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ADAPTIVE NOISE CANCELLATION OF AN ANALOG FIBER OPTIC LINK

By

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A project presented to
Ryerson University in partial fulfillment of the requirement for the degree of Master of Engineering in the program of Electrical and Computer Engineering.

Toronto, Ontario, Canada, 2004

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ADAPTIVE NOISE CANCELLATION OF AN ANALOG FIBER OPTIC LINK

Abstract

There are three dominant noise mechanisms in an analog optical fiber link. These are shot noise that is proportional to the mean optical power, relative intensity noise (RIN) that is proportional to the square of the instantaneous optical power and thermal noise that is a function of absolute temperature and independent of the optical power. This report describes an adaptive noise cancellation of these dominant noise processes that persist an analog optical fiber link. The performance of an analog optical fiber link is analyzed by taking the effects of these noise processes. Analytical and simulation results show that some improvement in signal to noise ratio (SNR) and this filter is effective to remove noise adaptively from the optical fiber link.

Keywords: Relative intensity noise (RIN), Adaptive filter, Recursive least square (RLS), Thermal noise, Shot noise, Poisson distribution, Additive white Gaussian noise (AWGN).

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Acknowledgments

The completion of this project report would not have been possible without the valuable advice, continual guidance and technical expertise of my supervisor, Prof. Xavier. N. Fernando.

I am thankful to my fellow graduate students in the wireless Networks and communication Research (WINCORE) group for their support, fruitful discussion, and for creating a pleasant work atmosphere.

My special thanks goes to my parents and my wife for their love, understanding, support and encouragement throughout my studies.

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Chapter 1

Noise Reduction in Analog Fiber Optic Link

In this chapter a brief description is given about the optical fiber link and its noise components. The necessity of adaptive filtering process is explained by comparing with the previous work done to remove noise from the fiber optic link. Later a proposed approach is described to cancel the noise from analog optical link.

1.1 Introduction

Fiber optic link is not only used for the transmission of digital signals but also is used for many potential applications of analog links. Analog optical links are important for transmission of signals over long distances due to the low loss of optical fiber. These range from individual voice channels (4KHz) to microwave links operating in Giga Hertz region. For an analog recevier the performance fidelity is measured in terms of a carrier–to–noise (CNR) ratio (which is defined by the root mean square (rms) carrier power to rms noise power at the input of the RF receiver following the photo detection process). A good SNR ratio is the demand of many applications. The various noise processes for an optical analog fiber link are phase noise, shot noise, relative intensity noise (RIN), and thermal noise. Noise in optical fiber link can be eliminated by (i) filters that are designed based on prior information and kept fixed in receiver (The receiver filter used for after detection to suppress the out of band noise is a typical example) or (ii) it may be

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adaptive, and designed each time a connection is established (as in equalization for polarization mode dispersion). Latter one is called adaptive filter regardless of the computation mechanism used for determining the filter coefficients. Lot of efforts has been given in the past to eliminate the above mentioned noise from the fiber optic link. Some of the previous work done to eliminate the noise from an analog optical fiber link is descried below.

1.2 Related Previous Work in this Area

R. S. Bondurant et al. in their paper describe a technique to cancel the frequency noise in semiconductor laser by nonlinear heterodyne detection [5]. In this technique two signals with same random phase noise but different frequencies or polarization are generated at the transmitter. If they propagate through the same channel and undergo the same random changes, for example phase and polarization, then the phase noise is canceled by performing a nonlinear operation on the two signals at the receiver .

Ackerman et al. in their work described how laser intensity noise can be reduced with a conventional laser noise suppression method of differential detection using two outputs of an external modulator with equal optical path delays [6],[7]. The two outputs from the Mach– Zehnder interferometer are out of phase. So subtracting them with a differential detector, the signal component remain unchanged while canceling the common mode laser intensity noise. The differential detection method can suppress the relative intensity noise over the modulation bandwidth as long as the path length from each output is carefully matched to a small fraction of the electrical wavelength. This critical length matching between fibers can be difficult when installing a link over a long distance.

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To avoid the length–matching problem of optical fiber Roger Helkey proposed and demonstrated a new bandpass differential method to cancel the laser relative intensity noise [8]. In this method two complementary output signals of the modulator are subtracted by delaying one output half of the modulation period and then optically summing the signals coherently in a polarization coupler. This incoherent summing uses polarization–maintaining fiber from the modulator output to the polarization coupler. This method uses only one long single mode fiber from the output of the polarization coupler to the detector, so no length matching is required after the polarization coupler.

Kazuro Kikuchi and Motoki Kakui in their work described a method to reduce the shot noise using the quantum correlation in light emitting diodes (LED's). The photon stream from a light emitting diode has the optical shot noise and as well as electrical shot noise. Using two LED's with electrical mutual coupling they show that these two kinds of shot noise have correlation with each other and using this quantum correlation between these two shot noise (electrical and optical) 0.45 dB noise reductions can be achieved [11].

K. J Williams and R. D Esman in their paper described a balanced photorecevier which is utilized to reject both laser intensity noise and noise added by erbium–doped fiber amplifier [12]. They demonstrated that a greater than 16 dB noise improvement can be achieved using this method.

Gunnar Jacobsen in his paper described a rigorous and accurate model for multichannel direct detection system where optical preamplificaion is used [13]. The model accounts

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for the influence of an optical bandlimiting filter as well as of a polarization filter. In this model he showed that how the multichannel analysis can be improved in accuracy and can be modified to determine the impacts of phase noise, spontaneous emission noise and receiver thermal noise.

Hyuck M. Kwon in his paper described an optical orthogonal code division multiple access (OOCDMA) system including the effects of avalanche photodiode noise (APD) and thermal noise as well as interference for the OOCDMA direct detection receiver [14]. In this system a hard–limiter placed at the front of the receiver in the presence of APD and thermal noise and he compared the performance of a system without hard–limiter.

For adaptive noise cancellation lots of work has so far been done in speech signal processing and biomedical engineering. Some of them will be mentioned in the following paragraphs.

Surindar Dhanjal in his paper described how to cancel the noise in speech signal by delayed linear prediction noise cancellation technique [9]. In this technique, the current clean speech signal sample is predicted as a linear combination of the past M noisy speech samples delayed by one pitch period T and then using the weighting coefficients determined by solving a set of linear equations similar to the set of equations solved in the classical linear prediction analysis.

Padma Akkiraju and D. C. Reddy in their paper have described an adaptive noise cancellation technique in processing Myoelectric activity of respiratory muscles. In their work they used the Widrow's adaptive noise canceler to solve the problem of reducing

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the interfering ECG (Electrocardiograph) activity from the recorded EMG (Electromyography), which is used as a diagnostics tool for the treatment of respiratory disease. The adaptive noise canceler implemented in a transversal structure was found to successfully reduce the corrupting cardiac activity [10].

1.3 Proposed Approach to Cancel the Noise from Analog Optical Link

Lots of work so far has been done to reduce the noise from the optical analog fiber link many different ways. But not much work has been done to adaptive cancellation of noise from the optical signal. From the previous references and analysis we can see that all of the authors in their approaches try to compensate the noise by using opto–electronic components. In their works they demonstrate how to compensate the noise individually such as some try to compensate laser relative intensity noise or shot noise or thermal noise components in receiver, transmitter, amplifier etc. Most of them try to design components with low noise (shot, thermal or relative intensity) figure.

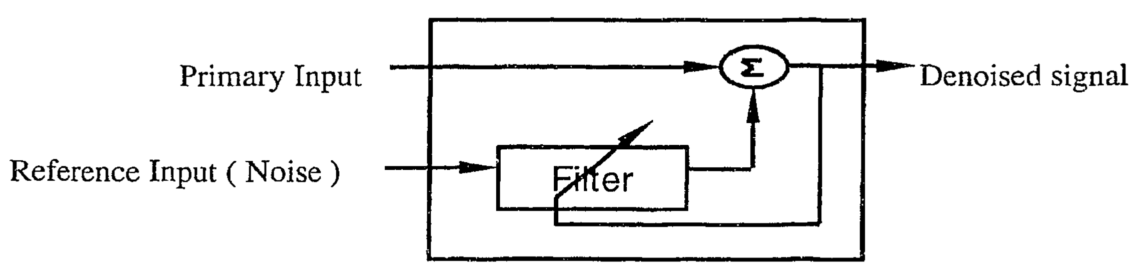

Fig. 1. Basic elements of an adaptive filter

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In my present work an adaptive noise cancellation technique is used to cancel the three–noise (shot, thermal and relative intensity) components. To realize the adaptive noise cancellation, we use two inputs and an adaptive filter. The basic elements of an adaptive filter is shown in Fig. 1. One input is the signal corrupted by noise (primary input). The other input contains noise (AWGN) related in some way to that in the main input but does not contain anything related to the signal (noise reference input). All the noise (thermal, shot, relative intensity noise) considered here are equivalent white Gaussian noise in their probability distribution. The filter co–efficients were adjusted using the Recursive least squares (RLS) algorithms [3] to approach the set of weights for which the output has minimum noise in the least square sense.

1.4 Thesis Organization

In our present work, we have discussed the method of adaptive noise cancellation technique for fiber optic link. This report is arranged in the following order: in Chapter 1, an introduction is given with previous work done in this area, in Chapter 2, the optical fiber link with its noise components is described, in Chapter 3, the algorithms used for noise cancellation and its implementation is shown and in Chapter 4 conclusion is given with discussion of results.

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Chapter 2

Noise in Optical Fiber Link

Any undesired interference or disturbance in a signal is known as noise. There are three dominant noise terms present in the analog optical fiber link. In this chapter a brief mathematical and analytical description is given to determine the variance of these noise components. Further the probability distribution of the noise is discussed and how we can consider these probability distributions for our simulation also described.

2.1 Analog Optical Link and its Noise Component

The basic element of an analog optical link is shown in Fig. 2. Usually a transmitter contains either a light emitting diode (LED) or a laser diode as an optical source.

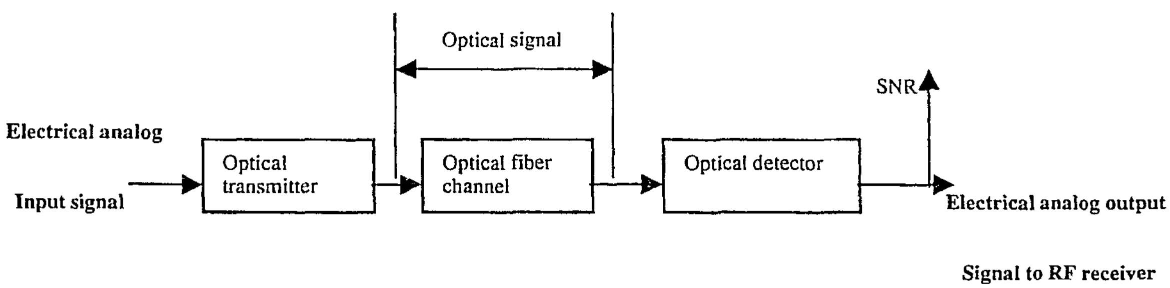

Fig. 2. Basic elements of an analog fiber optic link

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The simplest form for optical fiber links is direct intensity modulation, where the optical output from the source is modulated simply by varying the current around the bias point (at the source site it is approximately at the midpoint of the linear output region) in proportion of the message signal. In this way information signal is transmitted directly in the baseband. In the photodetector site a photodiode is used to detect the very weak optical signals. Detection of the weakest possible optical signals requires that the photodetector and its following amplification circuitry be optimized so that a given signal to noise ratio is maintained. The noise sources in the receiver arise from the photodetector noise resulting from the statistical nature of the photon to electron conversion process and the thermal noise associated with the amplifier circuitry.

