80.8-km BOSSNET SPECTS O-CDMA Field Trial Using Subpicosecond Pulses and a Fully Integrated, Compact AWG-Based Encoder/Decoder

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Abstract—We successfully demonstrate a spectral phase-encoded time-spreading (SPECTS) optical code-division multiple-access (O-CDMA) field trial on an 80.8-km link within the Boston-South Network (BOSSNET) using a fully-integrated, polarization-independent arrayed-waveguide grating (AWG)-based encoder/decoder. The subpicosecond pulse source is based on an ultrastable optical frequency comb generator employing dispersion-decreasing fiber. A novel tunable dispersion-slope compensator enables the use of subpicosecond pulses without extensive characterization of the field-deployed fiber. Bit-error rate (BER) and Ethernet traffic statistics are presented.

Index Terms—Access networks, nonlinear detection, optical code-division multiaccess, optical fiber communications.

I. INTRODUCTION

O PTICAL code-division multiple-access (O-CDMA) technologies [1], [2] are attractive for applications in high-bandwidth access networks. Increasing demand for broadband access has pushed service providers to look toward access systems that allow for high speeds while maintaining flexibility, reconfigurability, and simplified network control and management. Code-based access of optical networks can potentially solve many of these issues and the recent realization of fiber-to-the-premise (FTTP) has renewed interest in O-CDMA [3], [4]. Various implementations of O-CDMA have been proposed and demonstrated over the last two decades, including both 1-D [5]–[8] and 2-D [9]–[12] codes.

Among the various O-CDMA schemes, spectral phase-encoded time-spreading (SPECTS) has shown extreme promise as a high-speed access technique. Recent demonstrations showing successful recovery of subpicosecond, 10-Gb/s signals in the presence of up to 31 interfering signals [13] or with extremely high sensitivity [14] have reinforced the validity of the spectral phase encoding. In SPECTS O-CDMA, a phase code is applied to the spectrum of data-modulated pulses, spreading the pulses in time. Recovery of the signal requires the decoder to apply the conjugate phase code, resulting in a short pulse. In a multiuser system, a user receives his own phase code, and a nonlinear thresholder at the receiver differentiates between the desired signal and the interfering signals, which remain spread by virtue of code orthogonality. Many spectral phase-encoded O-CDMA implementations have been limited by their dependence on bulk optics-based encoders and decoders [15], [16], reducing their practicality in rigorous telecom environments. Although there have been initial SPECTS O-CDMA systems using integrated components, they have thus far been limited to short code lengths (up to 8 chips), leading to low signal-to-interference contrast [17]; or they have not incorporated components onto a single monolithic device [18]. Recently, alternative O-CDMA systems have been demonstrated in field trials; a 111-km field trial using spectral amplitude encoding [19], a 50-km field trial of a direct time-spreading O-CDMA [20], and a 200-km field trial of a wavelength-hopping, time-spreading O-CDMA scheme [21]. While a laboratory demonstration [22] has shown successful transmission of 500-fs pulses over 50 km of fiber, field fiber transmission of subpicosecond pulses is considered extremely challenging due to the combined effects of polarization-mode dispersion (PMD), chromatic dispersion, and optical nonlinearity.

This paper presents a SPECTS O-CDMA system field trial utilizing subpicosecond pulses and a compact, monolithic, fully integrated encoder/decoder based on polarization-independent, silica arrayed-waveguide grating (AWG) technology. The device supports code lengths of up to 64 chips, enabling signal-to-interferer contrasts that far exceed previous monolithic devices. For the field trial, we utilized an 80.8-km link at one end of the Boston-South Network (BOSSNET). BOSSNET is subject to environmental effects in the field fiber plant not easily
replicated in laboratory demonstrations, including temperature-induced fluctuations in the fiber’s refractive index, stress-related birefringence leading to time- and polarization-dependent loss, and dispersion. These effects, and others, limit the performance of optical networks. We overcome these obstacles and demonstrate the viability of SPECTS O-CDMA in practical networks.

II. FIELD TRIAL DESCRIPTION

Fig. 1 shows the SPECTS O-CDMA field trial setup. The five major parts are the optical source, the multiport AWG-based encoder/decoder, the field fiber, and the nonlinear thresholding receiver. The optical source is described in detail in Section II-B, and the tunable dispersion-slope compensator (TDSC) is described in Section II-C, while the remainder of the setup is detailed in the following section.

