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Optical header recognition using time stretch preprocessing ☆

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Abstract

We propose and demonstrate the time stretch optical header recognition technique where a high speed header is extracted and slowed down by more than an order of magnitude, in optical domain, to facilitate the capture and processing in electronic domain. The technique can be implemented in continuous time or discrete time. Both implementations are experimentally demonstrated for stretching a 10 Gb/s header by a factor of 20. Eye diagrams and Q values are generated to evaluate the quality of stretched headers. While both implementations are capable of slowing down the header bit rate, each method has its own advantages and disadvantages in terms of bandwidth, maximum header length, latency, and sensitivity to the sampling clock jitter.

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Keywords: Head recognition; Optical signal processing; Optical fiber communication; Packet switching; Time stretch

1. Introduction

In ultra highspeed optical networks, recognizing the destination of incoming data packet is essential for packet routing and add/drop multiplexing. Electronic packet routing at high data rates is restricted by the speed of electronics circuitry. To overcome this bottleneck, all-optical packet extraction and recognition has been extensively studied for more than a decade. Techniques that have been proposed include a correlation decoding scheme using Fiber Bragg Grating (FBG) and wavelength conversion [1] and the use of Optical Code Division Multiplex Access (OCDMA) coded headers [2]. In an alternative approach optical serial-to-parallel conversion combined with fast all-optical reflection switch, which is activated by a temporally aligned high-intensity probe pulse, has been demonstrated [3]. Serial-to-parallel conversion of the high speed header has also been implemented using

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multi-wavelength pulse trains [4]. Another approach is the optical label switching where the header is transmitted using a different modulation format [5] than the payload. An example is the subcarrier header recognition that relies on transmitting the header using a subcarrier and at different data rate compared to the payload [6]. In general, capability of accommodating larger header bits without increasing the complexity, polarization insensitivity to incoming data, and low latency have proven to be difficult to satisfy, simultaneously.

In this paper, we propose and demonstrate a new method where the header is optically extracted and slowed down, such that it can be processed with slow electronics running at lower speed than the incoming data rate. The proposed approach uses the time-stretch technique, which has recently been developed to enable ultrahigh speed analog-to-digital conversion [7,8]. The proposed time stretch header recognition scheme consists of four steps, as shown in Fig. 1. In the first step, the incoming packet header is gated and extracted by a linearly-chirped broadband pulse. The extracted header is then stretched in temporal domain to slow down the data rate by a predetermined factor. The slowed down data is then detected and processed by low speed electronic circuits. In the final step, the routing of delayed incoming data is done by optical switches. Being serial in nature, the complexity of this approach does not increase for long header lengths. Additionally, it is insensitive to the polarization of the incoming data and does not require different coding or transmission rate for the header bits.

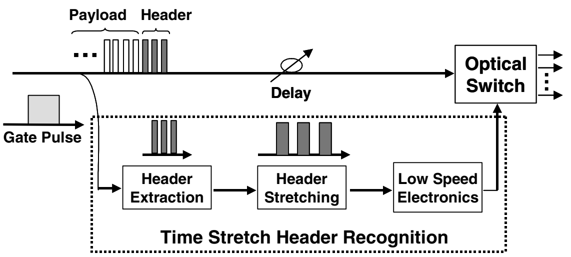

Fig. 1. Conceptual block diagram of the time stretch header recognition technique. The packet header is extracted and slowed down for detection using low speed electronics.

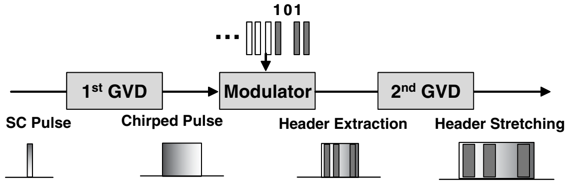

Fig. 2. The block diagram of the general time-stretch preprocessor for header recognition.

