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Analysis of a Time-lens based Optical Frame Synchronizer and Retimer for 10G Ethernet Aiming at a Tb/s Optical Router/Switch Design

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Abstract— **This paper analyzes experimentally and by numerical simulations an optical frame retimer and synchronizer unit for 10 Gbit/s Ethernet input frames. The unit is envisaged to be applied in the design of an optically transparent router for Optical Time Division Multiplexed (OTDM) links, aggregating traffic from several 10 Gbit/s Ethernet (10 GE) links. The scheme is based on time-lenses implemented through a combination of a sinusoidally driven optical phase modulation and linear dispersion. Our analysis extracts the operation range of the scheme used for synchronization and retiming in the context of 10 Gbit/s Ethernet, considering the frequency offset to the local clock within the specified standard tolerance (i.e. ± 1 MHz for 10 Gbit/s Ethernet) and the Ethernet frame size (i.e. up to 1526 bytes). We also provide preliminary design insights to increase the operation range.**

I. INTRODUCTION

Optical 10 Gbit/s Ethernet links are widely available and deployed worldwide. Therefore, this kind of link is likely to be present in the design of ultra-high throughput optically transparent switches/routers with Tb/s interfaces that will aggregate traffic from several lower bit rate links. More specifically, the presented work constitute an important building block required to design an optically transparent switch/router for high speed optical time division multiplexed (OTDM) interfaces that aggregates traffic from several 10 Gbit/s Ethernet links in serial optical data into a single fiber [1].

Optical 10 Gbit/s Ethernet links transmit frames asynchronously with NRZ line code. Also, signal speed variation to nominal must be within ±100 ppm, i.e. up to 1 MHz frequency offset between transmitter and receiver clocks must be tolerated [2].

These features have direct implications on the design of optically transparent switches. For instance OTDM is a bit-interleaved synchronous system based on RZ pulses [1], so an all-optical NRZ-RZ conversion is assumed here.

In this paper we are especially interested in optical synchronization and retiming of 10 Gbit/s Ethernet frames to a local clock corresponding to the base rate of an OTDM signal, without performing clock recovery on the input frame signal. We can briefly assess the requirements for such reception units, as follows:

(1) Frames are asynchronously transmitted and received. As there is no clock recovery, reception is performed in regard to a local clock reference. Therefore, synchronization of the arriving frame to the local clock is needed. In this case, synchronization means the temporal alignment between the first bit of the incoming frame and the minimum of the local sinusoidal signal.

(2) The bit rate of the incoming signal can vary from the local clock. Therefore, the incoming pulse train must be retimed to the local clock frequency.

(3) 10 Gbit/s Ethernet frames have a maximum frame size of 1526 bytes (including SFD (start of frame delimiter) and Preamble field) [2]. Retiming must be correctly performed to all bits of the pulse train of a maximum size Ethernet frame.

Up to date, several synchronization and retiming schemes have been proposed [3-8]. In [3-4] asynchronous extraction of the first pulse and asynchronous clock recovery are demonstrated. J. A. Harrison et al. [5] proposes an all-optical retiming scheme by generation of a linearly chirped square pulse that is AND’ed optically with the incoming signal, followed by dispersion compensation, which suppresses timing jitter and phase wander on a bit by bit basis. This approach, however, requires low jitter clock recovery circuits. Asynchronous retiming has also been demonstrated [6-7]. In [6], temporally broadened signal pulses are re-sampled, which reduces efficiency, while in [7] the light path is split by four, considering that one of the four paths will correctly modulate the asynchronous local clock. However, this scheme tolerates only very low frequency offset between remote and local clock.

The main contribution of this paper is the analysis of a time-lens [8-9] synchronization and retiming unit (SRU) for optical reception of 10 Gbit/s Ethernet frames, without clock recovery, fulfilling the requirements stated above. The analysis will be used to extract the operation range of a simplified version of the scheme reported in [9]. The operation range is addressed both through laboratory experiments and numerical simulations.

The remaining part of the paper is organized as follows. Section II describes the basic time-lens synchronization and retiming unit and its operational and design principles. In Section III we provide the analysis of the unit in the presence of the specific requirements related to 10 Gbit/s Ethernet frame reception. Laboratory experiments and numerical simulations are shown in Section IV. Section V contains our plans for future work and finally, Section VI our conclusions.