A. Field Trial Setup Detail

The optical frequency comb generator (OFCG) shown in Fig. 1 is a very stable subpicosecond optical pulse source. It produces 700-fs pulses at a 20-GHz repetition rate and a center wavelength of 1551.4 nm. This pulse stream is ON-OFF key modulated with a pseudorandom bit sequence (PRBS) of length $2^{31} - 1$ via a LiNbO$_3$ Mach–Zehnder modulator at 2.5 Gb/s. Thus, on average, each “1” bit is represented by eight pulses; and, in this experiment, the pseudorandom pattern generator (PPG) and OFCG are not synchronized. The data-modulated pulse stream is then split and separately amplified. A fixed delay and a variable time delay are used to temporally decorrelate the data and provide an adjustable relative time delay between the two signals.

SPECTS encoding and decoding is performed by a 64-channel, silica multiport AWG-pair with a 20-GHz passband spacing, a free-spectral range (FSR) of 1282.44 GHz, and a ~3-dB channel bandwidth of ~10 GHz. In this AWG-pair, the signal on an input port is demultiplexed by the first AWG into multiple channels, each with its own wavelength; i.e., $\lambda_1$, $\lambda_2$, etc. Each channel has its own thermo-optic-based phase modulator which can apply a polarization-independent zero to $\pi$ phase shift. A second AWG then multiplexes all of the wavelengths back into an output port. This multiport AWG-pair is designed so that each input–output pair (e.g., A-A’ or B-B’) is frequency shifted by 20 GHz with respect to the adjacent pairs. Unrelated input–output pairs have better than ~20-dB crosstalk. Looking at the depiction of the encoder in Fig. 1, if the input–output pair A-A’ has $\lambda_1$, $\lambda_2$, through $\lambda_{63}$ distributed across the channels as shown, then B-B’ would put $\lambda_{64}$, $\lambda_1$, $\lambda_2$, through $\lambda_{63}$ on those same respective channels. This behavior is very much like linear-feedback shift registers. In this experiment, 63-chip m-sequences are used for the spectral codes. Therefore, the device is applying one chip of the m-sequence to each mode (or line) of the source; truly line-by-line encoding [23]. We take advantage of the fact that different codes within a particular m-sequence group are cyclic bit-shifted versions of one another [24]. By applying a single m-sequence to the multiport AWG-pair, we simultaneously generate up to four uniquely encoded signals, one for each input–output port pair. The frequency stability of multiport AWG-pair is maintained via thermo-electric control which holds the temperature stable to within ±0.003°C, corresponding to a maximum drift of ±15 MHz.

Referring back to Fig. 1, the two data-modulated streams go through different input–output port pairs and, consequently, receive different spectral codes. The multiport AWG-pair is bidirectional and the B-B’ ports are used simultaneously as the encoder and decoder, where circulators at each port isolate the encoding and decoding operations. A variable attenuator equalizes power of the encoded signals, and polarization controllers (PC) are used to align and linearize the signals’ polarization before they are combined and amplified. A TDSC precompensates the dispersion slope of the BOSSNET link before further amplification and subsequent launch onto the BOSSNET. Although shown separately in the figure, the TDSC includes a 10.5-nm bandpass filter which blocks the unwanted FSR’s of the multiport AWG-pair and amplified spontaneous emission (ASE) from the erbium-doped fiber amplifiers (EDFA). All elements after the TDSC are polarization insensitive, and, thus,
no polarization tracking is required in the system beyond initial optimization for prelink components (i.e., the polarizing TDSC). This encoder/decoder configuration may be especially useful in passive optical networks (PON) which utilize $1 \times N$ configurations (i.e., tree architecture) [3] where the multiprotocol AWG would be housed at the optical line terminal (OLT), simultaneously encoding and decoding multiple users.

The field fiber is a BOSSNET link spanning between the MIT Lincoln Laboratory campus (Lexington, MA) and a point-of-presence (POP) in downtown Boston, MA. The link is composed of multiple 40.4-km LEAF fibers installed in the late 1990s with an unamplified loopback at the Boston POP (i.e., 80.8-km round trip). Upon return from BOSSNET, the signals are amplified and then dispersion compensated with dispersion compensating fiber (DCF). Although we were not able to quantify the link’s differential group delay (DGD), the output pulse shape and width did not have a significant dependence on its launch polarization, indicating a negligible amount of PMD. A circulator passes the signals through to the decoder, where one of the signals is correctly decoded to short pulses. The other signal (the interferer) that remains temporally spread is discriminated using a nonlinear thresholder. In the nonlinear thresholder [15], the high peak intensity of the short, correctly decoded user’s pulse generates additional spectral components through self-phase modulation and other nonlinear processes when propagating in the highly nonlinear fiber (HNLF), while the spectra of the incorrectly decoded pulses from the interferer remains unchanged due to their much lower peak intensity. A 3-nm wide bandpass filter is tuned to pass a portion of the nonlinear generated spectra to the 2.5-Gb/s optical receiver (HP 83446A) for bit-error rate (BER) measurement. The receiver incorporates both clock and data recovery (CDR), eliminating the need for a global clocking system.

