High-Speed Synchronization for Optical Packet Networks

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Abstract: *A statistical model is developed to assess synchronization requirements for high-speed OTDM packet network regeneration. The model is then applied to analyze asynchronous and synchronous regenerator architectures.*

1. Introduction

The rapid increase in data traffic [1], necessitate new solutions capable of combining the advantages of the network packet layer with the high-bandwidth optical transmission in the physical layer. This leads to new requirements for the optical physical layer, including:

1. High-speed OTDM channel transmission (40-100 Gb/s) [5]
2. Discontinuous or "bursty" transmission of variable length packets directly on the optical channel, due to dynamically varying traffic characteristics [2]
3. Jitter accumulation along the optical transmission path [3] [4]

To overcome scaling limitations due to noise and non-linear distortion accumulation along the optical path, 3R regeneration (*Re-amplification, Re-shaping, Re-timing*) becomes necessary. As transmission rate increases electronic approaches to 3R regeneration become not practical and new all-optical solutions are required [6]. However development of new high-speed all-optical 3R regeneration requires the effects of signal timing jitter to be understood and accurately quantified. This paper describes a statistical analysis of synchronization requirements (*jitter tolerance*) for optical 3R regeneration in high-speed OTDM packet networks. The statistical model developed is used to analyze different packet regeneration approaches.

2. Approaches to OTDM 3R Packet Regeneration

Regeneration can either be achieved by forcing the local source into synchronism with the incoming bit steam, or by forcing the incoming data into synchronism with the local source. The first approach is known as synchronous regeneration and operates in combination with clock extraction (*phase locked loop or mode-locked laser*). The second approach is known as asynchronous regeneration [6]. Fig.1 shows a synchronous regeneration solution for packet network application. Synchronization between the incoming data pulses and the local clock source pulses is obtained through the process of clock extraction. Regeneration is achieved by modulating the local clock signal with the input data signal. Each pulse in the data signal

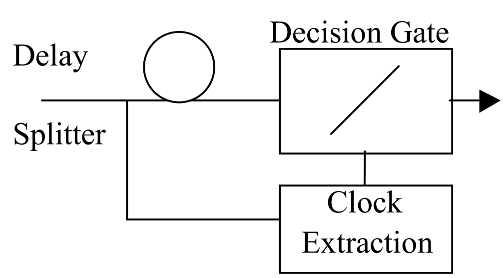

Fig.1 Synchronous Regenerator

causes a gate (*decision device*) to switch to transmission mode for a fixed time (*the gate window opening time W*), allowing a single pulse from the local clock source to pass through. Under this procedure the modulating pattern of the input data signal is transferred onto the local clock signal. Re-synchronization of the regenerator is achieved on a packet by packet basis at the cost of introducing a time delay in the system (equal to the clock extraction locking time). Fig.2 shows an asynchronous regenerator solution for packet network application [7]. In asynchronous regeneration the local clock pulse source is a free running oscillator and no clock recovery is used (therefore no delay due to synchronization time (*locking time*) is introduced). The incoming data pulses are used to simultaneously control the operation of 4 gates (4-gated architecture is the best compromise between equipment requirements and BER performance [7]). The output from the local clock oscillator is applied to the inputs of the 4 gates, each of these being delayed relative to the other by an amount T/4 (where T is the bit period). Since the phase of the local clock oscillator pulses relative to the incoming data pulses has arbitrary and unknown value in the interval [0, 2π], the gates window opening time are chosen so that, whatever the value of the incoming data phase, the local clock oscillator pulses will be correctly modulated by at least one of the 4 gates. Then on the basis of the optical energy $\langle E \rangle$ emerging from each gate integrated over the packet duration the selection of the correctly modulated gate can be achieved.

