

Time-division-multiplexing using pulse position locking for 100 Gb/s applications

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Abstract: Recently, there is a great interest in pushing communication technologies to 100 Gb/s. However, there are still many challenges to perform high speed (> 40 Gb/s) clock and data recovery, and data time-division-multiplexing (TDM). Here, we propose and numerically analyze an asynchronous optical packet retimer using parabolic or sinusoidal phase modulation and linear dispersion. This scheme is named pulse position locking (PPL). Numerical simulation shows that this scheme can effectively resynchronize input signals with arbitrary delays to the local clock, and reduce input jitter. The scheme can also be applied to TDM 10 Gb/s and 40 Gb/s signals to over 100 Gb/s.

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1. Introduction

Recently, there is a great interest in pushing the connection bandwidths towards 100 Gb/s. For example, many research works have been performed to demonstrate the possibility of putting 100 Gb/s serial optical data into optical fiber [1-3]. As predicted by the IEEE 802.3 Higher Speed Study Group (HSSG), future data network will require high speed clock and data recovery, as well as high speed time-division-multiplexer to time-division-multiplex (TDM) lower data rate Ethernet signals in the local servers to higher data rate signals for remote servers [4]. A typical scenario is shown in Fig. 1. The 100 GbE can also be wavelength division multiplexed (WDM) to $N \times 100$ GbE data transmitting among network nodes.

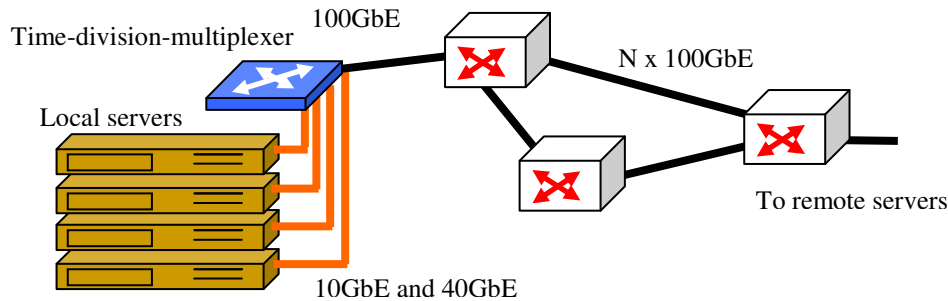


Fig. 1. Schematic of TDM 10GbE and 40GbE data from local servers to 100GbE data to remote servers.

Several high speed time synchronization techniques have been proposed, including soliton shepherding [5], the combination of all-optical phase modulation and dispersion using Gaussian and parabolic pulses [6], and square pulse generation and sampling [7]. Several of these techniques are highly energy efficient [7], with minimal excess losses from temporal shaping of signal pulses. However, they all require low jitter clock recovery circuits. For optical networks based on burst/packet transmission, asynchronous retiming has been proposed [8] and demonstrated [9, 10]. However, this approach fundamentally samples temporally broadened signal pulses dramatically reducing the efficiency of the device.

Here, we propose and numerically analyze a retiming scheme suitable for burst/packet switched networks, which is potentially energy efficient and does not require clock recovery. This scheme is named pulse position locking (PPL). This is achieved by combining two parabolic phase modulation based retiming modules with optimum clock phase selection. In addition, this technique offers several potential advantages over previously reported retiming units [9, 11], including a reduction in the required sampling clock channels from 4 to 2, and the removal of high speed optical-to-electrical-to-optical (OEO) conversion.

2. Operation principle

The proposed PPL retiming is based on the time lens effect [12]. The time-chirp acts as a time lens [12]. In the spatial analog, an off-axis spatial transverse pulse (the equivalent of a jittered time-pulse) gets focused by the lens to a spot in the focal plane, irrespective of the transverse offset of the pulse. In this scheme, a parabolic clock driven phase modulator (PM) will produce a phase shift to each incoming optical pulse, and the shift is quadratic in the arrival time. The instantaneous frequency (time-derivative of the phase) is then proportional to the arrival time. The addition of a dispersive element placed after a PM driven with a parabolic pulse will move each phase-shifted incoming pulse to the minimum position of the parabolic clock. We assume that the PM is driven by a local clock at frequency f_L , and the incoming optical signal is at frequency f_R . For a sufficiently small frequency difference ($f_R - f_L$) readily achieved in practice for 40 Gb/s data packets of up to 4,000 bytes, the phase difference between the incoming packet and the local clock will vary by an insignificant amount [9] and so the data packet can be correctly re-timed at frequency f_L .