B. Optical Frequency Comb Generator

The relatively narrow-channel passbands of the AWG-pair require the optical pulse source to have a very stable optical comb in the frequency domain. The amplitude and phase of the individual comb lines will acquire unintentional amplitude and phase change (due to the AWG-pair passbands) if the absolute position of the frequency comb shifts by more than a few hundred megahertz. More significantly, the modulated data that appears as upper and lower sidebands around each comb line will experience asymmetrical attenuation, leading to pattern-dependent amplitude changes in the AWG-pair output. For this reason, we have found that the harmonically mode-locked fiber laser used in previous SPECTS systems [15] is unsuitable. Initial testing using these sources show that the absolute center position of the frequency comb fluctuates by more than a few gigahertz, despite exhibiting an extremely stable repetition rate (i.e., frequency comb spacing). As an alternative, we utilize an optical pulse source that strongly modulates a stable single-frequency laser, generating sidebands around the optical carrier. Sources using this technique are often referred to as optical frequency comb generators (OFCG) [26] and they are becoming popular in optical arbitrary waveform generation. Amplitude modulation (AM) by itself is quite lossy and phase modulation (PM) by itself produces uneven comb amplitudes since the Bessel function determines the sideband amplitudes. However, as demonstrated by Fugiwara et al. [27], a combination of AM and PM can be used to flatten the frequency comb.

The OFCG used in this experiment is based on simultaneous AM/PM modulation of a tunable single-frequency laser using a single Mach–Zehnder modulator as originally proposed by Sakamoto et al. [28] with further compression in a dispersion decreasing fiber (DDF) [29]. This arrangement is shown in Fig. 2 and it produces a flattened optical comb via a single dual-electrode Mach–Zehnder modulator (DEMZM) (Sumitomo Osaka Cement, T.DEH1.5-40-ADC-P-FA). The DEMZM is simultaneously capable of both amplitude and phase modulation depending on the relative amplitude and phase differences of the driving radio frequency (RF) fields and the relative optical phase difference between the two arms of the interferometer (i.e., bias). The average powers at RF1 and RF2 are approximately +27 dBm and +25 dBm, respectively, and the bias has been adjusted to approximately $\pi/2$ rad. The optical loss through the DEMZM is approximately 9 dB in this configuration. The spectral phase at the output of the DEMZM is mostly quadratic in shape (i.e., linear frequency chirp) and is intrinsic to comb generators based on large phase modulation of CW laser light. A 1.08-km length of standard single-mode fiber (SMF) compensates the chirp and subsequently compresses the pulse from 25 to $\sim$5 ps before amplification. The DDF is designed to compress pulses with input widths of 2.5–5 ps. An EDFA amplifies the pulses to an average power of +22 dBm before launching them into the DDF. The 1-km DDF (PriTel, DDF-400) has an input dispersion of 9.8 ps/nm and it decreases linearly to 2.1 ps/nm at the output [30]. The DDF uses the interaction between the fiber nonlinearity and decreasing dispersion to compress the pulse in a soliton-like fashion. The output pulses are 700-fs wide and near-transform limited [29].

