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Abstract: An asynchronous 10G Ethernet packet is synchronized and retimed to a master clock using a time lens. The NRZ packet is converted into an RZ packet and multiplexed with a serial 1.28 Tb/s signal.

OCIS codes: (060.2330) Fiber optics communications; (060.1810) Buffers, couplers, routers, switches, and multiplexers; (070.0070) Fourier optics and signal processing.

1. Introduction

Terabit Ethernet interfaces that aggregate traffic from several 10 G Ethernet links into a serial Terabit optical data stream are promising for future ultra-fast communication networks. Optical time division multiplexing (OTDM) is an effective technology for building ultra-high speed networks, which has been demonstrated at a symbol rate of 1.28 TBaud on a single wavelength [1,2]. As Ethernet packets are asynchronous in nature but an OTDM system based on bit interleaving is synchronous, the Ethernet packets in each link have to be synchronized to a master clock at the Terabit Ethernet interfaces and then time division multiplexed into a serial Tb/s data stream.

In this paper, we demonstrate, based on a time lens [3-6], that an asynchronous Ethernet packet with maximum standardized size of 1518 bytes can be synchronized and retimed to a master clock with 200 kHz frequency offset. The scheme does not require any packet clock recovery or data buffer. In addition, the input packet with NRZ format is simultaneously converted to an RZ format, compressed into short data pulses with a pulse width of 400 fs, and finally time-division multiplexed with a serial 1.28 Tb/s RZ-OOK signal. The aggregated 1.29 Tb/s OTDM signal is received in an OTDM receiver and error-free performance for the demultiplexed 10 G Ethernet packet is achieved.

2. Operation principle

The time lens in this experiment consists of a cascaded phase modulator and Mach-Zehnder modulator (MZM) followed by a piece of fibre as dispersive element, as shown in Fig. 1. The phase modulator is driven by a sinusoidal signal, which approximates a quadratic phase modulation. The MZM is used to remove the part of the waveform subjected to the lower part of the sinusoidal phase modulation (corresponding to positive chirp). The dispersive element (dispersion compensating fiber (DCF) in this experiment) provides a temporal focus in the system. In Fourier analysis, a time shift or timing jitter only changes the phase in the frequency domain but does not change the envelope. This can be expressed as $x(t - nt_0 - \Delta t) \leftrightarrow X(\omega)e^{-j\omega(nt_0+\Delta t)}$.

Therefore, we can use the time lens to cancel the time wandering caused by asynchronism and to reduce the timing jitter. In addition, all the bits in the packet experience negative chirp and can be compressed into short pulses in the DCF, which in turn allows to format convert an NRZ signal into an RZ signal.

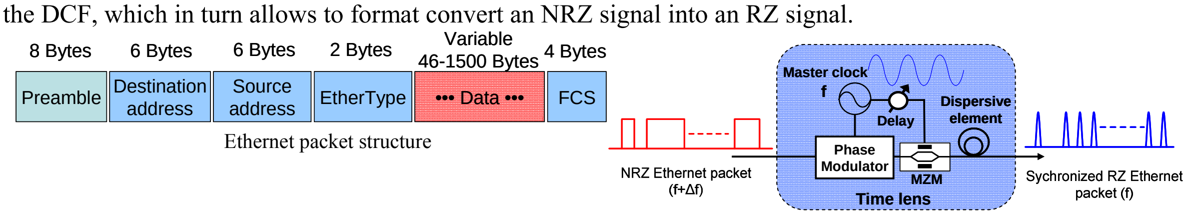

Fig. 1. Schematic of synchronization and NRZ-to-RZ conversion of Ethernet packets, based on a time lens. Inset: Ethernet packet structure.

3. Experimental setup

Fig. 2 shows the experimental setup for the time lens based 10 G Ethernet packet synchronization and retiming, and subsequent OTDM with a serial 1.28 Tb/s signal. It includes a 10 G Ethernet packet generator, an optical packet synchronizer and retimer, a pulse compressor, a multiplexer, a 1.28 Tb/s OTDM RZ-OOK transmitter and an OTDM receiver. A continuous wave (CW) light at 1556 nm is encoded by NRZ on-off keying (OOK) using a

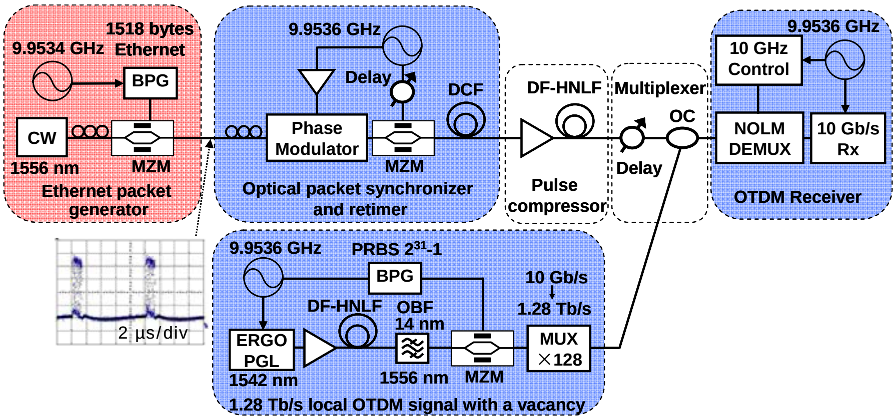

Fig. 2. Experimental setup for time lens based 10 G Ethernet packet synchronization and retiming, then subsequent optical time division multiplexing with a serial 1.28 Tb/s signal.