Fig. 2 shows the simplified block diagram of the time stretch processor [8]. Ultrashort broadband pulses, generated by a supercontinuum source, are linearly chirped after being dispersed in a Group Velocity Dispersion (GVD) element. Time to wavelength transformation is achieved when the data modulates the intensity of the chirped carrier. The modulation is stretched, in time, when the signal is dispersed again in the second GVD element.

Time stretch can be performed in continuous-time or discrete-time formats [7,8]. Both techniques are based on time-wavelength transformation enabled by GVD. The difference pertains to the method used to implement the GVD. In the continuous-time implementation, the GVD element is a dispersive fiber. In the discrete-time system, a discrete-wavelength GVD is created using WDM filters. Possible implementations include an Array Waveguide Grating (AWG) in loopback configuration (Fig. 3(a)) [9,10] or FBGs (Fig. 3(b)). Both techniques have been previously demonstrated in

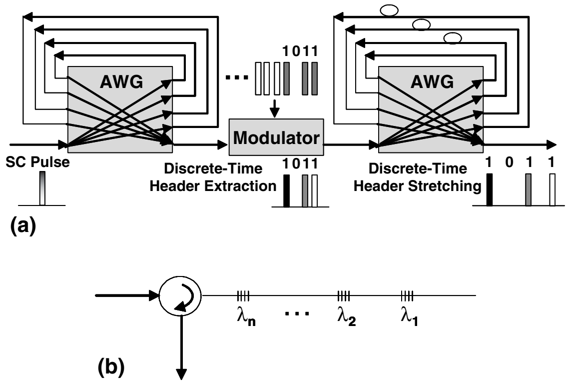

Fig. 3. The discrete-time implementation of the time-stretch system by (a) the re-circulating array waveguide grating or (b) the fiber Bragg gratings.

the optically assisted analog-to-digital conversion [7,9]. However, when considering bandwidth, latency, and sensitivity to sampling jitter of the overall system, each technique has its own advantages and disadvantages. In this paper, both techniques are applied in the demonstration of time stretch header recognition, and their pros and cons, as they relate to the header processing application, are analyzed.

The outline of paper is as follows: Section 2 describes an experiment with the continuous-time-stretch and quantifies the system performance using measured eye diagrams. The discrete-time experiment and similar analysis is discussed in Section 3. In Section 4, the two techniques are compared in terms of bandwidth, maximum header length, latency, and detection issues. Additionally, Section 5 contemplates issues that may arise in practical implementation of the time stretch header processing.

2. Continuous-time-stretch header processing experiment

Fig. 4 shows the experimental setup used for continuous time stretch header processing at 10 Gb/s. Around 1 ps pulses generated by a passively modelocked fiber laser at 20 MHz repetition rate and 1560 nm center frequency are used to generate broadband supercontinuum [11]. By using an optical bandpass filter centered at 1585 nm, ~20 nm spectrum of generated supercontinuum is sliced. The pulse power is set to around 1 mW. The sliced pulse then propagates through a spool of Dispersion Compensating Fiber (DCF) with total GVD of −120 ps/nm, creating a 2 ns linearly chirped pulse. The maximum header length that can be captured is determined by the 2 ns time aperture. To emulate an incoming 10 Gb/s packet stream, a $2^{31}-1$ pattern generator is used. With the packet rate set to the laser repetition rate, the header of each packet can be temporally aligned with the chirped optical pulse at the modulator. The header modulates the intensity of the chirped pulse in an electrooptic modulator. Here the chirped pulse serves as a time-gate extracting the header from the packet. Using a second spool of DCF with total dispersion of −2099 ps/nm, the extracted header bits are stretched in time. The stretch factor is $1 + D_2/D_1 \approx 20$, where D_1 and D_2 are the total GVD in the first and second fiber, respectively [7]. The slow data stream is then detected by a photodetector and captured by a real-time digital oscilloscope. In our experiments, proper synchronization could not be achieved because the optical source was a free-running passively mode-locked laser. Crude synchronization between the incoming packet and pulsed laser was performed by adjusting the data rate to match the 512th harmonic (~10.24 GHz) of the modelocked laser. However, as will be shown below, the lack of phase locking did compromise the quality of the recovered data. In a real application, the pulsed source must be locked to the incoming packet. This is a well known problem in the industry and a number of solutions have been proposed and demonstrated [12–14].