In an analog link, the time–varying electrical signal $s(t)$ is used to amplitude–modulate directly an optical source about some bias point defined by the bias current I_B. The transmitted optical power $P(t)$ is thus of the form [1]

$$P(t)=P_t[1+ms(t)] \tag{2.1}$$

where P_t is the average transmitted optical power, $s(t)$ is the analog modulation signal, and m is the modulation index.

At the receiver end, the photo current generated by the analog optical signal is

$$\begin{aligned} i_s(t) &= \Re M P_r[1+ms(t)] \\ &= I_p M[1+ms(t)] \end{aligned} \tag{2.2}$$

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where $\Re$ is the detector responsivity, P_r is the average received optical power, $I_p = \Re P_r$ is the primary photocurrent, and M is the photodetector gain. For PIN photodiode M is considered as unity. If $s(t)$ is a sinusoidally modulated signal, then the mean square signal current at the photodetector output is

$$\left\langle i_s^2 \right\rangle = \frac{1}{T}\int_0^T \Re^2 P^2(t)dt \tag{2.3}$$

If $P(t)$ is a sinusoidally modulated signal i.e., $P(t) = P_r(1 + m\cos\omega t)$

Then integration of the previous equation (2.3) becomes [1]

$$\left\langle i_s^2 \right\rangle = (\Re P_r)^2 + \frac{1}{2}(m\Re P_r)^2 \tag{2.4}$$

This is the mean square signal current at the photodetector. It consist of two components. Among them, first one is dc term and usually this term can be removed. If we remove the dc term and consider the photodetector gain M then the mean square signal current equation becomes [1]

$$\left\langle i_s^2 \right\rangle = ½(\Re MmP_r)^2 = \frac{1}{2}(MmI_p)^2 \tag{2.5}$$

This mean square signal current is important to calculate the signal to noise ratio, which is used for later calculation and simulation.

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2.2 Noise in Optical Link

In an optical fiber receiver usually *PIN* (positive intrinsic negative) or *APD* (avalanche photo diode) is used as a detector. Several noise mechanisms exist in a directly modulated analog fiber link such as polarization mode noise, mode–hopping noise, shot noise, relative intensity noise and thermal noise. Among these noise processes, we will analyze three dominant noise mechanisms in an analog optical fiber link. These are shot noise that is proportional to the mean optical power, relative intensity noise (*RIN*) that is proportional to the square of the instantaneous optical power and thermal noise that is a function of absolute temperature and independent of the optical power. In this section, we derive the expressions for the variances of optical link noise components. These expressions are needed to evaluate the signal to noise ratio that is done in the next section.

2.3 Shot Noise

The fundamental uncertainty when a photon emission event occurs produces a form of signal dependent noise called quantum noise or shot noise. It is a direct consequence of the independence of photon emission event. The quantum or shot noise arises from the statistical nature of the production and collection of photoelectrons when an optical signal is incident or r hotodetector. The quantum noise current has a mean square value in a bandwidth B that is proportional to the average value of the photocurrent I_p. In this

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section an expression is derived for the shot noise. If we consider a double side band (DSB) intensity modulation at the laser diode for RF–optical conversion and assume a linear electrical optical conversion then the instantaneous optical intensity output power $P(t)$ for the response of an electrical signal $s(t)$ is given by

$$P(t) = P_0[1 + ms(t)] \tag{2.6}$$

Here m is the modulation index, P_0 is the mean optical power and $s(t)$ is the electrical signal.

Photo detector at the receiver produces a detector current $I_P(t)$ which is proportional to the instantaneous optical power $P(t)$ in response of the received optical power. Since light is composed of photons which are discrete packets of energy. In shot noise process the arrival time of light occurs as discrete units or photons. Therefore the expression for $I_P(t)$ can be written as

$$I_P(t) = \sum_{i=-\infty}^{\infty} h_D(t - t_i) \tag{2.7}$$

where, $h_D(t)$ is the impulse response of the photo detector. To consider the effect of filtering after detection, let the detected current $I_P(t)$ be filtered by a filter with transfer function $H(f)$ to obtain an output current I(t). Then the mean value of I(t) is obtain simply the convolution of the received signal with the impulse response of the receiver filter h(t).

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$$E[I(t)] = \int_{-\infty}^{\infty} I_P(\tau) h(t-\tau) d\tau \tag{2.8}$$

Now, if we consider the detector responsivity $\Re$, which is defined as the photocurrent $I_p(t)$ generated per unit optical power *P(t)*. It is written as [1]

$$\Re = \frac{I_P(t)}{P(t)} = \frac{\eta q}{h\nu} \tag{2.9}$$

Here, η is the quantum efficiency of the photo–detector, h is Plank's constant ($6.625X10^{-34}$ Joules/sec) , q is the electron charge and ν is the frequency of the optical signal. Responsivity is constant for a given wavelength so it does not change with *P(t)*. Hence, if we include the responsivity the mean value of detector current is given by

$$E[I(t)] = \Re \int_{-\infty}^{\infty} P(\tau) h(t-\tau) d\tau \tag{2.10}$$

The variance of I(t) can be found using the moment generating function of the photodiode. It is important to mention that there appears q in the variance of I(t).

$$Var[I(t)] = \Re q \int_{-\infty}^{\infty} P(\tau) h^2 (t-\tau) d\tau \tag{2.11}$$

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From the above expressions of mean and variance of I(t) we see that both are time varying quantities and that are determined by linear filtering operation on $I_P(t)$. Usually the bandwidth B of the receiver filter is greater than the bandwidth of electrical signal $s(t)$. So, the received signal passes through the filter without any distortion. The filter however blocks the no frequency direct current term $\Re P_0$.

From the expression of the variance of I(t) we see that the signal P(t) filtered through a hypothetical filter that has an impulse response $h_2(t) = h^2(t)$. The frequency response of H(f) and $H_2(f)$ are obtained by performing the Fourier Transform on h(t) and $h_2(t)$. From the transfer function of $H_2(f)$, it is obvious that only the DC term $\Re P_0$ passes through this filter and both side bands are attenuated. Therefore the shot noise after filter for *PIN* is given by:

$$\langle i^2{}_Q \rangle = Var[I(t)] = 2qI_pB \tag{2.12}$$

For *APD* (avalanche photodiode) the expression for shot noise can be written as

$$\langle i_Q^2 \rangle = 2qI_PBM^2F(M) \tag{2.13}$$

where F (M) is a noise figure associated with the random nature of the avalanche process and M is the avalanche noise. It has been found that to a reasonable approximation

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$F(M) \approx M^x$ (with $0 \leq x \leq 1.0$) depends on the material. Both $F\ (M)$ and M are considered unity for *PIN* photodiode.

It has been demonstrated that statistics of distribution of shot noise follow a Poisson probability distribution [2]. The Poisson distribution has the property that the variance of fluctuation equals to the mean. In optical communication all sources obey the Poisson distribution. Shot noise is signal dependent because noise variance equals the average signal. The larger the mean signal, the larger the variance. The Gaussian approximation is used here to replace the discrete Poisson probability function. The continuous Gaussian pdf with a mean value m and variance σ^2 is given by

$$p_s(s) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{(s-m)^2}{2\sigma^2}\right] \tag{2.14}$$

To approximate the Poisson distribution, we can set mean of Poisson distribution $m = \sigma^2_m$. In this process of Gaussian approximation, we overestimate the value of Poisson distribution far below the mean and underestimate the value far above the mean. These errors approximately cancel out and Gaussian approximation can be satisfactory to estimate error probabilities. However, when small error rates are to be calculated, the approximation may not be accurate since these error rates use the 'tails ' of the distribution where the Gaussian and Poisson distribution are significantly different.

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2.4 Relative Intensity Noise (RIN)

The laser does not produce light that is stable in intensity. The basic physical mechanism of a laser is amplification by stimulated emission, which is random in nature. This randomness introduces a noise that increases with the optical power. This noise resulting from random intensity fluctuations is called relative intensity noise (*RIN*), which may be defined in terms of the mean–square intensity variations. A fluctuation in the optical output intensity due to the multiple reflections in fiber optic link leads to the optical intensity noise. The noise produce due to *RIN* is proportional to the square of the optical power. It can be written mathematically by the following equation

$$RIN = \langle \Delta P_0^2 \rangle / \langle P_0 \rangle^2 \tag{2.15}$$

Where $\langle \Delta P_0^2 \rangle$ is the mean square amplitude of the noise fluctuations per unit bandwidth and P_0 is the square of the optical power. For a given laser *RIN* is constant. The expression for the modulated transmitted optical signal considering relative intensity noise (RIN) is given by [21]

$$P\,(t) = [1 + ms(t)][P_0 + \Delta P(t)] \tag{2.16}$$

where P_0 is the average transmitted optical power, *s(t)* is the analog modulation signal, *m* is modulation index and is ΔP*(t)* the instantaneous fluctuation terms due to relative intensity noise.

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To obtain an expression of the detector current with *RIN*, the filter output current is convoluted with filter impulse response h(t) [21].

$$I_p(t) = \Re \int_{-\infty}^{\infty} P_{RIN}(\tau) h(t-\tau) d\tau \tag{2.17}$$

In the presence of relative intensity noise the primary shot noise process $I_p(t)$ is a doubly stochastic Poisson process. The mean and variance of this doubly stochastic output process are determined by the generalized Campbell theorem.

The average of $I_p(t)$ is given by the following equation considering ΔP(t) is a zero mean process.

$$E[I_p(t)] = E\left\{\Re \int_{-\infty}^{\infty} [1 + ms(\tau)][P_0 + \Delta P(\tau)] h(t-\tau) d\tau \right\} = I_D ms(t) \tag{2.18}$$

where I_D is the detected current produced by photo detector and it's intensity is proportional to the instantaneous optical power P(t).

The variance of $I_p(t)$ is given by

$$Var[I_p(t)] = E[I_P^2(t)] - \{E[I_p(t)]\}^2 \tag{2.19}$$

From equation (2.10) and (2.11), this simplifies to,

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$$Var[I_P(t)] = E\left\{\Re q \int_{-\infty}^{\infty} P(\tau) h^2(t-\tau) d\tau\right\} + Var\left\{\Re \int_{-\infty}^{\infty} P(\tau) h(t-\tau) d\tau\right\} \tag{2.20}$$

The first term in equation (2.20) is the variance of the shot noise due to the constant optical input power. The second term is the variance of the relative intensity noise after the receiver filter. Since shot noise already considered in article 2.3 so the relative intensity noise can be re–written as

$$\langle I_P^2 \rangle = Var\left\{\Re \int_{-\infty}^{\infty} P(\tau) h(t-\tau) d\tau\right\} \tag{2.21}$$

since variance is the expectation of the second order term and $P(t) = [1 + ms(t)][P_0 + \Delta P(t)]$, this simplifies

$$Var[I_p(t)] = E\left[\left\{\Re \int_{-\infty}^{\infty} [1 + ms(\tau)]\Delta P(\tau) h(t-\tau) d\tau\right\}^2\right] \tag{2.22}$$

Now if we define a new filter $h_3(t) = [1 + ms(t)][P_0 + \Delta P(t)]$ the previous equation simplifies to

$$\langle I_P^2 \rangle = \left[\left\{\Re \int_{-\infty}^{\infty} \Delta P(\tau) h_3(t-\tau) d\tau\right\}^2\right] \tag{2.23}$$

When this expression is converted to frequency domain it becomes

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$$\langle I_P^2 \rangle = \Re^2 \int_{-\infty}^{\infty} N_{RIN}(f) |H_3(f)|^2 df \tag{2.24}$$

Here, $N_{RIN}(f)$ is the double–sided power spectral density of the relative intensity noise. At frequency of interest for analog optical transmission this has a constant spectrum.