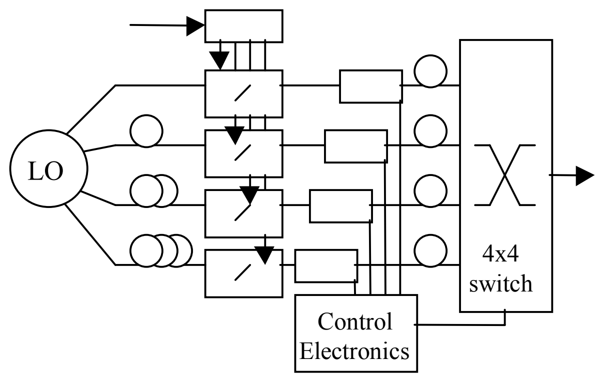

Fig.2 Asynchronous Regenerator

3. Modeling Bit Error Probability for High-Speed Regeneration

For high-speed (100 Gb/s) optical systems, the main cause of bit errors occurring in the process of packet regenerating is jitter in the time arrival of both input data and local clock pulses. Random fluctuation in the mean time arrival of the input data and local clock pulses increases the probability of the local oscillator pulse falling outside the gate window, and so of being not correctly modulated. Jitter in the input data signal is introduced during transmission. For synchronous regeneration, the local clock source is jittered as result of the limited level of jitter suppression achievable with clock extraction [8]. For asynchronous regeneration instead, random variation of the local free running oscillator are introduced by the limited accuracy of existing free running oscillators [9], and by possible frequency off-set between the local clock oscillator of the regenerator and local clock oscillator of the packet generator at the transmitter. The aim of this model is to analyze the bit error probability arising from timing jitter in the input and clock signal for asynchronous and synchronous regeneration. This can be done by modeling the local clock and data pulses time arrival as two random variable normally distributed [7] over the bit period (respectively φ_{lo} and φ_d), having standard deviation σ (*RMS timing jitter*).

4. Asynchronous Regeneration

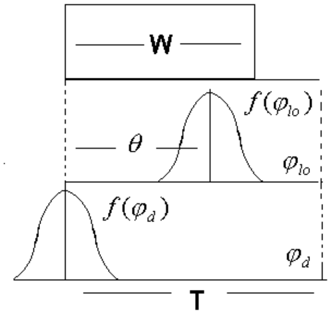

Fig.3 Probability density functions of data and local oscillator time arrival

Local oscillator and data signal pulse time arrivals are considered over one bit period T for one single gate. As both local oscillator and data pulses are affected by jitter their time arrivals are expected to fluctuate relatively to their respective means. Under asynchronous operation the mean value of the distribution of the local oscillator pulse time arrival $f(\varphi_{lo})$ occurs at time θ ($\theta \in [0,T]$), after the mean of the distribution of input data pulse time arrival $f(\varphi_d)$ (Fig.3). The characteristic function of the time arrival of the local oscillator pulse can be expressed as:

$$\Phi(\varphi_{lo}) = F[f(\varphi_{lo})] = \exp\left[j\omega(\theta) - \tfrac{1}{2}\sigma_{lo}^{2}\omega\right] \tag{1}$$

where φ_{lo} is the time arrival of the local oscillator signal, $f(\varphi_{lo})$ is the probability density function of the random variable φ_{lo}, *F[.]* is the Fourier transform operator, σ_{lo} is the local oscillator timing jitter and W is the regenerator gate window opening time. Similarly the characteristic function of the data pulse:

$$\Phi(\varphi_d) = F[f(\varphi_d)] = \exp\left[-\tfrac{1}{2}\sigma_d^{2}\omega\right] \tag{2}$$

where φ_d is the time arrival of the data signal, $f(\varphi_d)$ is the probability density function of the random variable φ_d and σ_d is the data signal timing jitter. Assuming φ_{lo} and φ_d are statistically uncorrelated, the relative difference in the time arrival between the local oscillator pulse and the data pulses can be expressed as a new random variable ΔM, where:

$$\Delta M = \varphi_{lo} - \varphi_d \tag{3}$$

$$\Phi(\Delta M) = \Phi(\varphi_{lo})\Phi(\varphi_d) = \exp\left[j\omega(\theta) - \tfrac{1}{2}\sigma_{\Delta M}^{2}\omega\right] \tag{4}$$

$$f(\Delta M) = F^{-1}[\Phi(\varphi_{lo})\Phi(\varphi_d)] = \frac{1}{\sqrt{2\pi}\sigma_{\Delta M}}\exp\left[-\frac{\Delta M - m_{\Delta M}}{2\sigma_{\Delta M}^{2}}\right] \tag{5}$$

$$\sigma_{\Delta M}^{2} = \sigma_{lo}^{2} + \sigma_d^{2} \tag{6}$$

$$m_{\Delta M} = \theta \tag{7}$$

Where $\Phi(\Delta M)$ is the characteristic function, $f(\Delta M)$ is the probability density function, $\sigma_{\Delta M}$ standard delineation, and $m_{\Delta M}$ the mean of the random variable ΔM. The local oscillator pulse will be correctly modulated by the data signal only if the difference in the time arrivals between the two pulses is smaller than the gate window opening time W of the regenerator decision device. So the probability of an error occurring is:

$$Pe(\Delta M) = P(W \le \Delta M \le 0) = 1 - P(0 \le \Delta M \le W) = 1 - \int_0^W f(\Delta M)\,d\Delta M \tag{8}$$

The average probability of error is calculated by considering the various combinations of values of each data pulse with its nearest neighbors, as shows in table 1.

