CHAPTER - 1

INTRODUCTION

Recent years have witnessed a phenomenal growth of research efforts and developmental activities in the optical fibre technology and optoelectronic devices. The optical fibre indeed offers itself as a versatile transmission medium. When suitably engineered it can be used in a variety of applications which range from data transmission over short links and equipment interconnections within a building to long haul telecommunication networks. The enormous information carrying capacity, freedom from electromagnetic interference, immunity from ground-loop problems, very low transmission loss, light weight and small size of the individual fibres, allowable small bending radius of curvature and the potential economy are some of the outstanding features that make fibre optic systems appear more attractive than the conventional systems.

In optical communication systems, due to the inherent nonlinear characteristics of the light sources, digital transmission is usually preferred to its analog counterpart. A digital transmission system requires a receiver that should be synchronized to the incoming signal format. In case of a baseband digital fibre optic transmission system employing direct detection technique, three levels of synchronization are usually encountered: (1) bit synchronization (2) word synchronization and, (3) frame synchronization. Bit synchronization is essential since an optimum bit detector requires precise knowledge of the bit transition time before a bit-by-bit detection is accomplished. Following bit synchronization, the word synchronization is needed to sort out the bits into the appropriate words. Finally the frame synchronization is required by the user to distinguish the word groups or frames.

There exist a number of avenues towards achieving the bit synchronization by using extra power and/or bandwidth. For instance, one can use start and stop signals to synchronize the encoder and decoder. A separate subchannel can also be dedicated exclusively to transmitting synchronizing information. On the other hand there exists a different class, called self bit synchronizers, which extract timing information directly from the received random data stream without any additional power, or bandwidth etc. added for the synchronization process.

Performance of bit synchronizers is in general assessed in terms of rms timing jitter or the expected magnitude of the timing jitter in the recovered clock. The effect of timing jitter on the receiver performance is normally evaluated in terms of the average bit error probability (BEP). Another important effect of imperfect bit synchronization on the receiver performance is the possible loss of bit integrity. In a digital receiver, the bit integrity gets lost when the recovered clock slips or gains one or more clock cycles. This causes addition or deletion of one or more data bits which in turn affects the word synchronization.

In the last few years the subject of bit synchronization has been studied in depth and a considerable body of literature is available for designing, evaluating, and testing synchronization circuits for conventional communication systems[1-30]. Unfortunately, the conventional synchronization theories, based on additive Gaussian noise assumption, are not directly applicable to optical channels. In an optical receiver, noise at the photodetector output is neither additive nor Gaussian, but a signal dependent nonstationary random process. There is further complication when the above process is amplified by a random multiplication process if the detector is an avalanche photodiode (APD).

The self bit synchronization in a digital receiver can be effected either through a closed loop data tracking scheme or by using an open loop timing extraction circuit. The latter class usually employs either a linear processing when the transmission is made in return-to-zero (RZ) signalling format, or a nonlinear processing when the transmission system employs a nonreturn-to-zero (NRZ) signalling format. There have been some useful studies on both the classes of bit synchronizers in optical receivers. An important early study on the tracking loop type synchronization in optical receiver is due to Gagliardi and Haney[31] who have considered optical synchronization from the viewpoint of phaselocking with shot noise process. The probability density function (pdf) of the tracking error has been derived for both first and second order tracking loops. The results are useful in ranging and doppler tracking using optical systems. Some studies have been made by Forrester and Snyder[32] on the performance in estimating a Wiener process that modulates the phase of a subcarrier in a direct-detection optical communication system. An approximation has been derived for the steady state pdf of the estimation error. The mean squared estimation error predicted using this density has been compared to theoretical lower bounds on the error and the sample mean square error obtained by simulation. The results have applications to the problem of establishing a coherent reference carrier in the presence of oscillator instability. Gagliardi[33] has studied the problem of synchronization using pulsed edge tracking of optical pulse position modulated (PPM) communication systems. The edge tracking operation in a binary PPM system has been examined taking into account the quantum nature of the optical transmissions. Consideration is given first to the synchronization using a periodic pulsed intensity, then extended to the case where position modulation is present and auxiliary bit decision is needed to aid the tracking operation. Performance analysis has been made in terms of the timing error and its associated statistics and, the timing error variances are shown as a function of system signal-to-noise ratio.