From the conservation of power, the power confined in the spectrum $|H_3(f)|^2$ is same as the average square value of the term $[1 + ms(t)]$ for an ideal filter. This is independent of the spectral shape of *s*(t). Therefore noise power due to *RIN* is given by

$$\langle I_P^2 \rangle = 2\Re^2 N_{RIN} B \left[1 + m^2 \langle s^2(t) \rangle \right] \tag{2.25}$$

This is the most accurate expression for *RIN* than the widely used expression for the variance of RIN. Many authors have omitted the second term $m^2 \langle s^2(t) \rangle$. This is due to the fact that most of the time m is in the range of 0.1 and $s(t) \ll 1$ so that the term is insignificant. But for higher value of m and $s(t)$ this term is not negligible. Considering the small value of m and $s(t) \ll 1$ the equation of *RIN* can be written as

$$\langle i^2{}_{RIN} \rangle = \sigma^2{}_{RIN} = RIN(\Re \overline{P})^2 B \tag{2.26}$$

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Here the *RIN,* which is measured in dB/Hz is defined by the noise to signal power ratio

$$RIN = \frac{(\Delta P_L)^2}{\overline{P}_L^{\,2}} \qquad (2.27)$$

where $(\Delta P_L)^2$ is the mean square intensity fluctuation of the laser output $\overline{P}_L$ is the average laser light intensity and B is the bandwidth. Typically, a *RIN* value is specified for a given laser diode in dBm/Hz. This *RIN* value is related to the double–sided power spectral density N_{RIN} by the following equation

$$RIN(dB / Hz = \langle 2N_{RIN} \rangle / P_0^2 \qquad (2.28)$$

In linear scale the *RIN* can be written as

$$\sigma_{RIN}^2 = I_p^2 .RIN_{lin} B \qquad (2.29)$$

where $RIN_{lin} = 10^{\frac{RIN(dB/Hz)}{10}}$ (2.30)

and $I_p = \Re \overline{P}$ (2.31)

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Here $\Re$ is the responsivity of photodiode, and it specifies the photocurrent generated per unit optical power, RIN is the relative intensity noise in linear scale, I_P is photocurrent and $\bar{P}$ is optical power.

The stochastic rate equations for laser simplified when Langevin forces are assumed to be Gaussian random process with zero mean and under Markovian approximation [4]. The definition of *RIN* is derived from this approximation so we can say that distribution of *RIN* is also a Gaussian and for our simulation we also consider the probability of distribution of relative intensity noise is white Gaussian.

When light travel through a fiber link some optical power gets reflected due to refractive index discontinuities in splices, coupler and filters etc. This reflected signal degrades the performance of receiver and transmitter. For high–speed analog link, we need to consider to minimize optical reflections back in to the laser otherwise it can cause intensity noise, phase noise and change its wavelength and linewidth. And hence reduce the signal to noise ratio. It has been demonstrated that because of back –reflected signals in an optical fiber link the *RIN* increases by 10–20 dB [1].

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2.5 Thermal Noise

Thermal noise in an electrical circuit arises due to the random fluctuation of electron and it is a function of absolute temperature. All the resistive elements of an electrical circuit is the main source of the thermal noise. The thermal noise is independent to the optical signal level but increase with the temperature (ie proportional to the absolute temperature). In an analog optical fiber link photodiode and amplifier are the main source of thermal noise. The equivalent current noise source has a double–sided power spectral density. To simplify the analysis of the receiver circuitry, if we assume that the amplifier input impedance is much greater than the load resistance (R_L), so that its thermal noise is much smaller than that of load resistance R_L. The photo detector load resistor contributes a mean–square thermal noise current, which can be express by the following equation

$$\langle i^2_T \rangle = \sigma^2_T = \frac{4k_B T}{R_L} B \tag{2.32}$$

Where k_B is Boltazmann's constant (1.38054 X 10^{-23} Ws/K), T is the absolute temperature in Kelvin, R_L is the receiver equivalent load resistance and B is the bandwidth of the receiver. Using a load resistor, which is large but still consistent with the receiver bandwidth requirements, can reduce this noise.

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The thermal noise spectral density is a constant independent of frequency and thus contains equal amount of power per unit bandwidth regardless of frequency. Therefore the noise spectrum is called white. Many methods of communication analysis are based on noise sources having a white power spectral density and a Gaussian probability density function. This type of noise model is called additive white Gaussian noise or AWGN. For our analysis we will consider thermal noise as an additive white Gaussian noise.

From mathematics we know that the sum of n statistically independent Gaussian random variables is also a Gaussian random variable. To demonstrate this point, let

$Y = \sum_{i=1}^{n} X_i$ where the X_i, i=1,2,..........n, are statistically independent Gaussian random variables with means m_i variances σ_i^2. For n statistically independent random variable the characteristic function of Y is given by the following equation

$$\psi_y(jv) = \prod_{i=1}^{n} \psi_{x_i}(jv)$$

$$= \prod_{i=1}^{n} e^{jvm_i - v^2\sigma_i^2/2}$$

$$= e^{jvm_y - v^2\sigma_y/2} \tag{2.33}$$

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Where $m_y = \sum_{i=1}^{n} m_i$, and $\sigma_y^2 = \sum_{i}^{n} \sigma_i^2$

Therefore, Y is Gaussian distributed with mean m_y and variance σ_y^2

For this moment, we assume that the Gaussian approximation is valid so that, both thermal and shot noise can be represented by continuous Gaussian distributions. *RIN* also considered zero mean Gaussian random process. The noise fluctuations caused by thermal effects, relative intensity noise and the shot noise fluctuations are uncorrelated because they are generated from independent physical process. Therefore, the total noise is the sum of three uncorrelated and thus independent Gaussian random variables, one for the shot noise with mean (m) equal to the variance σ_m^2, the other for thermal noise that is zero mean with variance σ_x^2 and for *RIN* zero mean with variance σ_r^2. The probability density function of the sum of these three random variables is also Gaussian with a mean m and a variance $\sigma^2 = \sigma_x^2 + \sigma_m^2 + \sigma_r^2$

2.6 Signal to Noise Ratio at the Receiver

The performance of photodetector in a light wave communication system is typically expressed using the signal –to–noise ratio (*SNR*) or carrier–to–noise ratio (*CNR*). Signal to noise ratio (*SNR*) in an analog receiver is defined as the ratio of the mean square signal current to the mean square noise current. On the other hand, the ratio of the rms power to

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the rms noise power at the input of the radio frequency receiver following the photo detection process is known as carrier to noise ratio (*CNR*). Let us assume a communication system with m modulation index per RF channel with a DC photocurrent of I_p and an effective noise bandwidth B at the receiver. Then the *SNR* can be written as,

$$SNR = \frac{\langle i_P^2 \rangle}{\left[\sigma_{shot}^2 + \sigma_{th}^2 + \sigma_{RIN}^2\right]B} \tag{2.34}$$

where $\langle i_P^2 \rangle = (mI_P)^2 / 2$ is the mean square signal photocurrent. Substituting for the shot noise, thermal noise and *RIN* noise we find the *SNR* at the photodetector is given by [1]

$$SNR = \frac{(mMI_P)^2}{\left[I_P^2 RIN + 2qI_P M^2 F(M) + \frac{4k_B T}{R_L}\right]2B} \tag{2.35}$$

When the optical power level at the receiver is low, the preamplifier circuit noise (thermal noise) dominate the system noise. For this case the *SNR* is given by

$$SNR = \frac{\frac{1}{2}(mI_P M)^2}{(4k_B T / R_L)B} \tag{2.36}$$

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In this case, signal to noise ratio is directly proportional to the square of the received optical power, so in this case for each -1dB variation in received optical power *SNR* will change by -2dB.

For intermediate power levels the quantum–noise (shot noise) term of the photodiode will dominate the system noise. In this case the *SNR* is given by [1]

$$SNR = \frac{\frac{1}{2}(mI_pM)^2}{2qM^2F(M)B} \tag{2.37}$$

so in intermediate power level *SNR* ratio will vary by 1 dB for every dB change in the received optical power.

If the laser has a high *RIN* value so that the reflection noise dominates over other noise terms, then SNR becomes [1]

$$SNR = \frac{\frac{1}{2}(mM)^2}{RIN.B} \tag{2.38}$$

which is a constant. It does not depend on the photo current in the receiver and can be improved by reducing laser *RIN* or increase the modulation index m. From the expression of various noise components namely shot, thermal and RIN noise we see that thermal

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noise has a constant variance and depends only on receiver resistance. This possesses a white spectrum. The variance of relative intensity noise varies with RF signal level because it is proportional to the square of the optical power. Since the instantaneous optical power in the fiber fluctuates at radio frequency, the square of its increase with RF signal level depends on the modulation index *m*. The variance of shot noise is linearly proportional to the mean optical power of fiber. The mean optical power does not change unless the DC bias current is changed. Therefore, we can say that the shot noise does not change with RF power and constant for a given modulation index *m*.

We can additionally points out that

(i) The higher the modulation index *m* yields better *SNR* or *CNR*. This is because more power is contained in the sidebands compared to the unmodulated carrier. But we cannot increase the modulation index as much as we like because nonlinear effects limit the modulation index *m* to a lower value. Usually modulation index *m* lower than 0.3.