software defined pattern to generate 9.9534 Gb/s Ethernet packets. As shown in the inset of Fig. 1, the Ethernet packet consists of a preamble, a destination address, a source address, an Ethertype, payload data and a frame check sequence (FCS). The maximum standardized size of 1518 bytes with a packet repetition rate of 100 kHz is generated in the experiment, and the waveform is shown in the inset of Fig. 2.

In the optical packet synchronizer and retimer, the 10 G Ethernet packet is launched into a cascaded phase modulator (modulation depth of 4 π) and MZM, both driven by the master clock of 9.9536 GHz (200 kHz offset from the input clock), and then launched into a 400 m DCF. As described above, the time-domain optical Fourier transform (OFT), or equivalently the time lens effect, can be obtained after the DCF. The 10 G input asynchronous Ethernet packet with the data rate of 9.9534 Gb/s is converted into a synchronized Ethernet packet with the data rate of 9.9536 Gb/s. At the same time, the Ethernet packet is format converted into an RZ signal with a full width at half maximum (FWHM) of 6 ps. Additionally, the converted RZ signal is further pulse compressed to a FWHM of 400 fs in a 500 m dispersion-flattened highly nonlinear fiber (DF-HNLF).

In the 1.28 Tb/s RZ-OOK transmitter, a 10 GHz pulse train is generated from an erbium glass oscillating (ERGO) laser and then compressed to 370 fs in a 400 m DF-HNLF [1]. The compressed pulses are OOK modulated by a 10 Gb/s PRBS (2^{31}-1) in a MZM. The modulated 10 Gbit/s RZ-OOK signal is multiplexed in time to 1.28 Tb/s including a vacant time slot using a passive fiber delay multiplexer (MUX × 128), as shown in Fig. 4 (b). The synchronized and pulse compressed Ethernet packet is positioned into the vacant time slot of the 1.28 Tbit/s OTDM signal through a 20 dB optical coupler (OC), aggregating a serial 1.29 Tbit/s OTDM signal, as shown in Fig. 4 (c).

In the receiver, which is synchronized to the master clock, a nonlinear optical loop mirror (NOLM) is used to demultiplex the 10 G Ethernet packet from the high speed serial data stream. The NOLM operation is based on cross-phase modulation (XPM) in a 50 m HNLF. The control pulse is at 1533 nm and has a pulsewidth of 470 fs. Finally, the demultiplexed 10 G Ethernet packet is detected by a 10 Gb/s receiver and measured by an oscilloscope and an error analyzer, which are both triggered by the master clock.

4. Experimental results

We first measured the electrical power spectrum of the synchronized packet and compared it with the spectrum of the input packet before the synchronization, as shown in Fig. 3. The 100 kHz spaced peaks are due to the packet repetition rate. We can see that the maximum frequency peak of the synchronized packet has been shifted from 9.9534 GHz to the master clock of 9.9536 GHz.

Fig. 4 (a) inset shows the eye diagram for the input NRZ packet when the oscilloscope is triggered by the original clock (9.9534 GHz), which has a timing jitter of 6 ps. Fig. 4 (a-c) show eye diagrams for the synchronized,

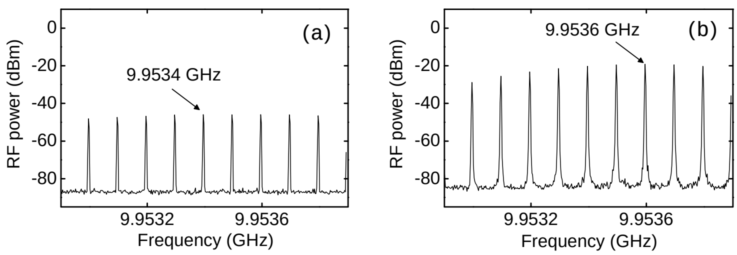

Fig. 3. (a) Electrical power spectrum of the input NRZ packet; (b) the synchronized RZ packet.