For a parabolic drive, an input pulse from a pulse train of bit period T will be phase

modulated by $\Delta\varphi$ according to the time difference t between its arrival time and the minimum (or center position) of the parabolic clock.

$$\Delta\varphi = \frac{\pi}{(T/2)^2} t^2 \quad (1)$$

This means the input pulse aligned to the minimum of the parabolic clock ($t=0$) is chirp-free ($\Delta\varphi=0$), since the time derivative of the parabolic clock is zero. If the input pulse is away from the parabolic minimum, it will experience a different frequency shift (or wavelength shift $\Delta\lambda$), which varies linearly with the amount of time difference t as:

$$\Delta\lambda = \frac{-\lambda^2}{c(T/2)^2} t \quad (2)$$

where c is the speed of light. Then we can use a dispersive element, such as single mode fibre (SMF), to move the pulse to the parabolic clock minimum and so cancel the initial temporal misalignment t . The dispersion parameter DL should be:

$$DL = \frac{c(T/2)^2}{\lambda^2} \quad (3)$$

This means that any incoming optical pulse will be position locked in time to the minimum point of the parabolic clock signal. In a practical system, a periodic drive signal is required, and the imposed phase modulation will necessarily deviate from the ideal parabolic shape. Thus in practice, precise retiming may only occur for up to 50% of the bit period. To resolve this synchronisation error without employing clock recovery, a second resynchronisation module with half-bit delay is employed, such that correct retiming is achieved for at least one of the two modules. It is also worth to mention that to make this scheme works, the phase shift does not need to be exactly π when $t = T/2$. The requirement is that the phase shift should be matched to the dispersion of the fiber in a consistent way, but there is no requirement that it generate precisely π phase shift at $T/2$. An alternative explanation of how the method works: the time-lens (parabolic chirp) and the dispersive SMF fiber (equivalent of a piece of free space in diffractive propagation) form the equivalent of a spatial Fourier Transformer (FT). This is why shifts of the pulse do not affect the “focal plane” FT, as it is well known that a shift in one domain does not shift the dual domain, but multiplies by a linear phase there.

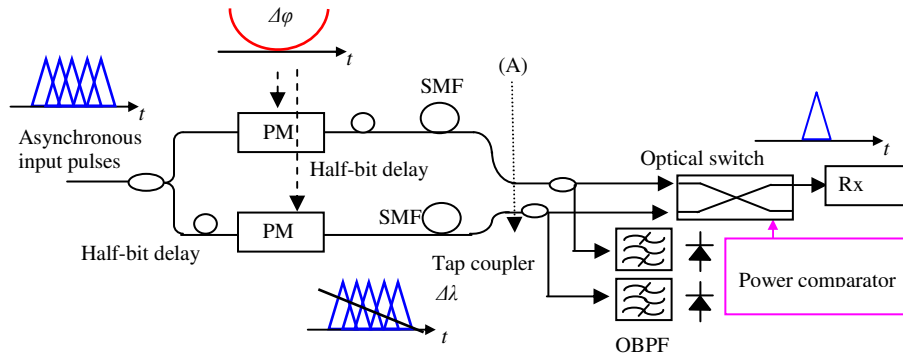


Fig. 2. Setup of PPL scheme. PM: phase modulator, SMF: single mode fiber, OBPF: optical bandpass filter.

Figure 2 shows the proposed setup of the PPL retiming unit, including two parabolic clock driven PM modules. The asynchronous optical input pulses of an optical burst or packet are first power divided into 2 equal parts by a 3-dB passive fiber coupler. They are then launched into the PMs, which are electrically driven by a continuous train of parabolic signals

simultaneously. The parabolic signal can be generated by using an electrical arbitrary waveform generator. The asynchronous optical input pulses in the lower arm are half-bit delayed before entering the PM. After parabolic phase modulation of the upper and lower arm signals, the half-bit delay is reversed by using an identical length of fiber located at the output of the PM at the upper arm. After this, the two signals travel over the same length of dispersive element, such as SMF, to complete the retiming process. Finally, asynchronous packet retiming can be achieved by selecting one of the two resynchronization channels (at 'A' in Fig. 2) which maximises the performance. The optimum channel may be detected by band-pass filtering the optical signals, to detect the mean induced wavelength shift, Eq. (2), using a simple power comparator. Passive fiber tap couplers are used to tap out optical power from each arm, and the signal from each arm will be band-pass filtered by an optical band-pass filter (OBPF). Both OBPFs are positioned at the center wavelength and fed to the power comparator to control the 2x1 optical switch. The optimum channel is selected using a 2x1 optical switch.