2.7Numerical Example of Signal to Noise Ratio

In this section a numerical example is given to show that how the *SNR* varies for different noise with variation of output power and modulation index (m). *SNR* for a typical system which is operating in optical wavelength 1300nm, Bandwidth 100MHz, received optical power $P_i = P_o[1+0.4\sin(\omega t)]$ where P_o the optical signal average power, ω is the message frequency, relative intensity noise for the laser source is

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−155dB/Hz, Pin photodiode produce a 4μA current in response to a 6μW optical illumination, the dark current is negligible, Load impedance is 1KΩ and the system operating at room temperature (300K) is given below (Fig. 3.):

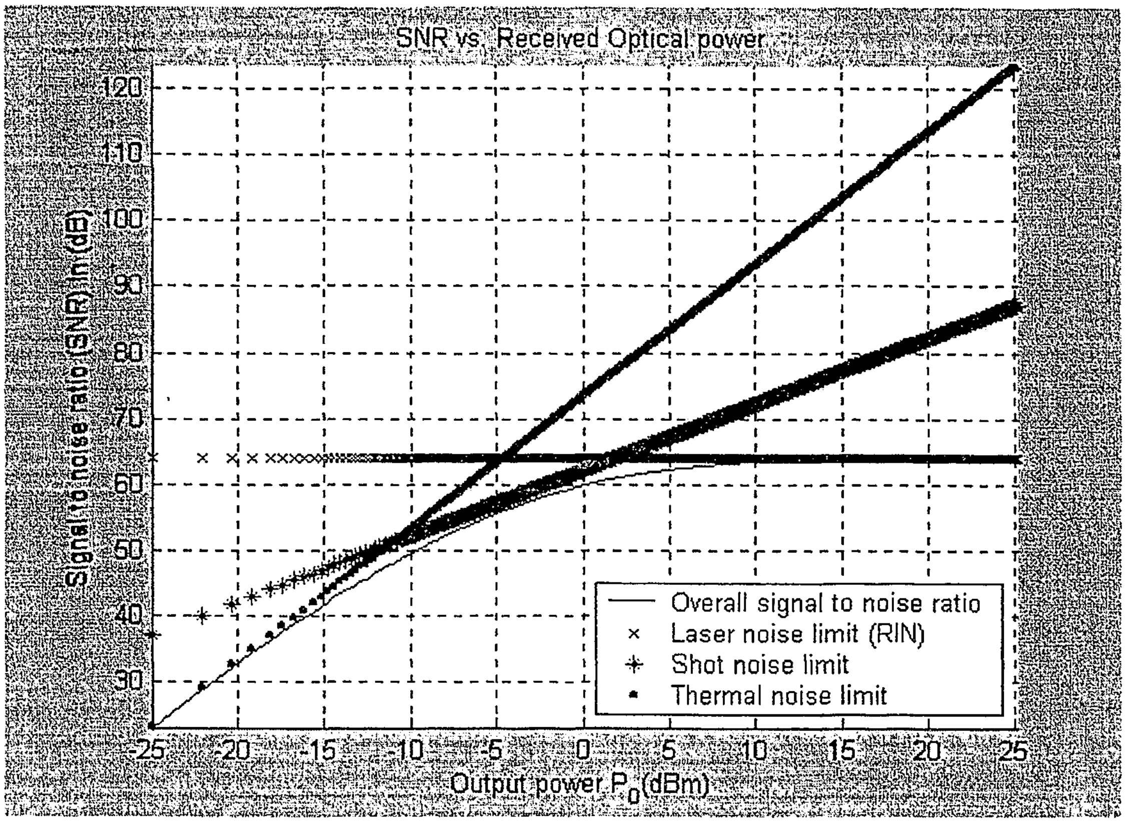

Fig. 3. The variation of SNR in dB with respect to output optical power in dBm

From Fig. 3. we can say that signal to noise (SNR) ratio for relative intensity noise is constant with output optical power whereas signal to noise ratio (SNR) for shot noise and thermal noise increases with increases of output optical power. Overall (considering three noise together) signal to noise ratio increases with output optical power but after sometimes it becomes constant when relative intensity noise dominates over other noise.

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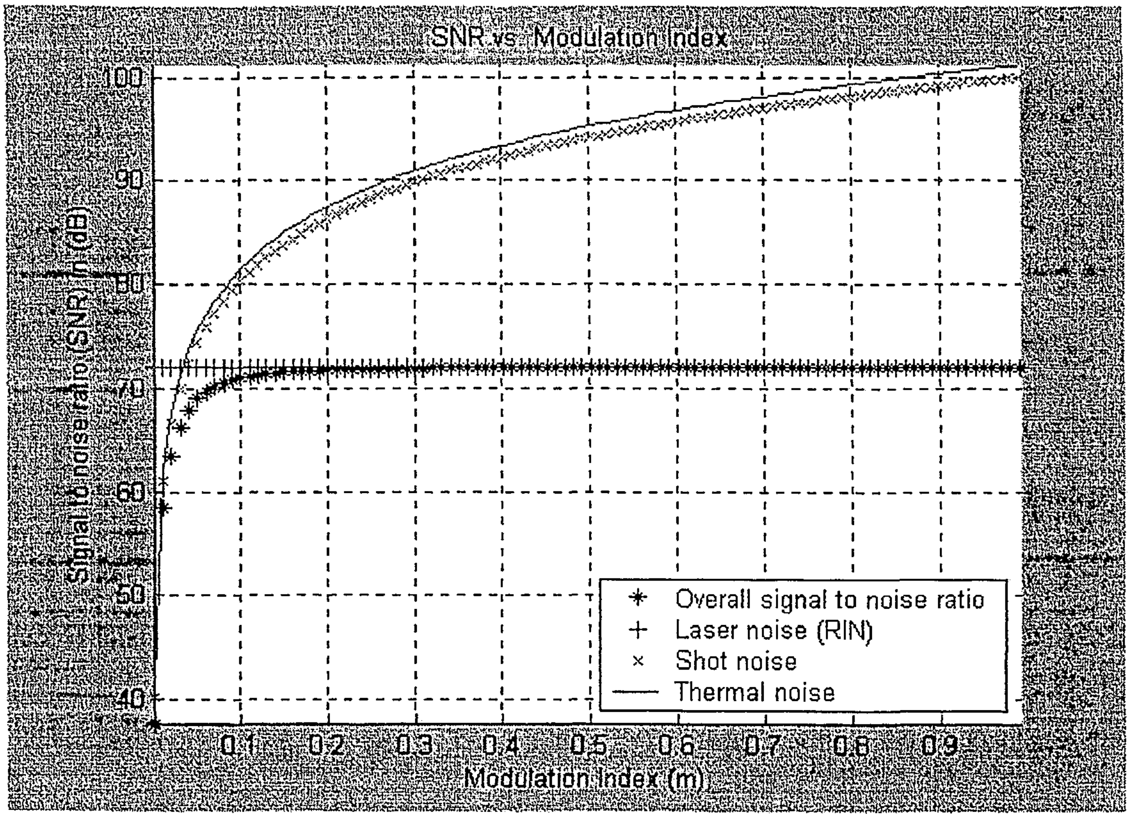

Fig. 4. Variation of SNR (in dB) with modulation index (*m*) for the typical system described above for a constant output power 10mW.

In Fig. 4. variation of SNR with modulation index is shown for the same system described above. From Fig. 4. we can say that signal to noise (SNR) ratio due to thermal and shot noise increases with increase of modulation index but for laser relative intensity noise it is constant with change of modulation index. Overall (considering three noise together) signal to noise ratio (SNR) increases with increase of modulation index and it remain constant after modulation index 0.15. It is due to the domination of relative intensity noise over other noise.

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Chapter 3

Adaptive Noise Cancellation Technique

In this chapter an adaptive noise cancellation technique is described to remove the noises from optical fiber link. A brief description is given about the step–by–step process of the algorithms used for noise cancellation. The simulation parameters and its implementation are described with figure. Later an effective discussion is given about the achieve result.

3.1 Algorithms for Adaptive Noise Cancellation

The basic idea of an adaptive noise cancellation algorithm is to pass the corrupted (signal mixed with noise) signal through a filter that tends to suppress the noise while leaving the signal unchanged. As we mentioned above, this is an adaptive process, which means it does not require a complete priori knowledge of signal or noise characteristics. The step–by–step process of the algorithm is described below:

(a) Choose or generate a signal corrupted by noise

(b) Generate a AWGN noise signal equivalent to three noise components (thermal noise, shot noise and RIN noise)

(c) Send the noise signal through adaptive filter and filter automatically generates a replica of noise

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(d) Filter adjusts itself to reduce the error between filter output and noise

(e) Filter output is subtracted from the corrupted signal and produces denoised signal

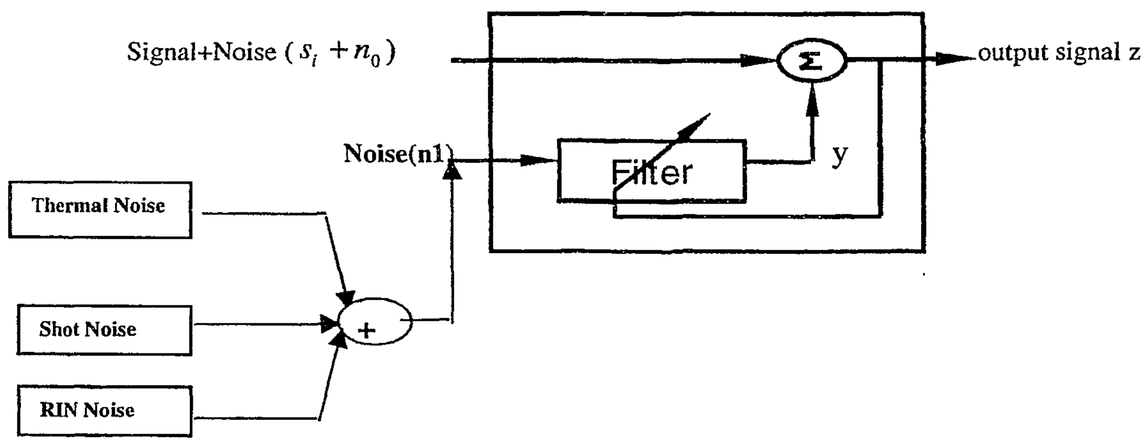

Fig. 5. Adaptive noise cancellation using three noise components

To realize the adaptive noise cancellation, we use two inputs and an adaptive filter Fig. 5. One input is the signal corrupted by noise (Primary Input, which can be expressed as $s_i + n_0$). The other input contains noise related in some way to that in the main input but

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does not contain anything related to the signal (noise reference input content three noise components thermal noise, shot noise and *RIN* noise, all of are assume white Gaussian noise, expressed as n_1) . The noise reference input pass through the adaptive filter and an output y is produced as close a replica as possible of n_0.

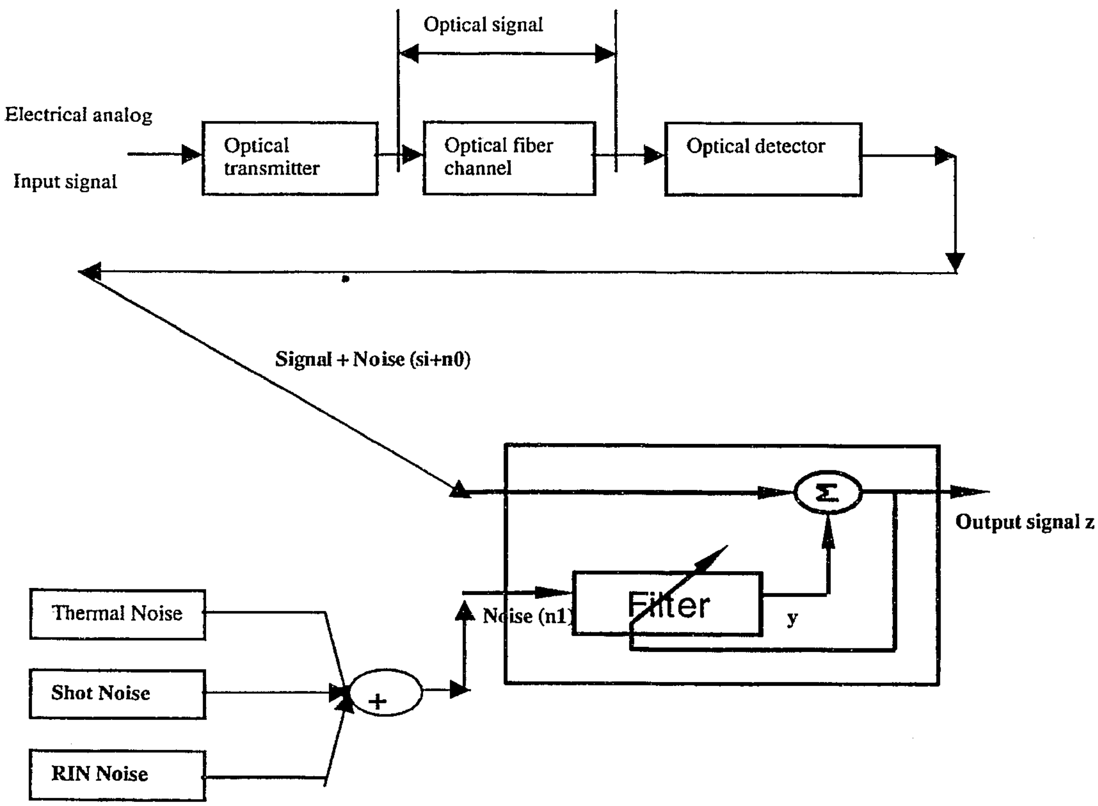

Fig. 6. Basic elements of an analog fiber optic link and adaptive noise cancellation