A snapshot of captured time stretched 24-bits header is shown in Fig. 5. The 10 Gb/s bit stream is slowed down to around 500 Mb/s. The amplitude envelope is due to the power spectrum of the supercontinuum source. In practice, spectral equalization by spatial light modulator or digital light

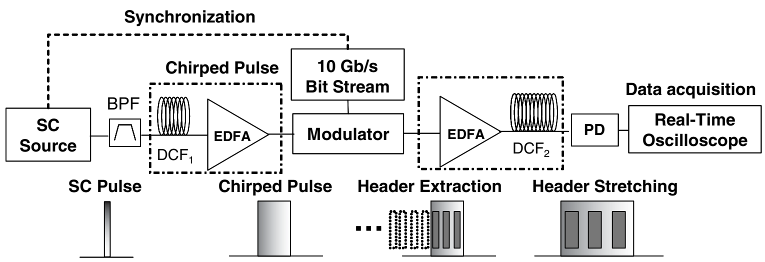

Fig. 4. Experimental setup for continuous time stretch header recognition at 10 Gb/s. The header is extracted and detected at 500 Mb/s. DCF: dispersion compensating fiber, BPF: bandpass filter, PD: photodetector, SC: supercontinuum.

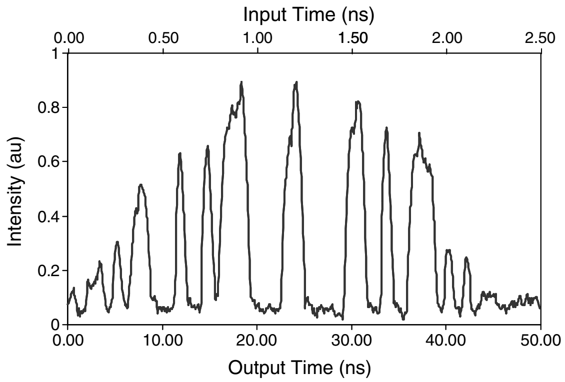

Fig. 5. Ten gigabytes per second packet header after it is slowed down to 500 Mb/s. The static nonuniformity across different bits originates from the nonuniform spectrum of supercontinuum source and the profile of optical filter.

modulator can be used for correction. In addition, since the bit rate is slowed down, it is also possible to use electronic equalization.

Fig. 6(a) shows the eye diagram of the time stretched header. The eye diagram is obtained by overlapping 2000 packet headers in the 100 μs acquisition time of the real-time oscilloscope (limited by its memory size). The Q value is calculated for different header bits. For the center of the supercontinuum spectrum, we calculate a Q value greater than 18 dBQ. Except for the edges of the supercontinuum spectrum, where the signal to noise ratio is lower, similar Q values are obtained.

Next performance degradation caused by the lack of complete synchronization is investigated. The crude synchronization used in the experiment, i.e., adjusting the data rate to match the harmonic of the mode locked laser, does not account for the drift of the laser repetition frequency. The eye diagram in Fig. 6(a) suggests incomplete synchronization between the packet and the supercontinuum source. To asses the impact of the absence of frequency and phase locking between the packet and laser, we make the manual correction in the digital domain. A constant frequency difference is estimated by comparing bit transitions in consecutive packets. By using the estimated frequency difference the amount of time delay in each packet is calculated. Each packet is then time shifted to compensate the frequency mismatch. The final eye diagram after timing