C. Tunable Dispersion-Slope Compensator

The TDSC is a small zero-dispersion fiber-coupled bulk-optics pulse shaper with a flexible cubic-shaped mirror placed at the Fourier plane [31]. Fig. 3 is a diagram illustrating this concept. After collimation, the grating in the pulse shaper...
spatially spreads the spectrum of an input pulse and the Fourier lens focuses each component of the spread spectrum onto a thin flexible mirror. The mirror is mechanically mounted so that it has a nearly pure cubic shape that it maintains while it is bent. This cubic shape causes a cubic phase shift as a function of wavelength across the spectrum of the pulse that is used to compensate the third-order dispersion (i.e., dispersion slope) present in optical fiber. The mirror shape mechanically adjusts to compensate up to $\pm 5.5$ ps/nm$^2$ of dispersion slope when the pulse shaper is configured in a double-pass arrangement. The total loss through the pulse shaper in the double-pass configuration is typically 9 dB when including the optical circulator that separates the input and output signals.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Recovery of subpicosecond pulses is necessary for the success of this SPECTS O-CDMA system. For fiber links longer than 1 km, this requires both dispersion and dispersion-slope compensation. Fig. 4 compares the dispersion between the 80.8-km link, the TDSC, and the combination of the two elements, as measured using a simple method based on the beating of modes from filtered subpicosecond pulses. Our method is similar to that of Mori, et al. [32] except that we use a 20-GHz sampling oscilloscope instead of lock-in detection. Fig. 4 clearly shows the dispersion slope has been nearly eliminated by the TDSC with a minimal amount of residual high-order dispersion being introduced. The +22 ps/nm of dispersion (at 1550 nm) is easily removed using additional DCF, as shown in Fig. 1. When compensating the residual dispersion, we would try to overshoot (by up to 5 m or $-0.5$ ps/nm) the nominal length of DCF and any excess negative dispersion was then compensated using SMF-28 patchcords.

In the back-to-back case (i.e., no fiber transmission), it is only necessary to compensate for phase errors between channels of the multiport AWG-pair and to carefully measure the calibration constant of the phase modulators. Only then, will the applied zero or $\pi$ phase shifts be correct. All of these basic measurements, including verification of the applied phase shifts with cross-correlation frequency-resolved optical gating (XFROG) [33], were performed in the laboratory before going out on the field trial [34]. Errors in device fabrication leave unwanted random path-length differences in the channels between the AWGs. When encoding a signal, these path-length differences translate into spectral phase errors. Both the phase-error correction and the $m$-sequence need to be applied simultaneously to the AWG-pair channels. By only applying the voltages necessary to obtain an $m$-sequence, the encoding and decoding process will not produce a short pulse, but instead a pulse encoded with random phase errors.

In the laboratory, the phase response versus applied voltage (calibration constant) was measured for several channels. The phase errors were determined by sending the pulses from the OFCG through the AWG-pair, and calculating the spectral phase difference between the input and output waveforms. The phase correction applied to the AWG-pair channels is then the measured phase error multiplied by the calibration constant. Fig. 5(a) shows the measured encoded pulses’ spectrum and the measured applied $m$-sequence across all channels of the AWG-pair. The phase transitions are approximately $\pi$ across the entire spectrum. Accurate $\pi$-phase shifts between chips are required for the AWG-pair double-pass encoding–decoding operation since we are essentially applying the same code twice and depending on the mathematical equivalency of a zero or $2\pi$ phase shift; instead of applying the conjugate code. Residual errors in the phase shifts result from crosstalk between channels, and nonlinearity and nonuniformity of the phase-calibration constant between channels. The encoding could further be improved
by remeasuring the phase errors of the $m$-sequence code and applying an additional correction. The retrieved time-domain data for the encoded signal [Fig. 5(b)] reveals the 63-chip $m$-sequence spreads the pulse evenly across the entire 50-ps period. This complete spreading is a direct result of the mode-by-mode spectral phase modulation. Fig. 6(a) shows the correctly decoded signal’s spectral intensity and phase. The residual coding- and phase errors are mostly rapidly fluctuating in nature (bounces up and down with mode number), indicating that the phase-error correction was able to remove the large slowly-fluctuating errors (those that change gradually with mode number) that primarily influence the pulse width. Fig. 6(b) shows the time-domain waveform of the correctly decoded pulse. Clearly, the spectral phase is flat enough to generate a short pulse, the mode-by-mode encoding and decoding was successful. Note that it is the residual rapidly-fluctuating spectral phase errors that result in the low-amplitude intensity noise throughout the time window and the slowly-fluctuating spectral phase errors that broaden and distort the main peak of the pulse.

Experimental results in Fig. 7(a) were obtained from the field trial; using the autocorrelations confirms correct encoding/decoding. It is apparent from the traces that the high contrast between the correctly decoded pulse and the incorrectly decoded pulse was maintained. Fig. 7(b) shows the autocorrelations for the OFCG output directly (dashed line), then the correctly decoded user after transmission on a dispersion-compensated 400-m interbuilding link (grey line), and finally the correctly decoded user after transmission through 80.8 km of BOSSNET. Spectral filtering from the multiport AWG-pair during encoding and decoding contributes the most significant amount of broadening as demonstrated by Fig. 7(b).

Fig. 8. BER performance of the SPECTS O-CDMA field trial operating at 2.5 Gb/s/user. Power/user is measured at the input to the nonlinear thresholder. Corresponding eye diagrams are taken at the lowest BER for each curve.