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The filter readjusts itself continuously to minimize the error between n_0 and y during this process. Then the output y is subtracted from the primary input to produce the system output which is the denoised signal. The basic elements of the an analog fiber optic link to adaptive noise cancellation of the noise is shown in Fig. 6. Assume that s_i, n_0, n_1 and y are statistically stationary and have zero means. Suppose that s_i is uncorrelated with n_0 and n_1, n_1 is correlated with n_0. We can get the following equation of expectations:

$$E\,[z^2] = E\,[s_i^2] + E\,[(n_0 - y)^2] \tag{3.1}$$

When the filter is adjusted so that $E[z^2]$ is minimized, $E\,[(n_0 - y)^2]$ is also minimized. So the system output z can serve as the error signal for the adaptive filter. Several algorithms can be used for the adaptive filter. The Least Mean Squared (LMS) algorithm is the most widely used and the simplest one. But it is not effective for convergence of high–speed signal. The second one is Recursive Least Squares or RLS algorithms. Several investigators derived RLS independently. However, the original reference on the RLS algorithms given by Placket in 1950 [3]. The RLS algorithms use the information contained in all the previous input data to estimate the inverse of the autocorrelation matrix of the input vector. It uses this estimate to properly adjust the tap weights of the filter. The algorithm works in following sequence:

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- Compute output of the signal
- Compute Error
- Compute the Kalman gain vector
- Update inverse of the correlation matrix
- Update the co–efficient

The following are the equations [19] used for calculating various data for the RLS algorithm

Compute Kalman gain vector $k(n) = \dfrac{\lambda^{-1} P(n-1)U(n)}{1+\lambda^{-1}U^{T}(n)P(n-1)U(n)}$ (3.2)

Compute output $y(n) = w^{T}(n-1)U(n)$ (3.3)

Compute error $e(n) = d(n) - y(n)$ (3.4)

Update coefficients $w(n) = w(n-1) + k(n)e(n)$ (3.5)

Update inverse of the correlation matrix $P(n) = \lambda^{-1}P(n-1) - \lambda^{-1}k(n)U^{T}(n)P(n-1)$ (3.6)

in the above equations P corresponds to the inverse of the autocorrelation matrix of the input signal, *k* is called the Kalman gain vector. Lambda is the forgetting factor, which tells the filter to forget the earlier inputs. e is the error signal, *w* is the weight co–efficient

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of the filter, y is the output. Here we used stationary inputs, for this reason lambda is set to 1, which is known as the infinite memory version of the algorithm.

3.2 Simulation Results

Based on the RLS algorithm an original signal is recovered from corrupted signal. Here noise are considered as random Gaussian in nature and artificially generated. The entire noise signal is assumed white Gaussian noise because all the noise can be represented by equivalent AWGN noise. The flow chart for the entire adaptive noise cancellation process is shown in Fig. 7.

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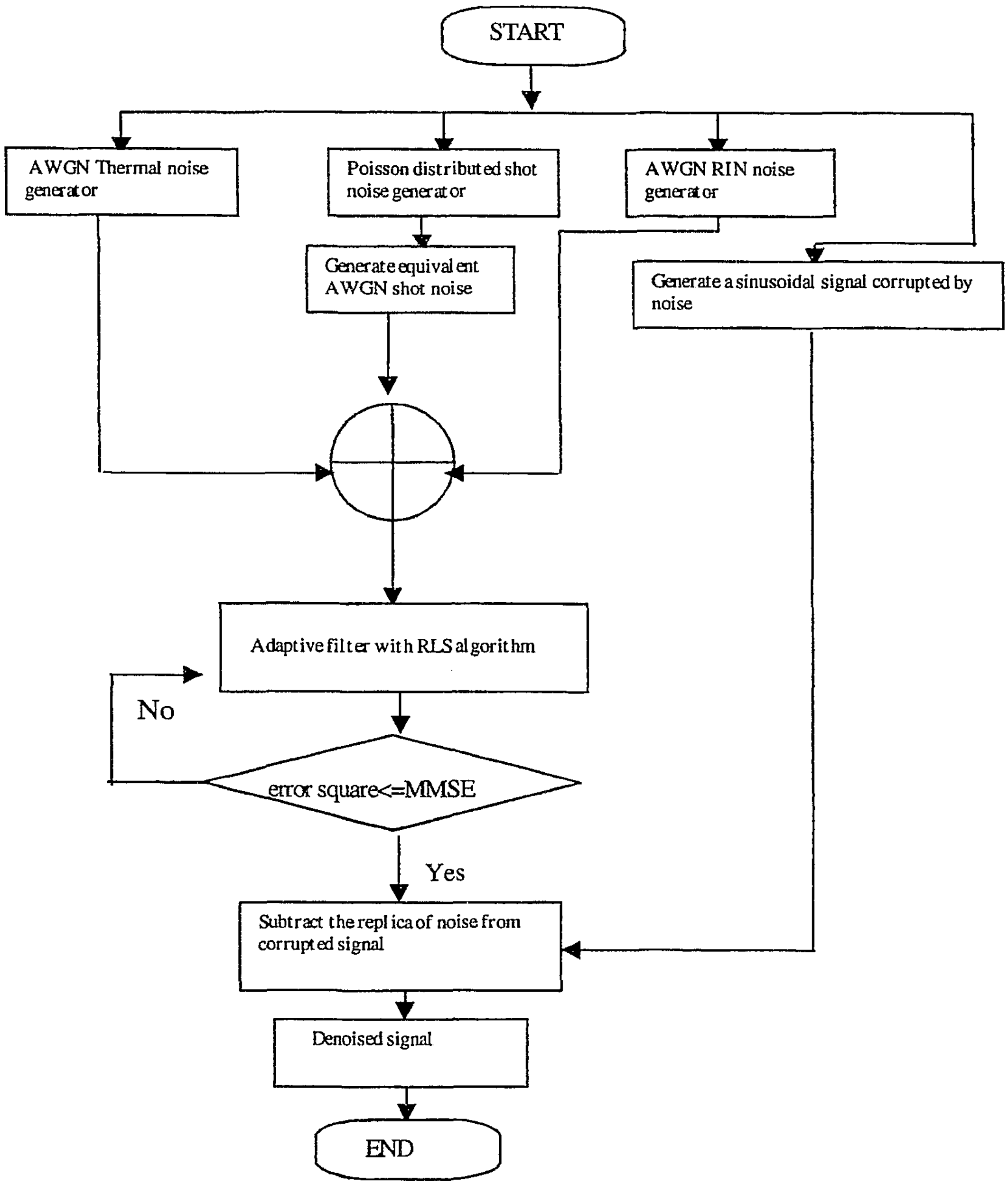

Fig. 7. Flowchart for the adaptive noise cancellation from analog optical link

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For the simulation the parameter chosen is given below:

- Bandwidth of the signal is 10 MHz
- Sampling frequency is chosen as 40 MHz
- Tap weights for filters is 8
- Lambda is chosen 1

For our simulation we consider a typical system which operating at a temperature 300 degree Kelvin, Relative intensity noise is −155 dB/Hz, photocurrent $I_P = 4x10^{-6} A$, optical power $P_0 = 6x10^{-6} watt$, load resistance is 1000 Ohms, Bandwidth (B) for the system is considered 10 MHz. By applying the equation (2.12) the shot noise variance for the system is calculated, from equation (2.29) relative intensity noise variance is calculated and from equation (2.32) thermal noise variance is calculated . By adding these three noise variances we can get the variance for the overall noise signal. In simulation all the three noise variance add together to get the the variance of the over all noise . This overall variance is used to generate a random Gaussian noise signal. Sample computer program for the simulation is shown in appendix.

We can see from Fig. 8. the filter tap weight amplitude variation with number of samples of the signal, where w(0), w(1).......w(7) are the filter tap weights. Vector of the amplitude of the tap weights is given by w=[2.65, −2.1, 0.9, −0.8, 0.4, −0.4, 0.2, 0]. It is evident that 8 tap weights are sufficient for cancellation of noise from the signal.

From the learning curve given in Fig. 12. to Fig. 14. we can say that average error square of the signal become 10^{-4} and for Fig. 16 to Fig. 18 it becomes 10^{-6} after almost few samples.

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Fig. 9. shows the noise with signal and Fig. 10. shows the denoised signal after removal of the noise from signal. From the Fig. 11. we can see that how the filter removed the noises from a low frequency sinusoid signal. Both the corrupted signal and denoised signal shown in this Fig .11.

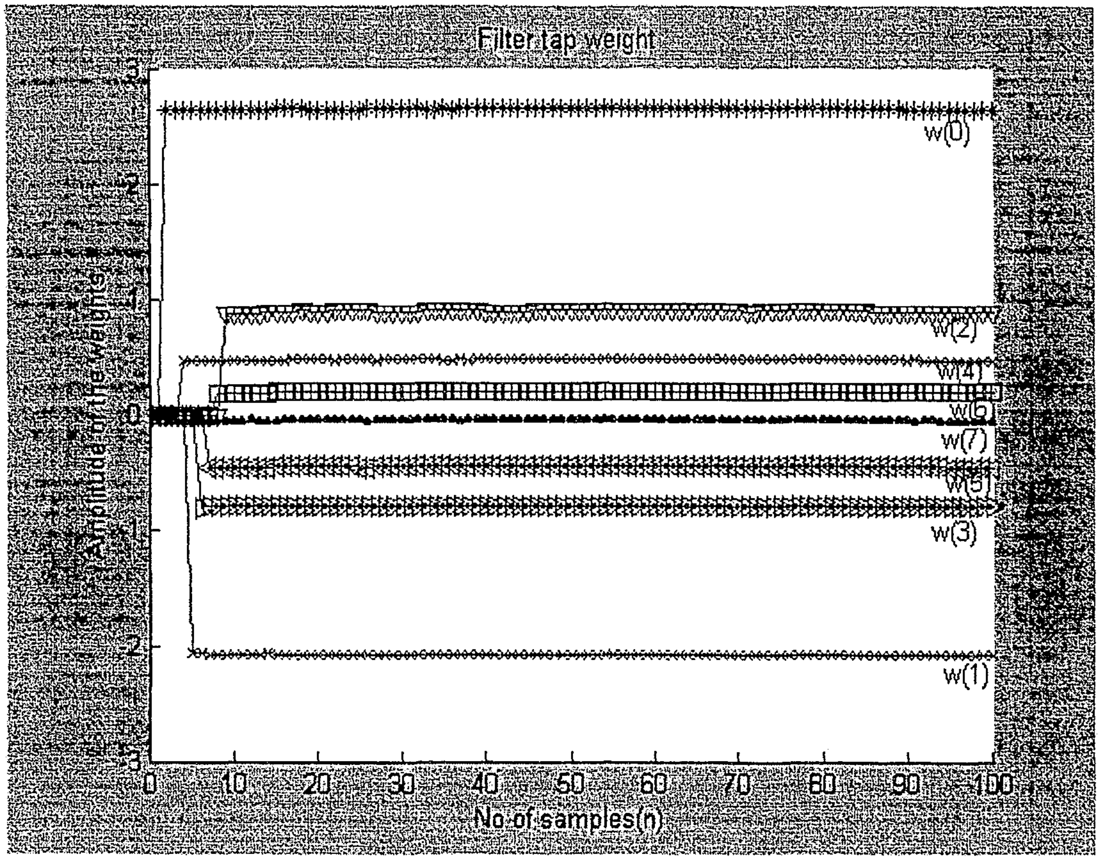

Fig. 8. Filter tap weights

From Fig. 12. to Fig. 21. we can see the learning curve of the filter for different modulation indexes and bandwidth. The learning curve for different bandwidths with a constant modulation shows that the average error square of the signal becomes 10^{-4} after 5 to 20 samples for bandwidth upto 75 MHz and for bandwidth greater than 75