II. TIME-LENS SYNCHRONIZATION AND RETIMING UNIT

A time-lens is a concept that arises from the time-space duality in optical processing that refers to the analogy between the paraxial diffraction of beams through space and the dispersion of narrowband pulses through dielectric media in time [8-10]. Practical time-lenses are usually realized by an optical phase modulator (PM) driven with an electrical sinusoidal voltage of frequency f_L ($T_L = 1/f_L$) combined with a dispersive element, usually a single mode fiber (SMF).

Fig.1 shows the schematic setup for the synchronization and retiming unit. The input signal is an asynchronous frame consisting of serialized data over the fiber at a nominal line rate of f. The bit period is T = $1/f$. The local clock is a sinusoidal signal with frequency f_L and the frequency offset between local and arriving frame clocks is $\Delta f = f - f_L$. The asynchronous arrival of the input frame implies an initial time misalignment Δt_0 between the local clock and the arriving pulse train. Formally, Δt_0 is defined as the temporal difference between the center of the first bit and the minimum of the clock sinusoidal signal. It is assumed that the signal has been NRZ to RZ converted making it appropriate for OTDM signals [1].

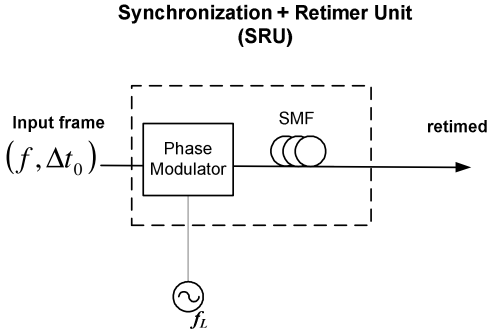


Fig. 1 Basic time-lens synchronization and retiming unit

A. Operational Principle

The scheme is based on the time-lens effect, which may be used to lock the pulse position in the time-domain [9]. Fig. 2 shows input pulses in various time misalignments with the local sinusoidal clock. The initial time misalignment (Δt_0) results from the asynchronous arrival of the frame. The time misalignment (Δt) will change by $\Delta T = 1/f - 1/f_L$ for each successive pulse because of the frequency offset Δf.

In Fig. 2, when the input signal is aligned with the minimum of the sinusoidal clock, the pulse at the output of the PM is chirp-free, since the time derivative of the sinusoidal phase is zero. The part of the input signal on the right side will experience a negative chirp and the input signal on the left side will experience a positive chirp. The signal, which is further away from the central signal will be more chirped. If they pass through a dispersive element, the different amounts of chirp will move the data pulses to the position of the minimum of the clock signal. The initial time misalignment (Δt_0) will thus be cancelled. Note that this pulse position locking is performed on a bit-by-bit basis.

In practice, the wavelength shift resulting from the chirp unit should be monotonically decreasing or increasing. As a consequence, the position lock will occur properly only for certain time misalignments, in the interval of ± $T_L/4$ from the minimum of the sinusoidal local clock. Inside this range, the sinusoidal drive is an approximation of the ideal parabolic drive.

There are two direct consequences from the above statement. First, the actual initial time misalignment can assume any value in the interval of ± $T_L/2$ in our simplified scheme from the minimum of the sinusoidal local clock. So, the basic SRU is unable to perform the pulse position lock accurately for arbitrary initial time misalignment – only within a specified operation range. We will discuss this issue in more details in this paper.

Second, as the frequency offset implies a variation in the time misalignment, the difference of the frequencies will, finally, limit the frame size that can be retimed by the SRU. This aspect is not considered in other literature.