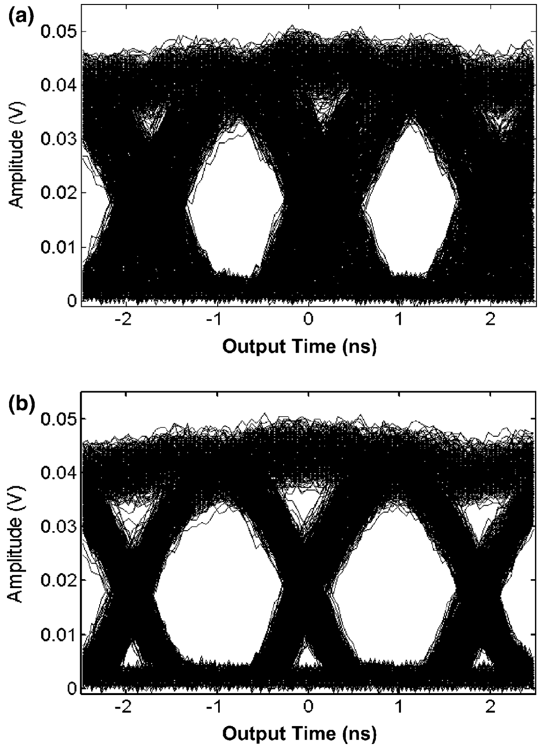

Fig. 6. Eye diagram for the 10 Gb/s header after it has been slowed down to 500 Mb/s, (a) before and (b) after digital synchronization. Optical Q values of ~18 and ~22 dBQ are obtained, respectively.

adjustment is shown in Fig. 6(b). An improved Q value of 22 dBQ is obtained suggesting that ~4 dB penalty caused by incomplete synchronization in the experiment. The eye diagram in Fig. 6(b) suggests that there is still residual frequency mismatch, which cannot be corrected due to discrete time nature of the oscilloscope. In other words, the finite sampling rate of scope limits the accuracy of timing adjustment. However, this suggests that the actual performance can be better than 22 dBQ.

The above results suggest that the continuous-time stretch technique can slow down the header bits for processing with low speed electronics and that adequate Q values can be achieved once proper synchronization between the optical source and the incoming data is implemented. However, the stretching was achieved by propagating the signal in several kilometers of DCF – a requirement to obtain a GVD of −2099 ps/nm. The resulting latency caused by the propagation delay is undesirable. As shown in Fig. 1, the data must be delayed by the same amount as the latency suffered by the header, before the packet switching can be performed. This problem is quantified and analyzed in Section 4.

3. Discrete-time-stretch header processing experiment

The discrete-time-stretch system is realized by replacing the second GVD elements in Fig. 2 with a discrete-wavelength GVD device, otherwise known as wavelength selective time delay and shown in Fig. 3. The experimental setup using the AWG approach (Fig. 3(a)) is shown in Fig. 7. The header extraction is identical to that in the previous experiment. The length of the DCF is chose to produce −120 ps/nm of GVD. This is done so that after time-wavelength transformation, the bit interval of ∼100 ps (10 Gb/s data) corresponds to the AWG channel spacing of 0.8 nm (center wavelength is 1585 nm). An optical bandpass filter is used to avoid aliasing that would otherwise exist due to the finite FSR (free spectral range) of the AWG. To create discrete-wavelength GVD, 8 channels of the 32-channel AWG are looped back with 2 ns relative delays between the adjacent channels. The output of the AWG is detected by a photodetector and fed into the real time oscilloscope to capture the stretched header. An additional fiber of ∼240 ps/nm dispersion is inserted before oscilloscope to broaden the incoming pulses and hence reduce the influence of the sampling jitter of the digital scope. The final slowed-down data rate is found to be around 590 Mb/s. Similar to the previous experiment, crude synchronization is obtained by matching the data rate to the harmonic of supercontinuum pulse train near 10 GHz.