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MHz the average error square of the signal becomes 10^{-4} after few hundreds samples ie there still present some noise for these bandwidths.

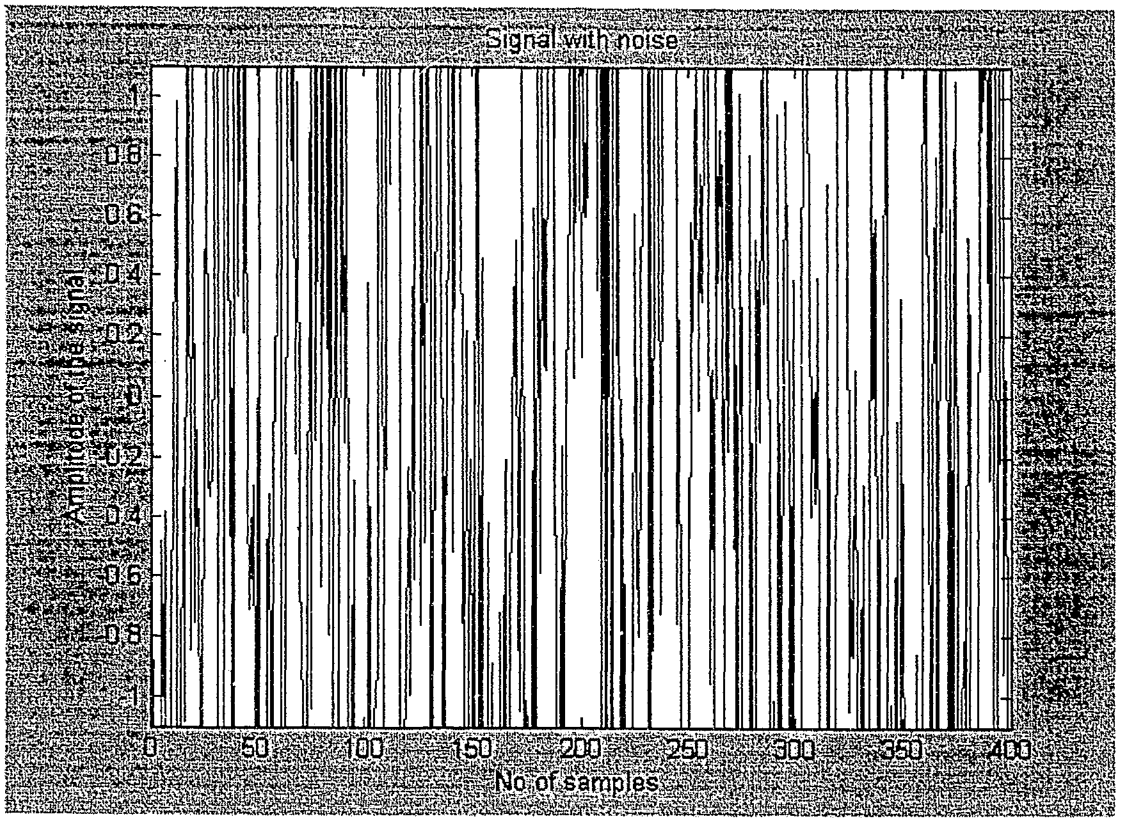

Fig. 9. Signal with noise

So we can say that this filter can remove noise from the corrupted signal reasonably for bandwidth upto 75 MHz but after that bandwidths it can remove noise with some error. It also evident from the learning curve of the filter that it can remove noise from signal with constant bandwidth (Fig. 16. to Fig. 18.) with variable

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modulation index and vice versa (Fig. 19. to Fig. 21.). By using this filter we can achieve some amount of signal to noise ratio (SNR) improvement depending on the nature of the noise, bandwidth, modulation index and signal power.

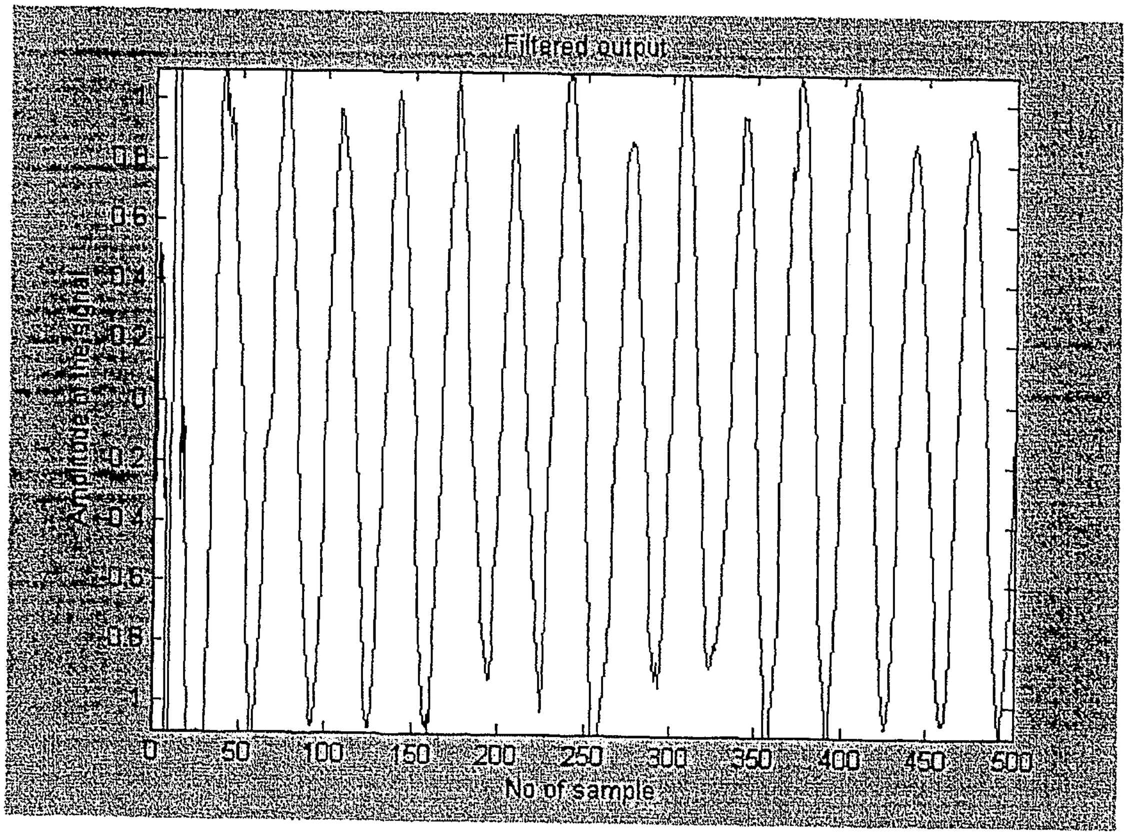

Fig. 10. Denoised signal

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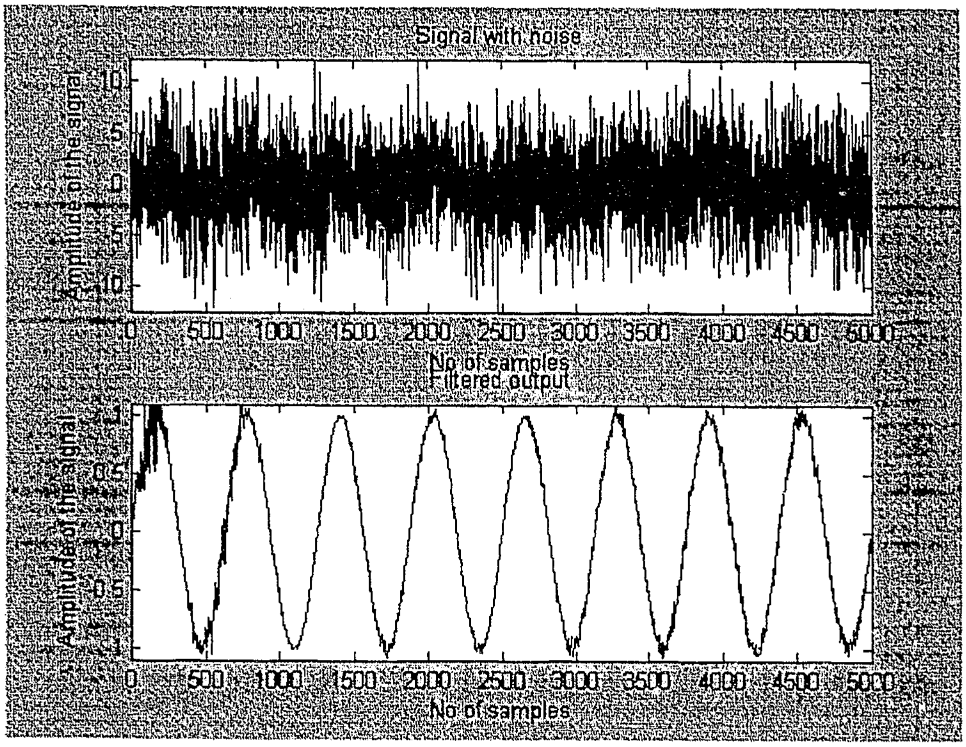