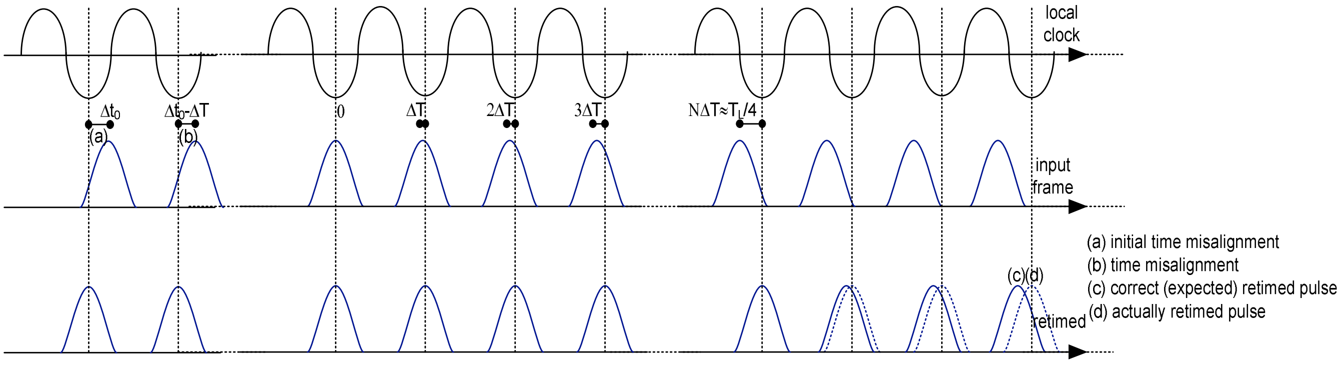


Fig. 2 Operational principle for basic time-lens synchronization and retiming unit

III. ANALYSIS

We consider the SRU shown in Fig. 1 and the requirements described in Section I. The input signal is an Ethernet 10G BASE-R frame consisting of serialized data over the fiber at a nominal line rate of $f = 10.3125 + \Delta f$ Gbit/s. Local clock is a sinusoidal signal with frequency f_L = 10.3125 GHz and the maximum frequency offset Δf is limited to ±1 MHz.

We are interested in evaluating the operational conditions of the unit in regard to (A) frequency offset and (B) frame size. As illustrated in Fig. 2, in the presence of a frequency offset, the basic SRU performance depends on the initial time misalignment and on the frame size. We aim at analyzing this dependence. As seen in Fig. 2, some pulses will experience a temporal misalignment compared to the ideal temporal position, as seen in Fig. 2(c)(d). In an eye-diagram this would manifest itself as timing jitter. Root mean square (RMS) timing jitter is therefore a good performance metric for the system.

We can derive an approximate theoretical expression for the maximum frame size (number of bits) for correct SRU operation, directly from Fig. 2. The time misalignment for the nth pulse in the frame can be expressed as (1):

$$\Delta t = \Delta t_0 + \mathrm{n}\Delta T \qquad (1)$$

In Fig. 2, $f_L < f$ ($\Delta f > 0$). In this case, the time misalignment variation ΔT is negative and time misalignment is decreasing. Thus, the SRU will perform properly if $\Delta t > -T_L/4$. In the case where $f_L > f$ ($\Delta f < 0$), the time misalignment variation ΔT is positive, time misalignment is increasing and SRU will perform correctly while $\Delta t < T_L/4$. Thus, we can compute the maximum frame size for the cases of $\Delta f > 0$ and $\Delta f < 0$ as (2a) and (2b) respectively.

$$n < \frac{1}{|\Delta T|}\left(\Delta t_0 + T_L/4\right) \qquad (2a)$$

$$n < \frac{1}{|\Delta T|}\left(T_L/4 - \Delta t_0\right) \qquad (2b)$$

For 10 Gbit/s Ethernet conditions, we can readily compute the maximum frame size using (2a) and (2b) for various frequency offsets, as shown in Table I. So for f = 10.3125 GHz + 1MHz, f_L = 10.3125 GHz and an initial temporal offset of Δt_0 set to ~$T/4$ to cover the longest possible frame, the result is that 5054 bits can be synchronized using this scheme. The elements in Table 1 are derived the same way.

The results shown in Table I are very encouraging, as it is seen that quite large frames can be handled by this simple scheme. For the maximum, and worst case, frequency offset of 1MHz, frames up to 5000 bits can readily be synchronized, if the temporal offset between the sinusoidal and incoming bits is adjusted appropriately. 1 MHz is the maximum frequency offset one will encounter in an Ethernet environment, according to standardized specifications, and hence in many case a smaller frequency offset is encountered. Therefore, we also calculated how long packets could be tolerated for less than the worst case scenario. Table I shows that by reducing the worst case scenario frequency offset on 10% actually enables this scheme to handle even the maximum length frames of 12208 bits. This is indeed promising results and encourages further work with this simple scheme. However, it should be noted that strictly speaking, the simple scheme presented here does not fully live up to the requirements of the 10 Gbit/s Ethernet, as the maximum frame size cannot be handled when coinciding with the maximum frequency offset. However, this may be solved, as discussed in section V.