Mengali[34] has studied the synchronization problem for data transmission over optical channels under the hypothesis of negligible intersymbol interference (ISI). In particular the Maximum Likelihood (ML) estimation of the timing parameters has been found assuming known data symbols at the receiver. Analogous results have been attained for the case of unknown symbols but with some deviation from the ML criterion. Practical implementations of these estimators have been discussed and various tracking loop type approximations have been suggested to accommodate different signal shapes and modulation formats. It has been found that the performance of one of the suggested synchronizer structures (a decision directed version of the well known early-late gate tracker), used for binary PPM signal, performs better than an analogous synchronization system studied elsewhere[35]. Finally, the advantage of exploiting the knowledge of the received data has been estimated in the case of binary pulse amplitude modulation (PAM).

An important study on the tracking properties of the phase locked loops (PLL) in optical receivers is due to Mengali and Pezzani[36]. The variance of phase errors of the loop has been found as a function of relevant system parameters and of the modulation formats. Two modulation formats have been considered. In the first case, the transmitted optical power is considered to be pulse amplitude modulated and the synchronization information is extracted directly from the information bearing signal. In the second case the timing information is sent separately by sinusoidally modulating the optical power at a frequency equal to the transmission rate. The restriction of the analysis has been stated to be the assumption of negligible phase errors. However, such operating conditions are usually met in a practical receiver because the timing information produced in the synchronizer subsystem must be quite accurate to avoid unacceptable increases in the error probability. For PAM case, the total phase error variance has been expressed as a sum of three components contributed by the pattern randomness of the received data stream, shot noise in the photodetector and the receiver thermal noise. For the sinusoidal modulation case, the same method has been adapted except that the pattern noise component has been set to zero. The results obtained in the second case has been compared with the results obtained by other workers[31,32,37]. It has been pointed out that their results are rather general insofar as they do not make restrictions on the amplitude of phase error. On the other hand this paper[36] considers a finite duration impulse response (rectangular) for the photodetector circuit while the previous workers assumed a broadband photodetector with a delta function as its impulse response.

The open loop timing recovery scheme with simple linear filtering proves to be a useful means for RZ signalling format particularly when the transmission rate becomes very large. A detailed analysis has been provided by Andreucci and Mengali[38] on the linear timing circuit employing a tuned filter in an optical receiver. The sensitivity of the timing jitter to the received signal count, different pulse shapes, and filter detuning has been investigated in an exhaustive manner. It has been observed that, other things being equal, asymmetric pulses lead to better performance of the regenerator than symmetric pulses.

In a chain of self-timed regenerative repeaters for data transmission, each regenerator extracts the timing information from the incoming signal which is subsequently used in the receiver decision circuit to obtain the desired data stream. However, the finite timing jitter present in the recovered timing clock produces effectively a position modulation of the regenerated signal which generally reduces the timing extraction capability of the next repeater. Consequently the jitter accumulates along the repeater chain which in effect limits the maximum allowable length of the digital link.

Considerable work has been carried out on the jitter accumulation problem for conventional communication systems. There have also been some useful studies in the same direction on optical communication systems. Mengali and Pirani[39] have derived simple formulae for evaluating the timing jitter accumulation in a chain of regenerative repeaters for optical fibre transmissions. The timing circuit in each repeater has been modelled as a PLL. The behaviour of jitter variance as a function of the number of repeaters for a 140 Mbps system has been reported. The problem of evaluating the performance of fibre optic PCM systems with a chain of regenerative repeaters has been considered by Dogliotti, Luvison, Mengali and Pirani[40]. The timing recovery scheme has been considered to consist of a nonlinear circuit followed by a resonant filter. A method has been provided to evaluate the accumulation of timing jitter and alignment error along the repeater chain. The effects of alignment error on the average error probability have also been evaluated.

Another work in this direction is due to Luvison, Pirani and Mengali[41]. A detailed study has been made on the jitter generation and propagation along the chain of optical PCM repeaters. Assuming the signalling format as the RZ type, the timing circuits in the repeaters have been considered as simple resonant circuit tuned at the frequency equal to the transmission rate. The timing circuit in a regenerator has been viewed as a model that relates the output and input jitter through a linear time-varying filter which has been subsequently simplified by using a time-invariant approximation for analytical simplicity. The computed results reveal that the timing jitter variance reaches a limit with the increase in the number of repeaters, whereas in most of the conventional systems, variances increase without limit along the repeater chain.

It may be recalled that the effect of timing uncertainty on the receiver performance is normally assessed in terms of the average bit error probability (BEP). Evaluation of the average BEP is effected by averaging the conditional BEP for a fixed timing error over the statistics of the random timing error in the synchronization subsystem. A comparison of the required signal powers to achieve a specified error probability in presence and absence of the timing uncertainty gives the measure of power penalty that one needs to pay due to the imperfect synchronization. This becomes useful to system designers in making the total power budget for the entire transmission system.