Fig. 11. Signal with noise and denoised signal

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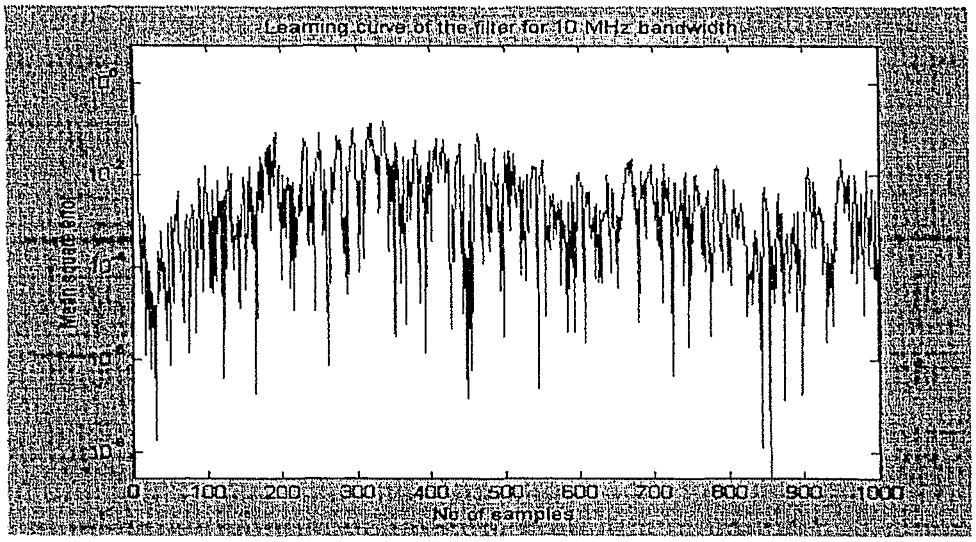

Fig. 12. Learning curve of the filter for 10 MHz bandwidth

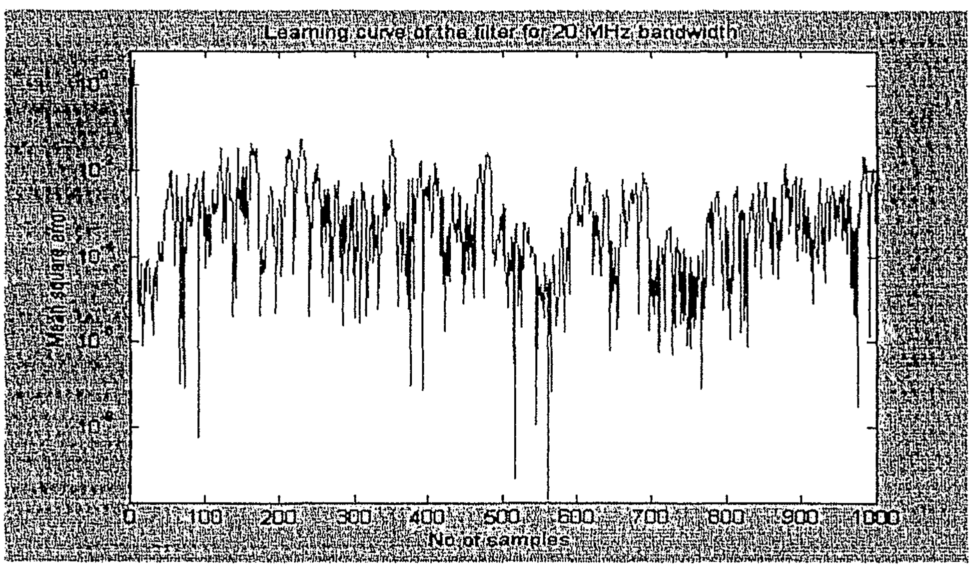

Fig. 13. Learning curve of the filter for 20 MHz bandwidth

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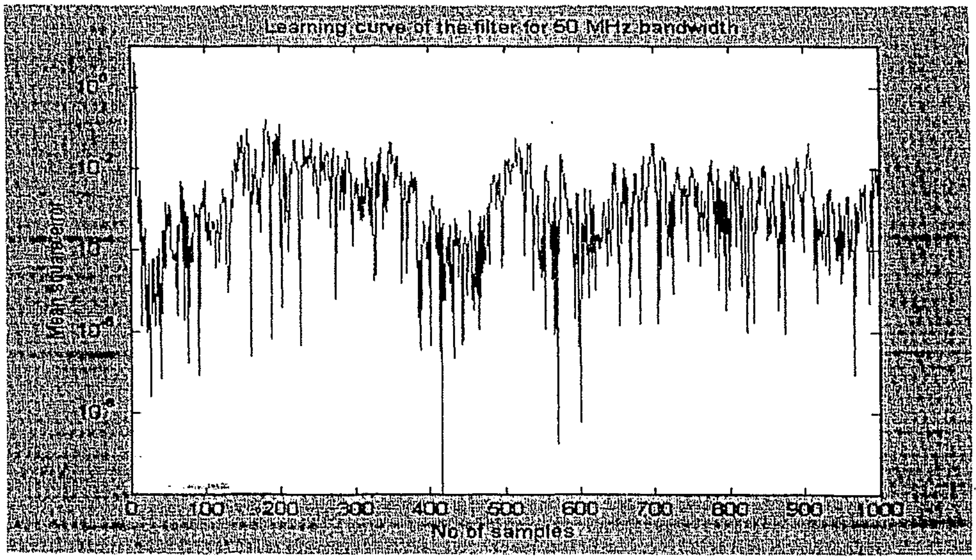

Fig. 14. Learning curve of the filter for 50 MHz bandwidth

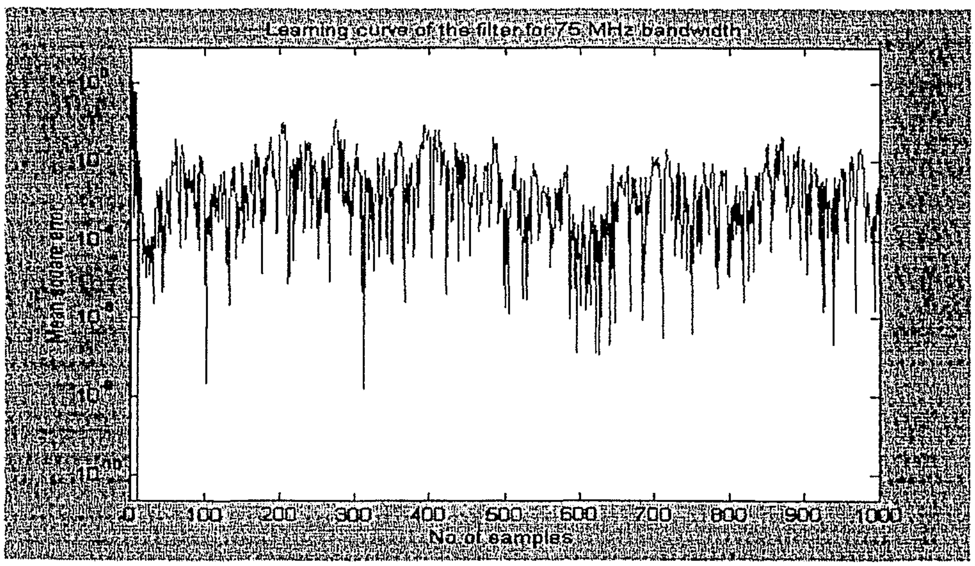

Fig. 15. Learning curve of the filter for 75 MHz bandwidth

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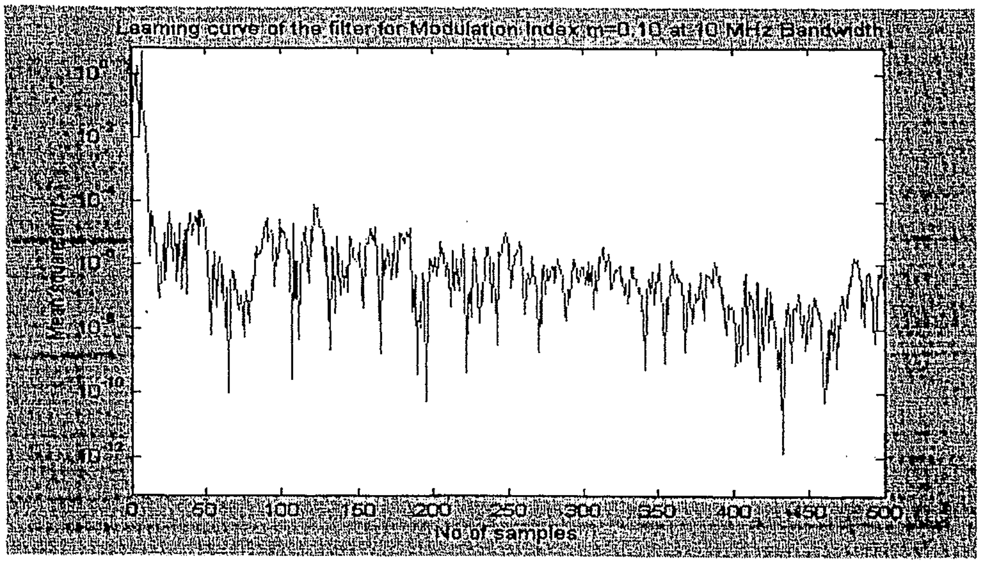

Fig. 16. Learning curve of the filter for modulation index 0.10
and 10 MHz bandwidth

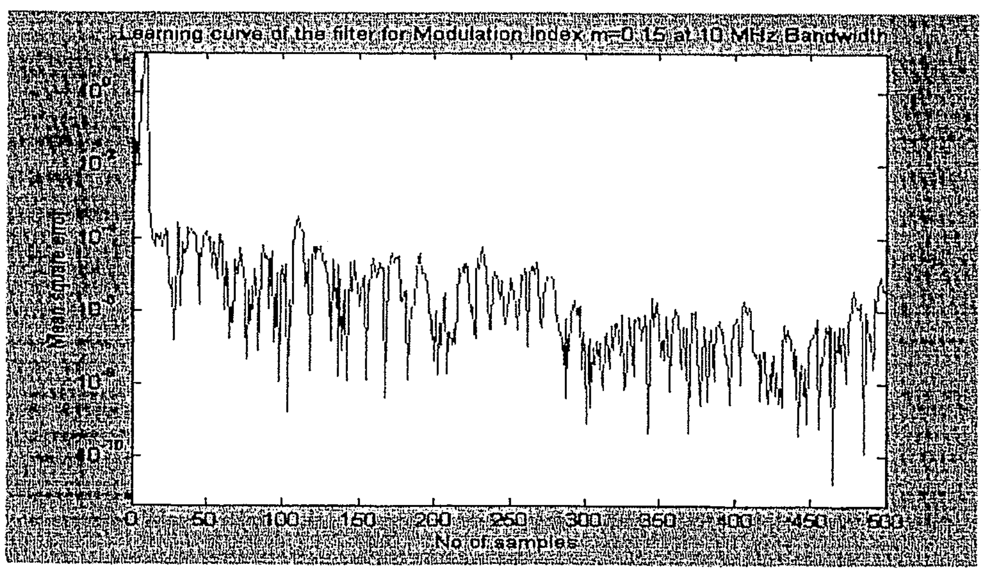

Fig. 17. Learning curve of the filter for modulation index 0.15
and 10 MHz bandwidth

