifted fiber [6]. The nonlinear thresholder rejects improperly decoded pulses from interfering CDMA users (manifested as low-intensity pseudonoise signals) and recognizes properly decoded pulses from a desired CDMA user (clean subpicosecond pulses) based on signal peak power [6]. Since the WDM interference is also of low intensity, any residual WDM interference after the notch filter is completely rejected by the nonlinear thresholder as well. We note that the use of a nonlinear thresholder is required even in a pure ultrashort-pulse CDMA system. Moreover, since the residual WDM interference can be totally eliminated by the thresholder, WDM signals need not be completely separated from the CDMA data at the decoder. The WDM power only needs to be reduced enough to avoid saturating the fiber amplifier.

III. Experiments and Results

We performed back-to-back system experiments and measured the BER performance of one ultrashort-pulse CDMA channel spectrally overlaid with one 2.5-Gb/s WDM channel. A fiber laser was used was used to generate nearly transform-limited pulses (FWHM pulsewidth ~480 fs, ~6 nm bandwidth) centered at 1560 nm at 40 MHz repetition rate. The laser pulses were then synchronously modulated at 40 Mb/s with a length $-2^{23}-1$ pseudorandom bit stream (PRBS). By applying either a constant phase or a length-31 *m*-sequence phase code in the decoder, we emulated the properly and improperly decoded CDMA signals, respectively. The decoder has an insertion loss of 8 dB for the CDMA signals. The average power of CDMA pulses is > 5 μW before the decoder and > 250 μW before the fiber thresholder. At this energy level, the output contrast ratio after the thresholder between the properly and improperly decoded CDMA pulses was >20 dB for the LWPF cutoff wavelength at 1572 nm. We note that the CDMA power used here is set by thresholder requirement. In principle, it could be lowered possibly by developing a thresholder with lower power requirement.

The WDM signal was generated from a temperature-stabilized DFB laser centered at the peak of CDMA spectrum at 1560.4-nm (FWHM <0.1 nm) and modulated with 2.5-Gb/s $2^{31}-1$ NRZ PRBS data. In order to demonstrate the ability to reject strong WDM interference, we set the average power of WDM signals before the CDMA decoder to ~ 75 μW, which is much higher than needed to yield simultaneous error-free detection in the WDM detector. This is also ~15 times higher than the CDMA power prior to the decoder. We used a thin-wire notch filter (FWHM ~0.3 nm) in the pulse shaper to block the WDM component with an extinction ratio of 30 dB (this includes the 8-dB insertion loss of the pulse shaper itself). The output spectrum after the decoder with the WDM channel blocked is shown in Fig. 2(a). Fig. 2(b) shows the BER performance of the CDMA channel with and without the WDM interference. Our results show no observable power penalty to CDMA detection from the WDM data stream. It indicates that the WDM interference has been completely removed in the CDMA detection path by the spectral notch filter and the fiber thresholder. Note that without the nonlinear thresholder, the residual WDM components, whose strength is about one tenth of CDMA signals after the decoder, will severely impair the CDMA detection. The use of nonlinear thresholder is very effective in suppressing the low-intensity WDM components. We found in experiments that the thresholder can tolerate as high as 1-mW WDM residual interference. This CDMA detection scheme should work equally well for gigabit-per-second CDMA data rates as long as the output of the fiber amplifier is increased proportionally.

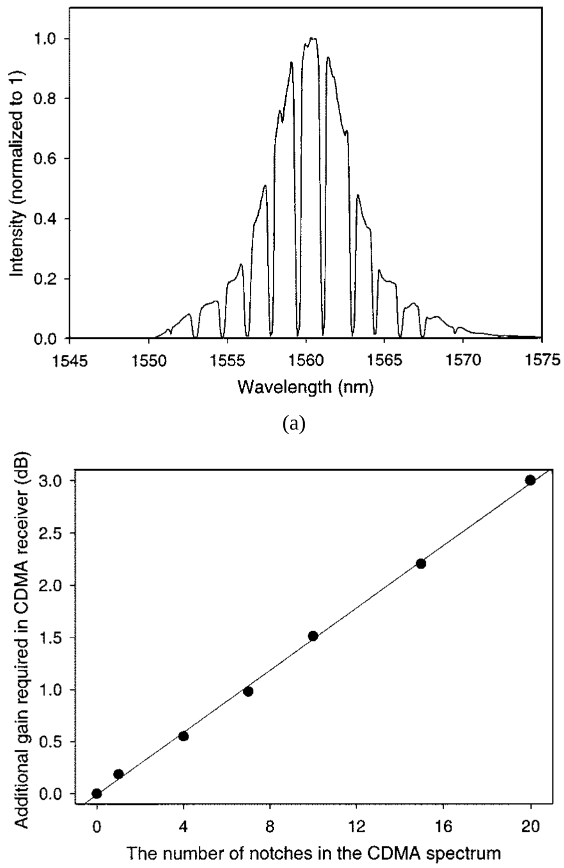
For a system with many closely spaced WDM users, we expect the major impairment to CDMA detection in the hybrid scheme will arise from a reduction of energy and a distortion of the ultrashort pulses before the fiber thresholder due to multiple



(a)

(b)

Fig. 2. (a) Output spectrum of the CDMA decoder with one spectral notch filter blocking the WDM channel at 1560.4 nm. (b) BER of a CDMA channel with (▲) and without (●) WDM interference before the CDMA decoder.



(a)

(b)

Fig. 3. (a) Output spectrum after the decoder with 10 narrow-band notches in the CDMA spectrum. (b) Additional gain required for spectrally notched CDMA signals to achieve the same ∼20-dB contrast ratio in the fiber thresholder compared to unnotched CDMA signals. Solid line: linear regression curve.

spectral notches. To show the feasibility of data detection with multiple notches in the CDMA spectrum, we performed experiments in which we applied different numbers of spectral notches (from zero to 20) in the CDMA decoder and measured the additional gain required before the thresholder in order to maintain a 20-dB contrast ratio between properly and improperly decoded CDMA signals. A CDMA spectrum with ten notches is shown as an example in Fig. 3(a). Fig. 3(b) shows the additional gain required in the CDMA detector. We found that compared to the case of no spectral notch, less than 3-dB additional gain is required to compensate the peak power reduction in the CDMA signals for up to 20 notches, which would correspond to 20 WDM channels with ∼100-GHz channel separation. Hence, error-free CDMA detection with low power penalty should be possible with closely spaced WDM users in the overlay hybrid operation.

IV. Conclusion

We have demonstrated for the first time the error-free detection of ultrashort pulse CDMA signals, which are spectrally overlaid with a 2.5-Gb/s WDM channel. We show that the WDM interference can be easily eliminated by the use of spectral notch filters and a fiber nonlinear thresholder.

Acknowledgment

The authors acknowledge discussions with Prof. M. Bell, Prof. E. Coyle, and Prof. J. Lehnert leading to the WDM-CDMA overlay concept.

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