An exact evaluation of BEP in an optical receiver is not a trivial task even in absence of any timing error. This is because the inherent noise in the photodetection process is signal dependent in nature. Several attempts have been made so far for accurate as well as approximate evaluation of BEP with perfect synchronization. For shot noise limited receivers with ideal photodetection, performance results have been well documented[35,42,43] for the class of conditional Poisson counting models. However, when the receiver operation is no longer shot noise limited (i.e., the receiver thermal noise becomes significant) and avalanche photodetection is to be employed for better receiver sensitivity, the evaluation of BEP becomes extremely complicated. Personick[44], in one of his early studies, has evaluated the BEP using signal-to-noise ratio approximation which represents the statistics of an APD receiver by a single Gaussian pdf. Mazo and Salz[45] have determined the BEP in closed form in absence of thermal noise for an APD with exponentially distributed avalanche gains. They have also provided the bounds on the receiver performance when ISI is present but with no avalanche gain.

A detailed description and comparison of four approaches to the BEP calculation have been provided by Personick, Balaban, Bobsin and Kumar[46]. One of these approaches deals with the exact calculation which makes use of the APD output statistics given by McIntyre[47]. It has been found that the exact calculation is difficult to implement except in certain limited system parameter ranges. The other three methods provide approximate calculations using Monte Carlo simulation, Chernoff bounds and the Gaussian approximation. Monte Carlo calculations have been found in complete agreement with the exact results which allows Monte Carlo results to be used to calibrate other methods. For simpler calculations or to obtain analytical expressions for the effects of parameter variations, the Gaussian approximation has been recommended. An accurate procedure has been reported by Balaban which is based on Monte Carlo method with importance sampling[48]. An approximate version[49] of McIntyre's model[47] has been used for the APD output process and the bit error rate has been evaluated for an integrate and dump type receiver.

Sorensen and Gagliardi[50] have used the exact[47] and approximate[49] APD statistics to evaluate the receiver performance in shot noise limited case. In presence of thermal noise they have used a simplified Gaussian distribution for APD output process which has been subsequently used to represent the receiver output voltage in a Gauss-Gauss form. Gagliardi and Prati[51] have determined the conditions under which the integral of a Gauss-Gauss pdf can be accurately represented by the integral of a single Gaussian pdf. An accurate assessment of the error involved in the approximation has been made.

It may be mentioned that the effect of ISI in BEP calculation needs to be considered particularly when one attempts to evaluate the performance of a long haul high bit rate transmission system. An important study in this direction is due to Cariolaro[52] who has developed two approaches for accurate BEP evaluation in APD receivers with due considerations of the ISI as well as the shot noise and the additive Gaussian noise. One of his approaches uses an exhaustive method which has been found to be inconvenient as its computational complexity increases exponentially with the number of interferers.

The other approach uses the classical Gram-Charlier expansion method and can be used even when the number of interferers is quite large. Finally, the theory has been used to compute the BEP for mutually independent symbols with various realistic shapes of the received optical pulses. Another accurate method for BEP evaluation in presence of ISI has been reported by Dogliotti, Luvison and Pirani[53]. An exact expression for BEP has been obtained in an integral form which takes into account the effects of ISI, shot noise and thermal noise. An exhaustive method to evaluate the integral has been illustrated and this has also been found to be unfeasible because of large computation time requirement with a large number of interfering samples. As an alternative to the exhaustive method, an accurate method has been devised which uses non-classical Gauss quadrature rules. In particular a fast and accurate method has been developed which can take into account a realistic model of the overall system and a precise characterization of the statistical properties of the system disturbances.

It appears from the foregoing discussions that there have been a considerable amount of work on the performance evaluation of optical receivers employing avalanche photodetection. However, it is noted that most of these works are based on the assumption that the receiver works with perfect synchronization. In fact, there is very little work on the problem of BEP evaluation in optical receivers in the presence of timing uncertainty. An important early work in this direction is due to Gagliardi[54] who has evaluated the average BEP in a shot noise limited optical receiver in the presence of timing error. In particular the effects of imperfect timing in optical receivers have been investigated both for PPM and ON-OFF keying systems. For both the cases, conditional BEP has been evaluated for fixed timing errors which have been subsequently used to compute the average BEP for a specific synchronization method. The computed results indicate that, for PPM system, the average BEP exhibits a usual falloff with increasing signal energy followed by an asymptotic flattening to a minimum value at large signal energy. With ON-OFF keying, average BEP shows a similar falloff as in the case of PPM system, but with further increase in signal energy, it begins increasing after achieving a minimum value. The latter fact tends to favour PPM operation over ON-OFF keying when the receiver is operating in presence of timing uncertainty. It has been pointed out that the 'bottoming' of average BEP in both the systems is extremely important since it represents a residual nonreducible error probability that depends only on the sync system, and can not be overcome by increasing the bit energy in the received signal. Finally, the results are compared with those of conventional microwave communication system which reveals that, to obtain the same value of the residual BEP, the optical system requires more sync power.