To better understand the operation principle, let's consider the case when the input pulse arrives at the time between two adjacent parabolic pulses, then the pulse at the upper arm (Fig. 2) will be phase modulated by $\pm \pi$, Eq. (2), having maximum wavelength shift with respect to the center wavelength. The half-bit delayed pulse at the lower arm, on the other hand, will have zero wavelength shift, producing higher detected power levels in the power comparator after the OBPF. Then, the power comparator controls the optical switch to select the correctly resynchronized channel according to the received power difference. In a burst/packet switched network, the selection process can be performed at the burst/packet rate using relatively low speed electronics (bandwidth of switch $> 1/\text{guardtime}$).

3. Numerical analysis, results and discussion

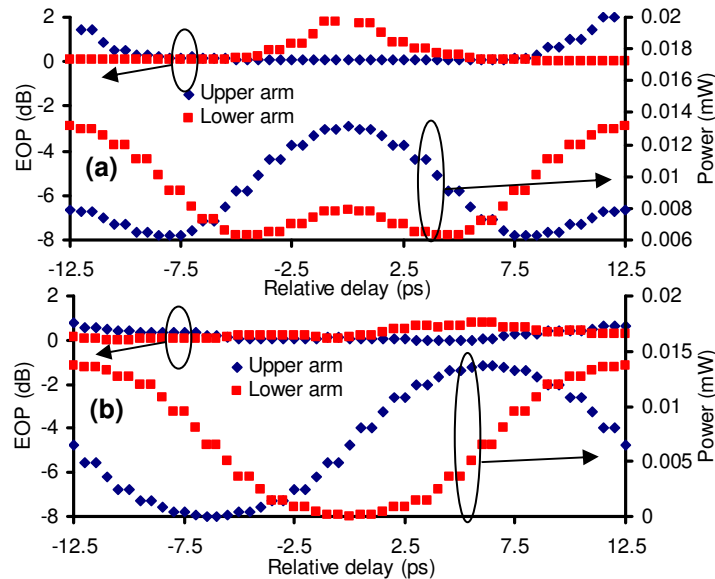


Fig. 3. Optical power and EOP of the PPL retiming unit at relative delay between input signal and local clock at 40 GHz, driven by (a) parabolic and (b) sinusoidal signals.

Numerical analysis was performed using VPI Transmission Maker V7.1, at 40 Gb/s, de Bruijn bit sequence (DBBS) of 2^7 . A Gaussian return-to-zero (RZ) signal produced by an intensity modulator [full width half maximum (FWHM) pulse width of 6 ps] was launched to the PPL retiming unit. The PMs were driven at 40 GHz either by an periodic parabolic pulse train at V_π or a sine wave of frequency $1/T$, where T is the data bit period. The dispersive element had

a total dispersion of 18.7 ps/nm and was simulated as a 1.1 km length of SMF. The OBPF used was 1st order Gaussian shaped, having a 3-dB bandwidth of 10 GHz. The selected signal was amplified by an erbium doped fiber amplifier (EDFA)-preamplifier (noise figure 5 dB) and detected using a 32 GHz bandwidth optical PIN receiver. We evaluated the performance in terms of eye opening, defined as $20\log_{10}[(U_{1min}-U_{0max})/(u_1-u_0)]$, where U_{1min} is minimum value of “ones”, U_{0max} is maximum value of “zeros”, u_1, u_0 are the respective mean values. An eye opening penalty (EOP) was obtained by normalising the eye opening to the input signal.

First, we studied the resynchronization property of the PPL retiming unit by sweeping the relative delay between the input RZ signal and the local clock. We also studied the case when a 40 GHz sinusoidal signal is electrically driving the retiming unit. In the case of using the sinusoidal signal, the configuration of the PPL unit should be slightly modified. The time delay between the 2 PMs was set to $T/4$, and the 2 OBPFs were offset to + 40 GHz and - 40 GHz respectively for better channel selection. The reason of modifying the time delay from $T/2$ (in parabolic driving) to $T/4$ (in sinusoidal driving) is that in parabolic driving, the wavelength shift, Eq. (2), is monotonic decreasing for the whole period T . Hence, a complementary channel of time delay of $T/2$ is needed. For the case of sinusoidal driving, the monotonic decreasing wavelength shift region is only $T/2$, hence, the complementary channel with delay of $T/4$ should be used. Figure 3(a) shows that at least one channel can fully resynchronize the incoming data with negligible degradation, and that we can effectively use the tapped optical power to control the 2x1 optical switch, since when the powers are equal both channels exhibit negligible penalties. Figure 3(b) shows that despite small errors in retiming for extreme values of phase offset, the sine wave driven retiming unit performs as well as the parabolic one with an additional penalty of only 0.4 dB at the worst relative delay. Figures 4 show the schematic timing diagrams of the phase shift and the corresponding wavelength shift using parabolic and sinusoidal driving respectively. Incoming pulses will be time aligned after passing through the SMF.