A. BER Experiments

Fig. 8 shows the BER statistics and corresponding eye diagrams of the field trial for one and two users, each operating at 2.5 Gb/s. The BER is plotted versus the power/user at the input to the nonlinear thresholder. For these measurements, the delay of the interferer was adjusted so as not to coincide with the larger peaks of the user signal to minimize coherent beat interference. The back-to-back data were taken with the TDSC, DCF, and BOSSNET link bypassed (Fig. 1). The nonlinear thresholder was optimized for two-user operation; i.e., the position of the 3-nm bandpass filter and the input power to the HNLF were adjusted to minimize the BER when two users were present. This created an $\sim$1-dB negative power penalty between two- and one-user data in the back-to-back case. The corresponding eye diagrams were taken from the auxiliary output of the HP 83446A receiver which bypasses the data recovery circuit and is a good indication of the true optical eye diagram. The last data points for both curves indicate where the system performs error-free (BER < $10^{-10}$) for a period of more than $3 \times 10^{10}$ bits. For 80.8-km transmission, the TDSC, DCF, and BOSSNET links were added and the nonlinear thresholder optimized for two users. The temporal broadening of the recovered pulse requires tuning the optimal bandpass filter center wavelength from 1561 to 1559 nm. This result was expected, since the broader pulse generates less power at the longer wavelengths. In the 80.8-km case, there is a significant power penalty going from one to two users for lower powers, but the curves eventually converge for low BERs. The behavior of the 80.8-km one-user BER curve
is not well understood at this point; although it was very repeatable. The change in slope at $\text{BER} < 10^{-9}$ and eventual convergence with the two-user BER curve was not expected. Basic optical signal-to-noise models, multiaccess interference, or thresholder operation do not seem to address the behavior. Nonetheless, all BER curves still achieve $\text{BER} < 10^{-9}$.

B. Ethernet Traffic Experiment

The SPECTS O-CDMA network performance testing utilized an IXIA traffic generator and performance analyzer on gigabit Ethernet (GbE) ports. The IXIA units employ a 1000Base-SX SFP (small-form-factor pluggable) module to transmit and receive a 1.25-Gb/s, 850-nm optical data stream, without the need for serialization and deserialization. To be compatible with the data modulator in the system, the Ethernet optical stream is converted into a serial nonreturn-to-zero (NRZ) electrical signal using a simple optical–electrical (O–E) transceiver that does not implement any media access control for the data frames. Likewise, an E–O transceiver is required after the O–E receiver of Fig. 1 to send an 850-nm optical data signal back to the IXIA.

The Ethernet traffic was scripted to follow the testing procedures described by RFC 2544. Various frame sizes were transmitted to test throughput and latency across the O-CDMA link. Latency was less than the measurement limit for all link configurations. The percent frame loss is shown in Table I for frame sizes from 64 to 1518 B and three different link configurations. The first measurement was with two users and no fiber link (0 km). A small spurious frame loss does show up at the 256-B frame size, but, otherwise, no frame loss was detected. The second column of data is for a single user on the 80.8-km link. The frame loss rates are well below 0.0002% for all frame sizes. We have also conducted experiments for two users over an 80.8-km transmission link. Relatively high frame losses were measured (even though BER values were below $10^{-7}$), but, unfortunately, there was insufficient time to repeat the measurements to obtain reliable data before losing access to BOSSNET during its reconfiguration. The final column shows data for a two-user case with a 0.4-km interbuilding link in place. Here, the frame loss is between 1 and 5% and tends to be slightly higher for larger frame sizes. When measured, the BER for this configuration is below $10^{-10}$. However, the MUI from the second user negatively affects the amount of frame loss.

IV. CONCLUSION

We have performed a field trial of a SPECTS O-CDMA system over an 80.8-km link of BOSSNET by utilizing a compact, integrated encoder/decoder and subpicosecond pulses. The encoders/decoders are based on a multiport AWG-pair which is capable of encoding and decoding multiple signals simultaneously and supports coding lengths of up to 64 chips. A unique tunable dispersion-slope compensator and standard DCF enabled the propagation of subpicosecond pulses over the 80.8-km link. The SPECTS O-CDMA link experiment achieved $\text{BER} < 10^{-9}$ for two users at 2.5 Gb/s/user without forward error correction (FEC). Finally, we presented frame-loss statistics for 1-Gb/s optical Ethernet data over the O-CDMA 80.8-km link.

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REFERENCES


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