i-1	*I*	*I+1*	**Logical Equation**	***P(error)***
0	0	0	0	0
0	0	1	$Pe(\Delta M_{i+1})$	$Pe(\Delta M_{i+1})$
0	1	0	$1-Pe(\Delta M_i)$	$1-Pe(\Delta M_i)$
0	1	1	$[1-Pe(\Delta M_i)]AND[1-Pe(\Delta M_{i+1})]$	$[1-Pe(\Delta M_i)]\cdot[1-Pe(\Delta M_{i+1})]$
1	0	0	$Pe(\Delta M_{i-1})$	$Pe(\Delta M_{i-1})$
1	0	1	$[Pe(\Delta M_{i-1})]OR[Pe(\Delta M_{i+1})]$	$1-\{[1-Pe(\Delta M_{i-1})]\cdot[1-Pe(\Delta M_{i+1})]\}$
1	1	0	$[1-Pe(\Delta M_i)]AND[1-Pe(\Delta M_{i-1})]$	$[1-Pe(\Delta M_i)]\cdot[1-Pe(\Delta M_{i-1})]$
1	1	1	$[1-Pe(\Delta M_i)]AND[1-Pe(\Delta M_{i-1})]$ $AND[1-Pe(\Delta M_{i+1})]$	$[1-Pe(\Delta M_i)]\cdot[1-Pe(\Delta M_{i-1})]$ $[1-Pe(\Delta M_{i+1})]$

Tab.1 Bit Error Probability in the i^{th} pulse position

Where $Pe(\Delta M_i)$ is calculated as in equation (8). $Pe(\Delta M_{i+1})$ defines the probability of an error being caused by the interaction of the local oscillator pulse with the subsequent data pulse, while $Pe(\Delta M_{i-1})$ defines the probability of an error being caused by the interaction of the local oscillator pulse with the previous data pulse.

The statistics of ΔM_{i+1} is defined as:

$$\Delta M_{i+1} = \varphi_{lo} - \varphi_{d+1} \tag{9}$$

$$Pe(\Delta M_{i+1}) = P(0 \le \Delta M_{i+1} \le W) = \int_0^W f(\Delta M_{i+1})d\Delta M_{i+1} \tag{10}$$

Where $f(\Delta M_{i+1})$ is identical to $f(\Delta M_i)$, except for the mean which is given by:

$$m_{\Delta M_{i+1}} = W/2 - 1 \tag{11}$$

The statistics of ΔM_{i-1} is defined as:

$$\Delta M_{i-1} = \varphi_{lo} - \varphi_{d-1} \tag{12}$$

$$Pe(\Delta M_{i-1}) = P(0 \le \Delta M_{i-1} \le W) = \int_0^W f(\Delta M_{i-1})d\Delta M_{i-1} \tag{13}$$

Where $f(\Delta M_{i-1})$ is identical to $f(\Delta M_i)$, except for the mean which is given by:

$$m_{\Delta M_{i-1}} = W/2 + 1 \tag{14}$$

The average probability of error at the output of the regenerator is obtained by summing the probabilities listed in Tab.1. The same procedure is applied to calculate the probability of error for all 4 gates. In particular as the clock pulses are arranged to arrive later in time to each gate by an amount *T/4*, equation (1) for gate 2 is evaluated for $\theta_2 = \theta + T/4$, for gate 3 is evaluated for $\theta_3 = \theta + T/2$ and for gate 4 is evaluated for $\theta_4 = \theta + 2T/3$. The BER (*Bit Error Rate*) at the output of the four gates is plotted in

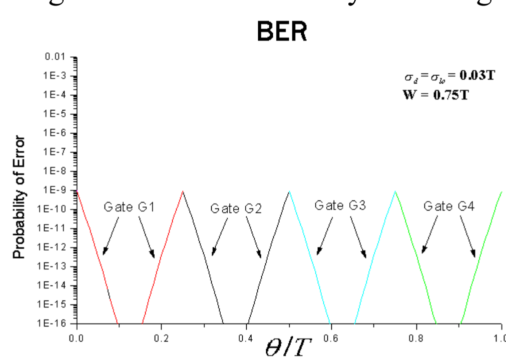

Fig.4 BER of 4-gate regenerator

Fig.4. No further error is added by the process of gate selection when approach [7] is used:

If $\left(\langle E_j\rangle = \min\{\langle E_i\rangle\}\right)$ then select gate (1 + (j + 1) mod4) (15)

Where $\{\langle E_i\rangle\}$ denotes the set $\{\langle E_1\rangle, \langle E_2\rangle, \langle E_3\rangle, \langle E_4\rangle\}$ and $\langle E_i\rangle$ the optical energy measured at the output of the *i* gate.