Fig. 8(a) shows the 8-bit header (1 1 1 1 0 0 0 0) information after slowing down to 590 Mb/s. Fig. 8(b) shows the spectral domain representation of 100 GHz spaced 8-channel header bits, which is mapped into eight different wavelengths. Since a PRBS generator is used to create the header bits and payload of the incoming data stream, header information changes from packet to packet. Thus, the figure shows the time-averaged spectrum. In the present experiment, an 8-bit header was used for demonstration purpose. Longer headers can be accommodated by using more channels of the AWG.

Next the eye diagram of the packet headers is created and optical Q values are calculated. Fig. 9 shows the eye diagram created by overlapping header bits from 2000 packets. Even though the original data is non-return-to-zero (NRZ) format, the discrete nature of the method converts data to return-to-zero (RZ) format. The Q values are calculated for different bits of optical header. Optical Q values of >19 dBQ are created for different bits. Similar to Section 2, the impact of the incomplete synchronization between supercontinuum source and bit stream is mitigated by timing adjustment in the digital domain.

By avoiding long lengths of dispersive fiber in the second GVD element, the discrete-time-stretch offers low latency. The following section provides a detailed comparison of the continuous- and the discrete-time techniques in terms of latency and other relevant parameters.

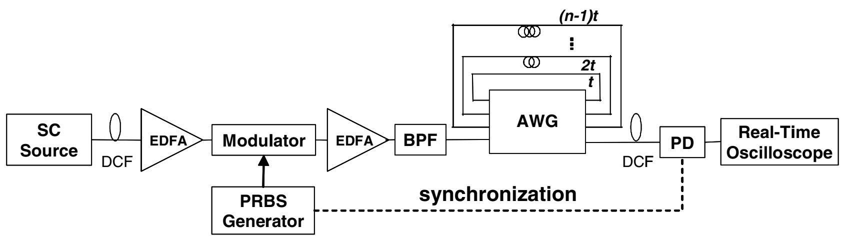

Fig. 7. Experimental setup used for the discrete time header processing. Header of 10 Gb/s packet is extracted and time stretched in array waveguide grating to 590 Mb/s.

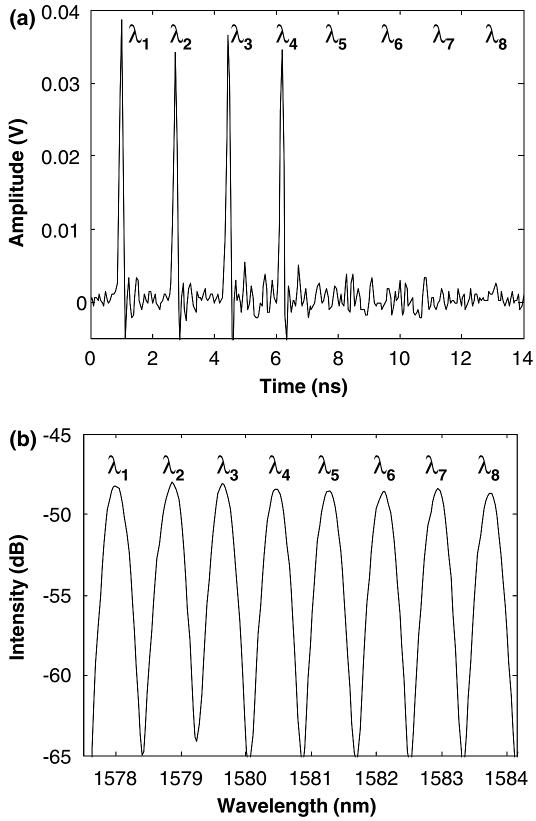

Fig. 8. (a) A snapshot of 10 Gb/s 8-bit header slowed down to 590 Mb/s "11110000" and (b) the corresponding 8-channel spectrum.