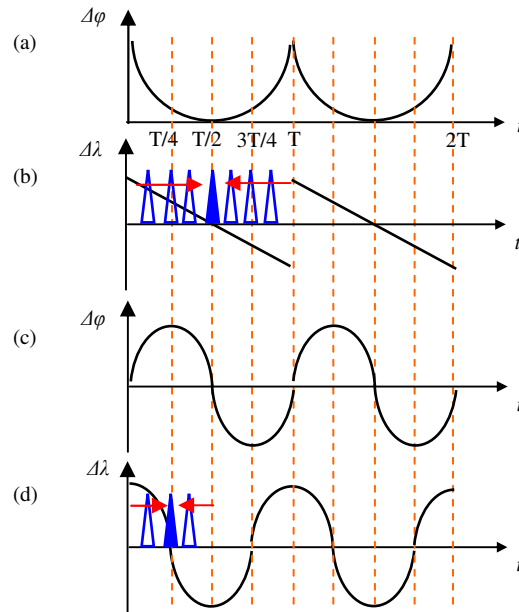


Fig. 4. Schematic timing diagrams of (a) phase shift and (b) wavelength shift in parabolic driving; (c) phase shift and (d) wavelength shift in sinusoidal driving. Incoming pulses will be time aligned after passing through the SMF.

However, since all pulses are equally phase modulated by the retiming circuit, errors are only expected in the presence of timing jitter, resulting in the potential for erroneous channel selection and imperfect retiming. Different random jitter values were applied to the input RZ signal using the built-in VPI function, and the results are shown in Fig. 5. The results show that this approach can reduce timing jitter even at the worst relative delay when input root mean square (rms) jitter is up to 10.25 ps.

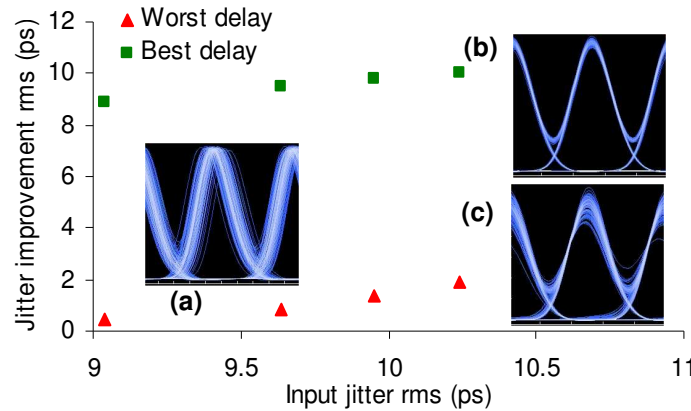


Fig. 5. Jitter improvement versus input rms timing jitter. Inset: 40Gbit/s eye diagrams of (a) input, output at (b) best and (c) worst delay when input jitter 10.25ps rms.

The PPL retiming proposed here is evaluated just prior to the receiver or an all optical processing node, however, in order to be used in intermediate network node requiring onwards transmission, the induced chirp of the retimed signal should be removed, and this can be performed by using phase insensitive wavelength conversion or using OEO conversion. One limitation of this scheme is the potential chirp carried by the input pulses. Chirp may be imparted to a pulse that was launched chirp-less, and the amount of chirp depends on the propagation configuration. The driving signal to the PM could be modified for the chirped pulses, however, this will complicate the scheme.

An optical TDM can be constructed by using several of the PPL retiming units. For example, three channels of 40 Gb/s signals from different local servers can be resynchronized by using three PPL units, which are synchronized to the local system clock of the TDM. Hence, after the PPL units, all the three input channels will be aligned in time [13]. Then, by introduction of appropriate delays among them, a TDM optical signal at 120 Gb/s can be formed.

4. Conclusion

In this investigation, we proposed and numerically analyzed, using commercial available numerical simulation tools, an energy efficient asynchronous PPL optical packet retimer using parabolic or sinusoidal phase modulation and linear dispersion. Simulations were performed at 40 Gb/s, showing that it can effectively resynchronize input RZ data with arbitrary phases. It can also reduce timing jitter even at the worst delay when the input rms jitter is up to 10.25 ps.

Acknowledgments

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