Another relevant study in this direction is due to Dogliotti et. al.[40] (already discussed once in a different context) who have computed the average BEP in a regenerative repeater chain with due consideration of the alignment jitter. The conditional BEP for a fixed alignment error has been evaluated using a previous work[53] which has been subsequently averaged over the statistics of alignment error using Gauss quadrature rule.

From the brief review presented above it becomes evident that the subject of bit synchronization in optical communication systems and the related problems are currently under vigorous investigation. Although the subject has received great attention in the last few years, still many important aspects need further studies. In particular, the influence of the photodetector noise process on the performance of bit synchronizers employing various nonlinear schemes is yet to be investigated in details. Also the problems on the effects of timing jitter on the performance of optical receivers are yet to receive adequate attention.

The present thesis embodies the results of theoretical, simulation and experimental studies on several aspects of self bit synchronization in fibre optic digital receivers. The major topics that are specifically dealt with are

1. Theoretical studies on a bit synchronizer using

a digital timing recovery scheme in optical receivers with avalanche photodetection.

2. Studies of various conventional nonlinear timing extraction schemes in APD-receivers through digital computer simulation.

3. Theoretical studies on the performance of APD-receivers in the presence of bit timing uncertainty.

4. Implementation of a digital fibre optic link with self bit synchronization and experimental evaluation of the link and the bit synchronizer.

Chapter 2 presents a detailed theoretical analysis of a digital timing recovery scheme in an optical receiver employing avalanche photodetection[55,56]. The scheme is basically nonlinear and employs a comparator followed by a circuit consisiting of a delay element and an Exclusive-OR gate to generate discrete spectral lines at the bit rate frequency and at its harmonics. The spectral line component at the bit rate frequency is extracted using a PLL as a narrow bandpass filter. The performance of the bit synchronizer is evaluated in terms of the rms timing jitter in the recovered clock and the tone to interfering noise ratio ($[SNR]_{BW}$) in the PLL. The determination of the rms timing jitter and $[SNR]_{BW}$ are effected through the spectral analysis of the PLL input signal with due considerations of the signal dependent shot noise and the excess noise in APD, the receiver thermal noise, and the smearing of received optical pulses due to the channel dispersion. Relative effects of the randomness in the received bit pattern and the bit transition jitter in the comparator output signal caused by the above three noise components and signal smearing are separately evaluated. The effects of the various system parameters on the synchronizer performance are discussed.

Chapter 3 presents the studies on linear and five different varieties of nonlinear timing extraction schemes in APD-receiver using digital computer simulation. An algorithm is developed to realize sample functions of the APD output process in the form of discrete time series. All the functional blocks used in the timing recovery schemes are implemented in the time domain. The rms timing jitter in the recovered jittery sinusoid is estimated by using a jitter estimation algorithm based on Bessel's interpolation method. The performance of the various timing recovery schemes are compared and the effects of relevant system parameters are evaluated.

The performance of APD-receivers in presence of timing errors is studied in Chapter 4[57,58,59]. Assuming perfect synchronization, the optimum threshold in the receiver decision circuit is evaluated from the likelihood criterion which is subsequently used to calculate the conditional BEP for a fixed timing error. This conditional BEP is averaged over the statistics of the random timing error of the synchronization subsystem to obtain the average BEP. The effects of system parameters on the conditional and the average BEP are discussed and an estimate of the receiver power penalty due to timing uncertainty is obtained.

The hardware implementation of a digital fibre optic link and the results of some experimental measurements on the same are presented in Chapter 5. The link employs the LED-APD combination with NRZ signalling format and a 3B-4B line coding scheme for optical transmission. The bit synchronizer is implemented using the timing extraction scheme studied in Chapter 2. The receiver performance is evaluated in terms of the measured BEP while the bit synchronizer is evaluated by measuring the rms timing jitter in the recovered clock. A direct method is developed and used for the measurement of the rms timing jitter in the recovered clock.

Finally, in Chapter 6 we present the conclusion of the studies made as well as the scope for future study.