TABLE I. MAXIMUM FRAME SIZE (IN BITS)

Time misalignment Δt_0	Frequency offset Δf (MHz)						
	-1.0	-0.5	-0.1	0.0	0.1	0.5	1
-0.24 T	5054	10107	12208[1]	12208[1]	1031	206	103
-0,125 T	3868	7735	12208[1]	12208[1]	12208[1]	2578	1289
0	2578	5157	12208[1]	12208[1]	12208[1]	5157	2578
0,125 T	1288	2578	12208[1]	12208[1]	12208[1]	7735	3868
0,24 T	103	206	1031	12208[1]	12208[1]	10107	5054

[1] maximum Ethernet frame size (1526 bytes) is 12208 bits.

IV. EXPERIMENTS AND NUMERICAL SIMULATIONS

In order to demonstrate the results in Table I, we executed experimental and numerical simulation tests.

A. Laboratory Experiment

We performed a laboratory experiment to validate the proof of principle of the SRU in the presence of –1 MHz frequency offset, with a 1024 bits frame size generated as a 2^7–1 pseudorandom bit Sequence (PRBS) based on RZ pulses (2 ps full width half maximum (FWHM). The experimental setup is shown in Fig. 3.

We used f = 9.9535 GHz, instead of the nominal f = 10.3125 *GHz* because of the used laser being bound to this constraint, but still showing the proof of principle of our scheme.

In practice, the 1024 bits frame is carved out from a continuous pulse stream by an intensity modulator controlled by an electrical pulse generator just prior to OOK data modulation. The pulse generator is in sync with the data signal. The On-Off-Keying Modulator (OOK) modulation is derived from a bit pattern generator (BPG). Phase modulation is then applied to the data frame with alignment of Δt_0 by an electrical variable time delay. The now chirped data signal is amplified in an EDFA to compensate for component losses, and subsequently transmitted through a dispersive medium, in this case a length of dispersion compensating fiber (600 m).

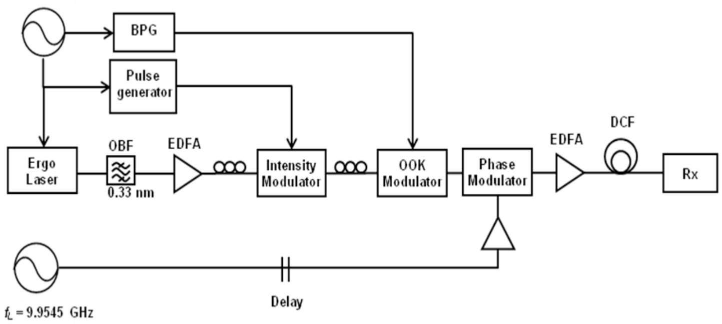
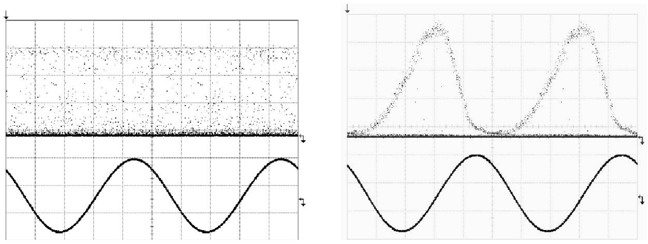


Fig. 3 Experimental set-up to realize a basic time-lens SRU.

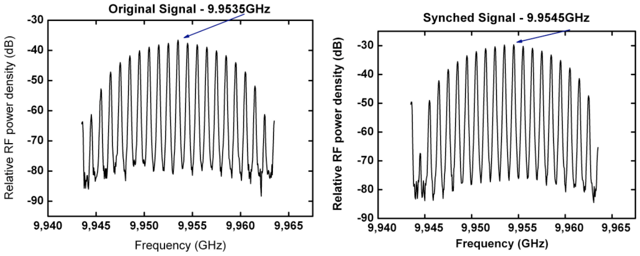


(a) (b)

Fig. 4 Experimental eye diagrams: (a) without PM and (b) with PM

Fig. 4 presents the experimental eye diagrams, without phase modulator, (a), and (b) with phase modulator. After the synchronization and retiming, a clear eye diagram (a) can be seen using the local clock as the trigger, thus clearly demonstrating that the data frame is now in sync with the local clock. (f_L). When the full time lens is employed, the data is clearly synchronized to the local clock.

Fig. 5 shows the electrical spectrum of the original (a) and retimed (b) signals. We can observe that the maximum frequency peak of the retimed signal has been adjusted to f_L = 9.9545 GHz.