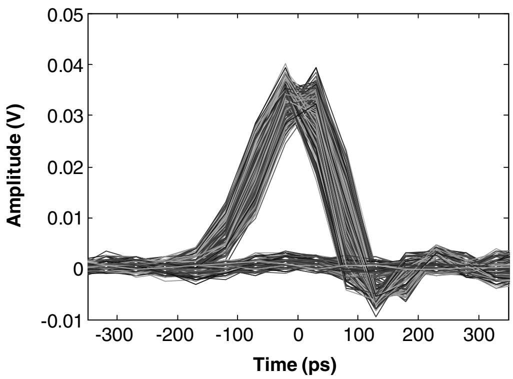

Fig. 9. Eye diagram of the RZ formatted stretched header, created by overlapping 2000 headers. Optical Q value is calculated to be >19 dBQ.

4. Comparisons of two techniques

Here we discuss relative merits of the continuous-time-stretch and the discrete-time-stretch techniques, as they relate to the problem of packet processing. Parameters that are considered include latency, maximum header length, bandwidth, receiver jitter tolerance and the uniformity of time stretch.

A major difference between two techniques is the latency of the time stretch preprocessing block. In the continuous-time-stretch, to generate a dispersion of −2099 ps/nm at 1585 nm (required to achieve a stretch factor of ∼20) around 20 km dispersion compensating fiber had to be used. This suggests a latency as large as 100 μs, dictated by the pulse propagating time. This limits the practical application of continuous-time-stretch header recognition because it requires means to store the payload for such a long duration. On the other hand, the latency in a discrete time stretch preprocessing block is minimal. The main contribution to latency is the feedback delays used slow down the bit rate. Specifically, the latency is equal to the pulse propagating time in AWGs and the longest delay in the feedback paths. For example, to realize a 20× stretch factor with a 64 bit header at 40 Gb/s, the latency will be ≈32 ns. This is a drastic improvement compared to the 100 μs in the continuous-time system. The discrete-time-stretch implemented using FBGs has the similar latency as the implementation using AWGs. Moreover, if dispersive fibers are replaced by continuously-chirped FBGs (which have sufficiently large optical bandwidths) the latency of continuous-time-stretch can be comparable to that of discrete-time-stretch.

For the continuous-time-stretch where dispersive fiber is used as the second GVD element, dispersion penalty will pose a limitation on the maximum number of header bits that can be processed [15]. Dispersion penalty, a well known problem in digital and analog optical links, refers to the attenuation of signal's high frequency content. It is due to the deconstructive interference between the beating terms of carrier with the upper and the lower modulation sidebands. In the setup shown in Fig. 4, the maximum dispersion-limited 3 dB analog bandwidth is calculated to be 24 GHz [15]. If a larger bandwidth is needed (at the same stretch factor) shorter lengths for both DCF fibers must be used. However, reducing the length of the first fiber diminishes the time aperture, and hence the maximum header length that can be captured. The product of the 3 dB bandwidth and the time aperture determines the number of header bits that can be processed, independent of the bit rate. The resulting maximum number of header bits is then given by $\Delta f_{op}/2\Delta f_{rf}$, where Δf_{op} and Δf_{rf} are the optical and electrical bandwidths, respectively [15]. As an example, assuming that 40 GHz bandwidth is needed and a 20 nm optical bandwidth, the time stretch header recognition system can accommodate 32 header bits. In contrast, the discrete-time-stretch system does not suffer from dispersion penalty and hence is immune to this limit. The maximum accommodated header length in discrete time stretch is decided by the number of channels in the AWG. AWGs with as many as 1000 channels have been demonstrated [16], therefore this is not expected to be an issue.

A drawback of the discrete-time-stretch is the short pulses produced by the AWG. Slicing the spectrum of the linearly chirped optical carrier, the AWG generates RZ data with pulse width given by the product of the chirp rate and its channel passband. In the above experiment where −120 ps/nm of dispersion was used to generate the chirped carrier, the 0.3 nm (−3 dB) passband of the AWG corresponds to 36 ps pulses. Such short pulses impose a burden on the receiver bandwidth and clock jitter. In contrast, continuous time stretch is quite immune to the clock jitter because not only the bit spacing is stretched, the bits themselves are also stretched. The problem is further alleviated by the NRZ format of the output. In the present experiment, the RZ pulses produced by the AWG were broadened using a dispersive fiber before detection. However, this increases the latency and loss. In principle, a fast integrate-and-dump circuitry performing pulse energy detection can solve this problem. However, realization of such circuits operating in pico-second time scale is highly challenging.