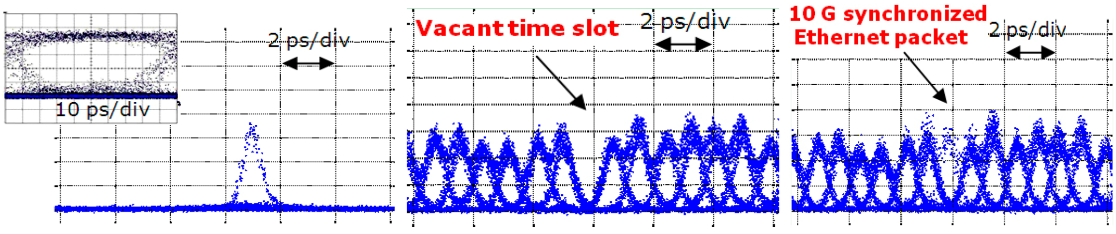

Fig. 4. (a) Optical sampling oscilloscope diagrams of the 10 Gb/s synchronized, retimed and compressed RZ packet ; (b) the 1.28 Tb/s OTDM serial signal with a vacant time slot ; (c) the synchronized Ethernet packet multiplexed with the 1.28 Tb/s signal. Inset: 10 Gb/s input NRZ packet.

retimed and compressed RZ packet, and the Tb/s serial signal before and after the addition of the synchronized 10 G Ethernet packet, when the optical sampling oscilloscope (OSO) is triggered by the master clock. The clear eye diagram shown on the oscilloscope (Fig. 4 (a)) indicates the packet has been synchronized to the master clock with strongly reduced timing jitter. The packet data pulse with a pulsewidth of 400 fs (measured by an autocorrelator) seems to be broader on the OSO due to the limited resolution of 1 ps. Fig. 4 (c) shows that the 10 G Ethernet packet is successfully synchronized and correctly positioned into a time slot in the aggregated serial 1.29 Tb/s signal.

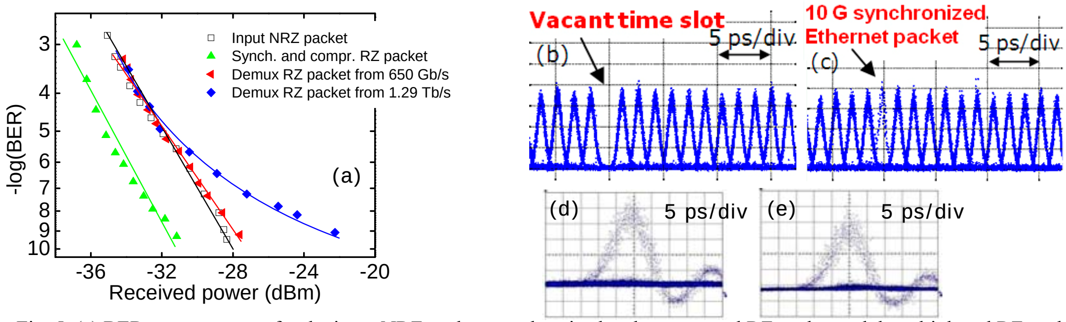

Fig. 5. (a) BER measurements for the input NRZ packet, synchronized and compressed RZ packet and demultiplexed RZ packet from the aggregated 650 Gb/s and 1.29 Tb/s OTDM signal; (b) the 640 Gb/s OTDM signal with a vacant time slot; (c) the aggregated 650 Gb/s OTDM signal with the 10 G synchronized Ethernet packet; (d) and (e) demultiplexed eye diagrams of the RZ packet from the aggregated 650 Gb/s OTDM signal and 1.29 Tb/s OTDM signal, respectively.

As shown in Fig. 5 (a), bit error rates (BER) are measured for the input NRZ packet, synchronized and compressed RZ packet and demultiplexed RZ packet from the aggregated 1.29 Tb/s OTDM signal and also from the aggregated 650 Gb/s OTDM signal when the receiver is triggered by the master clock. Fig. 5 (b) and (c) show the eye diagrams for 640 Gb/s signal including a vacant time slot and aggregated 650 Gb/s OTDM signal. Compared to the input NRZ packet, the synchronized and compressed RZ packet has 3.1 dB negative penalty which is a benefit from the NRZ-to-RZ format conversion. Compared to the synchronized RZ packet, the demultiplexed RZ packet from aggregated 650 Gb/s OTDM signal and 1.29 Tb/s OTDM signal has an additional power penalty of 3.8 dB and 8.7 dB at the BER of 10^{-9}, after the multiplexing and demultiplexing. Fig. 5 (d) and (e) show the eye diagrams of the demultiplexed RZ packet from the aggregated 650 Gb/s OTDM signal and 1.29 Tb/s OTDM signal, respectively. The pulse compressed 10 G Ethernet packet has a pedestal which distorts the adjacent OTDM channels, but the pedestal could be removed by passing through an off-center filtered pulse regenerator [1].

5. Conclusion

We have demonstrated that an Ethernet packet with the maximum standardized packet size of 1518 bytes can be synchronized and retimed to a master clock with 200 kHz (± 20 ppm) frequency offset and at the same time be format converted from NRZ to RZ. Subsequently, the synchronized RZ Ethernet packet is further pulse compressed and multiplexed in time with a 1.28 Tb/s or a 640 Gb/s OTDM signal having a vacant time slot, then aggregated to a 1.29 Tb/s or a 650 Gb/s serial signal, respectively. Error free performance of synchronizing, retiming, multiplexing with a 1.28 Tb/s or 640 Gb/s OTDM signal and finally demultiplexing back to 10 Gb/s of this Ethernet packet is achieved.

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