(a) (b)

Fig. 5. Electrical spectrum: (a) original and (b) retimed signal

Fig. 6 shows the RMS timing jitter of the synchronized data frames for various frequency offsets, considering a convenient initial time misalignment (delay) for the reception of the 1024 bits frames. The synchronization unit offers a less than 1 ps timing jitter within the frequency offset range of ±1 MHz. This result is adequate for the application considered here.

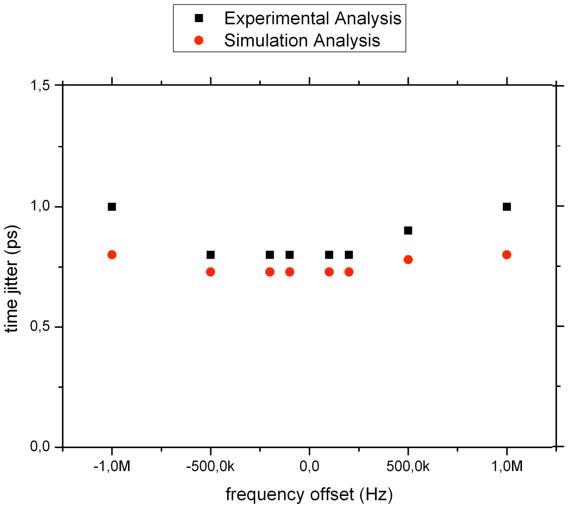


Fig. 6 RMS timing jitter vs. Δf for 1024 bits with ideal delay

The experimental results show the applicability of the SRU for synchronization and retiming of 10 Gbit/s Ethernet frames in the presence of a frequency offset, with small frame sizes. These results encourage us to research design workarounds (see Section V) in order to employ the SRU as a basic building block in the design of a synchronization and retiming scheme fully compliant with the requirements of all-optical 10 Gbit/s Ethernet frames.

B. Numerical Simulation

Numerical analysis is performed with a commercially available simulation tool, VPI Transmission Maker v. 8.0. Optical signal generation uses RZ Gaussian pulses modulated by OOK data at 1553 nm and a frequency of $f = 10.3125$ GHz $+\Delta f$. The RZ duty cycle is 0.06 and the power is 1 mW. This generated signal is a 2^7-1 (PRBS). The local clock is a sinusoidal voltage with $f_L = 10.3125$ GHz. A delay module is used to simulate different initial time misalignments (Δt_0). The SRU is represented by an optical phase modulator (PM) with $V_{pp} = 2.7\ V_\pi$ and the dispersive element is 2.0 km of SMF with 17 ps/nm/km dispersion, using the design parameters reported in [8-9].

We simulated the SRU operation for various frequency offsets and a 1024 bits frame size. The RMS timing jitter obtained in simulation is also shown in Fig.6, showing good agreement with and corroborating the experimental results.

In order to analyze the retiming capabilities of the basic SRU scheme, we evaluate the RMS timing jitter for $\Delta f = \pm 1$MHz at various initial time misalignments, for a 1024 bits frame size, as shown in Fig. 7.

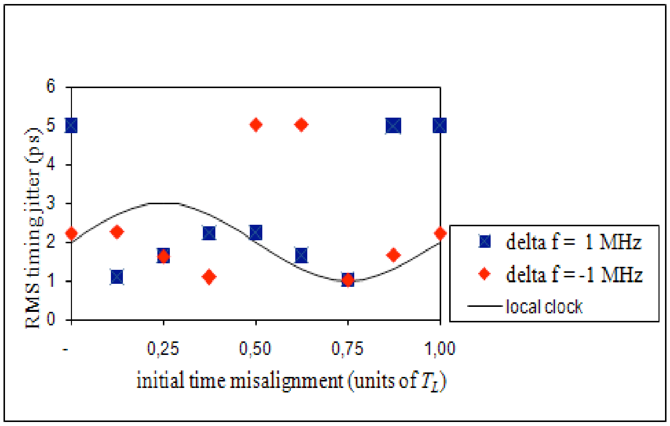
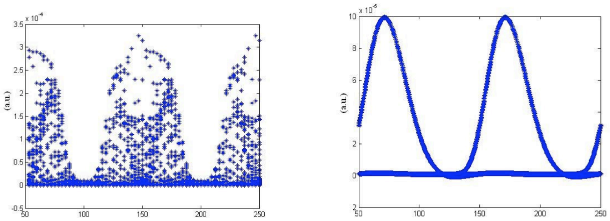


Fig. 7. RMS timing jitter as function of initial time misalignment (Δt_0)