Time stretch reduces the data rate by a predefined ratio. In the packet processing, this ratio is required to be constant across the time aperture. A nonuniform stretch factor will introduce the timing skew in the slowed bit stream. In the continuous-time-stretch, the stretch utilizes fiber dispersion. It is well known that fiber dispersion is the function of wavelength. The wavelength-dependence may lead to a nonuniform stretch. Fortunately, it has been previously proved that the stretch factor is independent of fiber dispersion characteristic as long as fibers 1 and 2 are the same fiber and possess the same dispersion characteristic per unit length [17]. This can be intuitively shown by the stretch factor calculation $1 + D_2/D_1$, where the division operation removes the higher-order dispersion terms. In the discrete-time-stretch, a fine control on the delay in the loopback paths is required to minimize the timing skew.

5. Discussions

The preliminary experimental results presented in previous sections demonstrate that both continuous and discrete time stretch techniques are able to slow down the digital optical header by more than an order of magnitude and with good fidelity. The primary performance limiting factors includes the supercontinuum noise, ASE-signal beat noise, and nonuniformity of the supercontinuum spectrum. Through time-wavelength transformation, spectrum nonuniformities are mapped into time domain and distort the header bits. Fortunately, the spectrum nonuniformities can be measured and spectrum equalization can be used to remove them. This can be implemented by a spatial light modulator or, in the case of the discrete-time system, by using variable optical attenuator in the AWG loopback paths. In addition, since the header bit rate is greatly reduced, the electronic correction is also a candidate.

After addressing the spectral nonuniformity, the supercontinuum noise and ASE-signal beat noise are the primary performance limiting factors. To obtain a better signal quality, a supercontinuum source with high power spectral density and signal-to-noise ratio is necessary. In addition, the supercontinuum source's stability could be improved by stabilizing the pulsed laser and optimizing supercontinuum generation method and parameters [18].

Since an electrooptical modulator is used to modulate the header onto the chirped optical carrier, the input to the time stretch systems demonstrated here is electrical, necessitating O/E conversion of the incoming optical bit stream. The O/E conversion may be avoided by using optical–optical modulation in place of electrooptical modulation. One of choices is cross gain modulation in a semiconductor optical amplifier. This all-optical modulation technique has been used in a packet routing demonstration involving the correlation header decoding scheme [1]. In general, the efficiency of the all-optical modulation and its impact on signal-to-noise ratio needs to be studied in order to establish the effectiveness of this approach.

6. Conclusion

In summary, we have proposed and demonstrated the time stretch header recognition technique. Two versions, namely the continuous-time-stretch and the discrete-time-stretch are demonstrated and compared. In the continuous-time experiment, a 10 Gb/s bit stream is stretched by the factor of 20 using ~20 km of dispersive fiber (DCF), allowing the its capture and processing with electronics running at 500 Mb/s. An optical quality factor of >22 dBQ value was achieved with digital assisted synchronization between the packet and the supercontinuum source. In the discrete-time experiment, an 8-bit header at 10 Gb/s data is extracted and slowed down to ~590 Mb/s. By avoiding the need for dispersive fiber, the discrete-time approach removes the latency problem that arises due to propagation delay in the dispersive fiber. Optical Q values of >19 dBQ are measured for the discrete-time system. The time-stretch header recognition method is insensitive to the polarization of the incoming data and does not require different coding or transmission rate for the header bits. Due to its serial nature, the complexity does not increase with header length. Practical implementation of the proposed scheme requires means to synchronize the supercontinuum source with the incoming data and equalization of the supercontinuum power spectrum.

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