5. Synchronous Regeneration

Synchronous regeneration is characterized by phase correlation between the input data and the local clock signal. Under synchronous operation the mean value of the distribution of the local oscillator pulse time arrival is forced (by the process of clock extraction) to occur at time W/2 (to minimize the effect of jitter on BER) after the mean of the distribution of input data pulse time arrival (Fig.5).

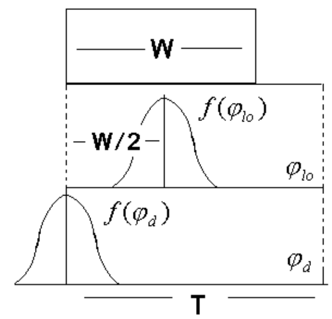

Fig.5 Probability density functions of data and local oscillator time arrival

The BER for synchronous regeneration is therefore calculated applying the same procedure which led to calculate the BER for a single gate in asynchronous regenerator setting $\theta = W/2$. Under this conditions equation (1) becomes:

$$\Phi(\varphi_{lo}) = F\left[f(\varphi_{lo})\right] = \exp\left[j\omega\left(W/2\right) - 1/2\,\sigma_{lo}^{\;2}\omega\right] \quad (16)$$

6. Results and Discussion

Fig.6 shows the calculated BER for synchronous regeneration as a function of the clock and input data signal jitter (normalized to bit period). The BER is plotted for dirac signal pulses (*impulses*) and for RZ rectangular shaped pulses with DutyRatio (*or DutyCycle*) equal to 0.1T and 0.2T. The gate-switching window was chosen to be 0.75T, to minimize the effects of jitter on the regenerator BER [7]. Rectangular pulse shapes were introduced in the model by re-shaping the window switching time. Fig. 7 shows the BER for asynchronous regeneration as a function of the clock and input data signal jitter (normalized to the bit period), under the same conditions used for synchronous regeneration.

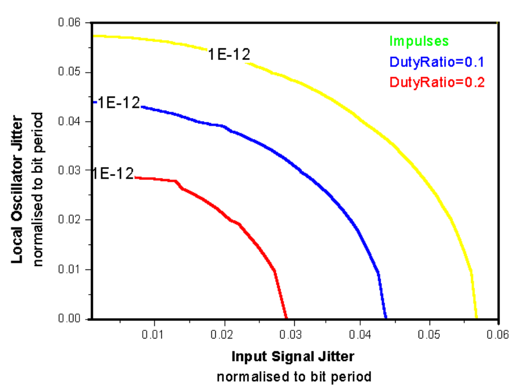

Fig.6 Synchronous Regenerator BER

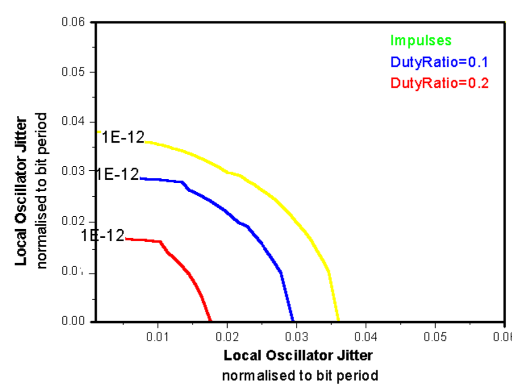

Fig.7 Asynchronous Regenerator BER

Results show serious limitations in the minimum level of jitter tolerable by regeneration. For synchronous regeneration on 40Gb/s (T = 25ps) transmission the average tolerable level of jitter on data and clock signal is limited to 1ps (for rectangular RZ pulses with DutyRatio = 0.2T). This implies that high level of jitter suppression must be performed at the clock extraction. If feedback systems are used to achieve synchronization then long locking time delay will be introduced at the regenerator. Asynchronous regeneration operation does not introduce locking delay but is sensitive to phase noise. In particular at 40Gb/s transmission only very low level of input jitter as 0.5ps can be tolerated (for rectangular RZ pulses with DutyRatio = 0.2T). Finally there is a clear limitation on the maximum pulse duty-ratio to be 0.2T for RZ transmission.

7. Conclusions

Synchronization requirements and regeneration techniques for RZ pulses in high-speed OTDM packet networks were investigated for bit-rates up to 100Gb/s. Synchronous regeneration schemes result in higher tolerance (0.5ps for 40Gb/s transmission) than asynchronous-gated devices, but require more equipment and delay lines for their realization. Due to tight jitter tolerances, network operating at 100Gb/s will require precise 3R regeneration for error-free transmission. Packet transmission requires much faster locking time (10's of bits = 10's of picoseconds) than can be achieved with standards electronic clock recovery devices (*PLL*).

8. Acknowledgment

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8. References

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