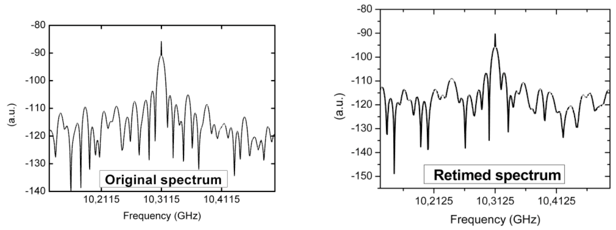
The retiming is not properly performed for the initial delay of 0.5T and 0.63T at $\Delta f = -1$ MHz and for $\Delta t_0 = 0{,}0T$ and 0.88T at $\Delta f = 1$ MHz. In these cases, the maximum frame size supported by the SRU (2b) is less than the generated frame size. The local clock is also plotted in Fig. 7 for easiness of visualization of the conditions discussed in Section III. This result shows that a convenient initial time misalignment is required in order to have proper operation of the SRU and also low RMS timing jitter, confirming our analysis in Section III.

Fig. 8 and 9 show, respectively, the eye diagram and the electric spectrum for both original (a) and retimed (b) signals, at $\Delta t_0 = 0.75T$. These are used for RMS timing jitter calculation and for correct retiming verification.



(a) (b)

Fig. 8 Eye diagram: (a) original and (b) retimed signal



(a) (b)

Fig. 9 Electrical spectrum: (a) original and (b) retimed

Finally, we simulate the SRU operation for various frame sizes in the presence of a frequency offset of $\Delta f = 1$ MHz, using the optimum initial delay, which depends on the length of the frame. The resulting RMS timing jitter is plotted in Fig. 10. Note that even if the retiming is occurring properly, the timing jitter increases considerably for frames with over 2500 bits size. Therefore, the actual maximum frame size range with acceptable timing jitter is reduced from the theoretical 5000 bits, assuming that it covers 50% but in practice covers only 43%, to 2500 bits, because of the high timing jitter in bigger frames. This is due to the deviation of the sinusoidal drive from the ideal parabolic drive, which occurs for Δt close to $\pm T_L/4$..

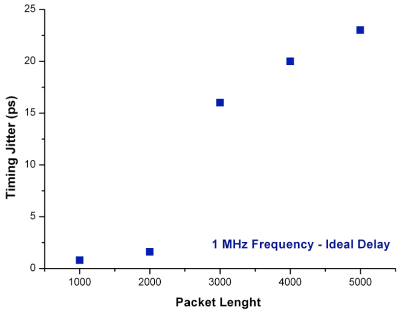


Fig. 10 RMS timing jitter vs. frame size

V. FUTURE WORKS

Analysis of the basic SRU shows that it can perform properly if we are able to meet the following conditions:

(A) Approximate the initial time misalignment experienced in the SRU to an appropriate misalignment with the maximum or minimum of the local sinusoidal clock.

(B) Process a limited amount of bits in the SRU.

In order to meet the above conditions, we are researching design workarounds for making the SRU a basic building-block of a synchronization and retiming circuit which is fully effective in 10 Gbit/s Ethernet requirements.

First, we may limit the basic SRU operation to up to 2048 bits. This number was chosen because of the 2500 bits limitation observed in Fig. 10. We propose to use a constant phase shift in the local electrical clock. The phase shift is controlled by an electronic envelop detector which detects the frame arrival and compares it to the phase of the local clock reference, in order to perform the choice for the correct phase shift. All the proposed complementary circuits are electronic, which provides a costly and efficiently design.

Next, we could combine different SRUs, in order to process up to full-sized 12.208 bits Ethernet frames. We are also working to extend it in order to consider transmission effects, which are not considered in the present analysis.

VI. CONCLUSIONS

In this paper we analyzed an optical 10GBASE-R Ethernet time-lens synchronizing and retiming unit. Experiments and simulations show that the basic SRU is able to cope with most usual requirements for asynchronous receiving of frames subjected to frequency offset inside the tolerance of 10 Gbit/s Ethernet. The basic SRU is capable of performing synchronization and retiming properly for frame sizes of up to 2048 bits, if we can set a convenient initial time misalignment choosing the phase of the reference local clock. We have indicated some possible design workarounds that could be useful at employing the basic SRU as a building-block for a synchronization and retiming unit fully-compliant with 10 Gbit/s Ethernet requirements. We are currently working on evaluation of the proposed design insights.

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