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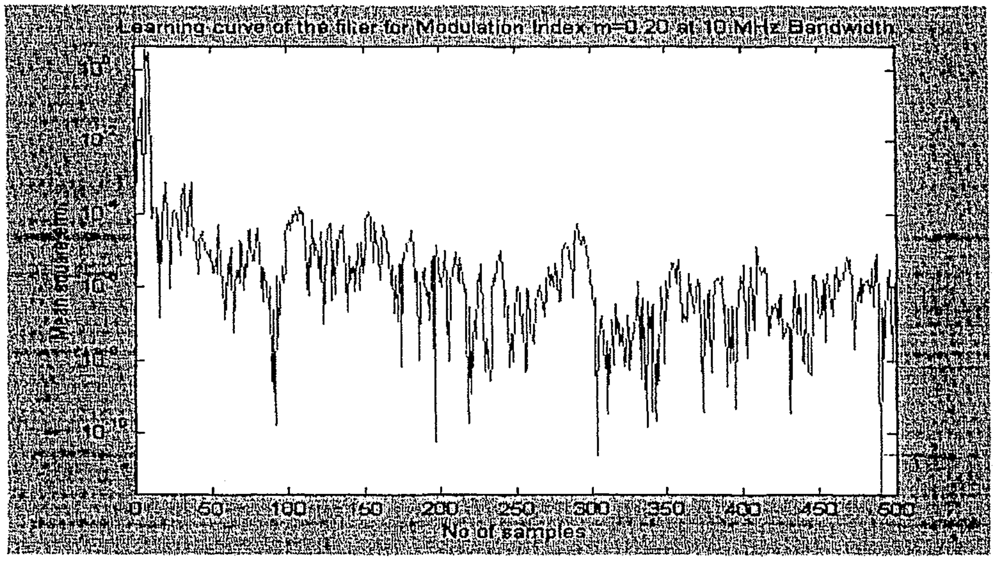

Fig. 18. Learning curve of the filter for modulation index 0.20 and 10 MHz bandwidth

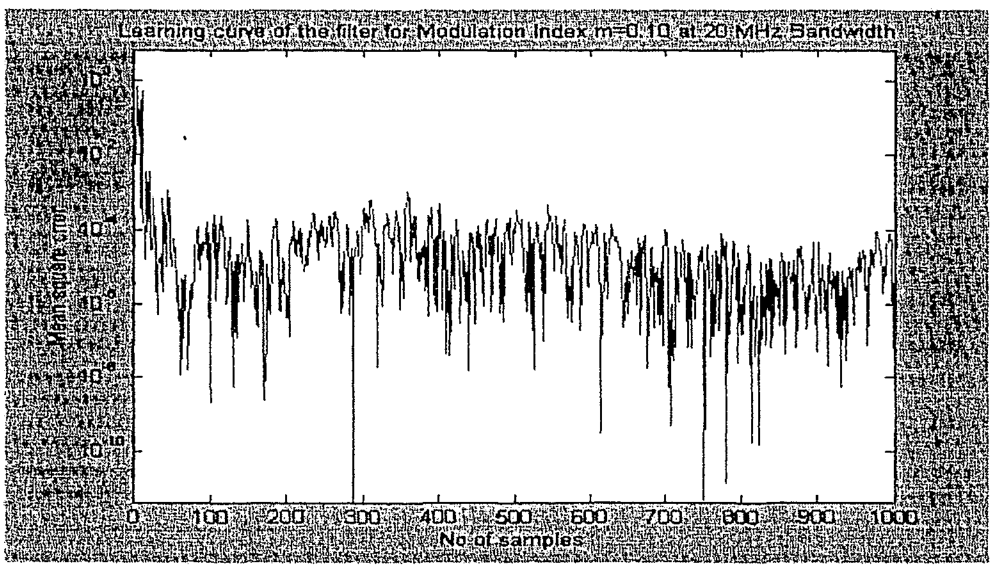

Fig. 19. Learning curve of the filter for modulation index 0.10 and 20 MHz bandwidth

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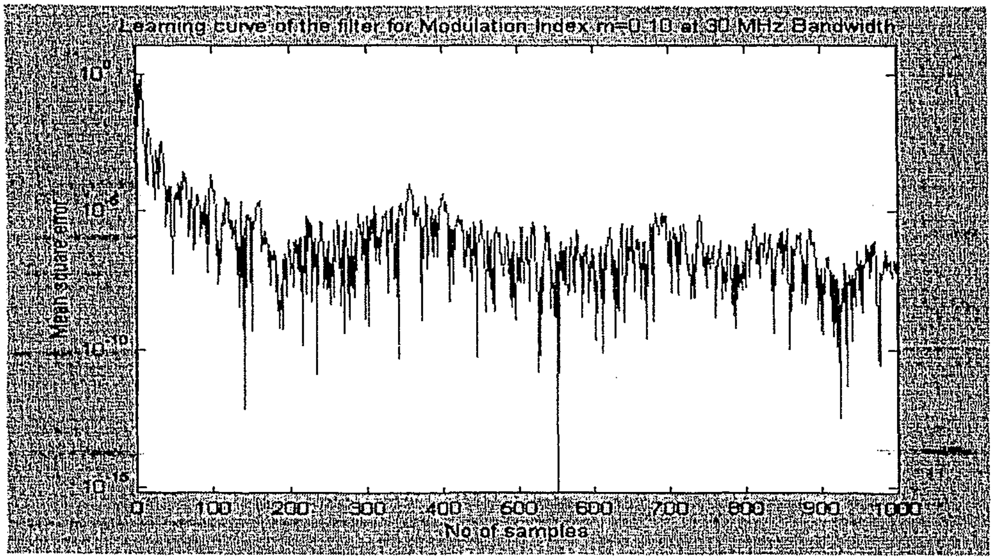

Fig. 20. Learning curve of the filter for modulation index 0.10
and 30 MHz bandwidth

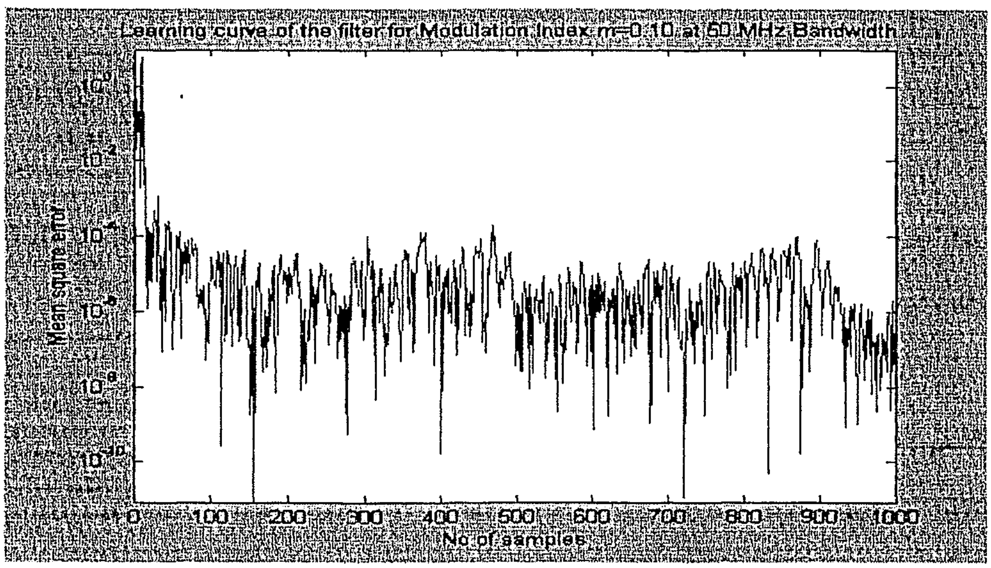

Fig. 21. Learning curve of the filter for modulation index 0.10
and 50 MHz bandwidth

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Chapter 4

Conclusion and Discussion

In this chapter a brief discussion is given on the simulation result. The future effort needed to implement the simulation for real case analysis also discussed with conclusion.

4.1 Discussion

Telecommunication (digital or analog) based on optical fiber link becomes one of the most active expanding areas due to rapidly growing demand for high data rate, multimedia signal etc. Analog optical links are important for transmission of signals over long distance and it has high demand due to low loss of optical fiber. Although it has high demand, its utilization is affected by a number of impairments such as different kind of noise (thermal, shot, RIN noise), dispersion etc. The performance of an analog receiver measured by the signal to noise ratio (SNR). Noise presence in the signal degrades the signal to noise ratio. So to improve the SNR is the demand for many potential applications of fiber optic link. The main noise of an analog fiber optic link mainly considered as phase noise, thermal noise, shot noise, relative intensity noise (RIN). For our analysis and simulation three main noise are considered. This project report illustrates a simulation model of an analog fiber optic link system using MATLAB software and provides a feasible solution to improve the performance of the fiber optic link by removing the noise from the corrupted signal.

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In our present work, we have discussed the method of adaptive noise cancellation technique for fiber optic link. In this project report we described the motivation for investigating the adaptive noise cancellation technique for fiber optic links with previous work done in these fields. It also includes a brief description of the system components and how they are considered in our analysis. At the end we described the algorithms used for cancellation of main three noise components (thermal, shot and RIN) from the optical fiber link and its implementation.

Lots of efforts so far have been given to eliminate or remove the above–mentioned noise from the analog optical fiber link many different ways. From the references and analysis we can see that all of the previous researchers try to compensate the noise individually such as some try to compensate laser relative intensity noise (RIN) or shot noise or thermal noise in transmitter, receiver, amplifier etc. Most of them try to design components (amplifier, transmitter, diode, receiver) with low noise (shot, thermal noise or relative intensity noise) figure.

In my present work an adaptive noise cancellation technique is used to cancel the three main noise (thermal noise, shot noise, and RIN noise). The signal is considered as a sinusoidal with different bandwidth and modulation index and noise in our simulation considered as an equivalent of the three noise (thermal, shot and relative intensity noise) which is randomly generated Gaussian noise. In our simulation different situation has been considered. Sometimes it considered bandwidth is constant but modulation index is variable and vice versa. From the demonstrated figure we can conclude that the noise

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(thermal noise, shot noise, RIN noise) from the optical fiber link can be eliminated adaptively without knowing their complete priori knowledge. From our simulation we achieve some improvement of *SNR* depending on the signal power, bandwidth, modulation index and noise.

From the learning curve for the signal for different bandwidth and modulation index we can conclude that the filter can remove noise from corruptesd signal with minimum mean square error (MMSE) 10^{-4} for different bandwidth and modulation indexes.

4.2 Future Direction

For our present approach and analysis all the noise components were converted to or assumed to be Gaussian distributed. We observed that the noise can be completely removed from the signal. For future works and analysis we can take the real noise with exact probability distribution and nature of the noise components without their approximation. Someone can take the real time multimedia signal, which is now in GHz range for the simulation and implement the adaptive filter in real case analysis for separate the noise from signal from the received corrupted signal.

From the demonstrated figure and learning curve of the filter we see that the filter can remove noise completely from a signal of different bandwidth and modulation index but future transmission efforts are given to work for greater bandwidth because noise power varies with the bandwidth.

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4.3 Conclusion

Adaptive noise cancellation technique is effective to remove the noise (thermal, shot and relative intensity noise) from the analog optical fiber link without the complete priori knowledge . This filter is effective in removing noise from the signal of bandwidth upto 75 MHz with Minimum Mean Square Error (MMSE) of 10^{-4} after 75 MHz MMSE is too high. By using this adaptive filter we observed that some SNR increase is possible for the optical fiber link. For smaller bandwidth SNR increase is greater than the larger ones.

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APPENDIX

```
%%Sample program for Adaptive noise cancellation from an fiber optic link by RLS
algorithm
clear all;
close all;
refgain=1;
nvari1=0.0001; %% noise variance for shot noise
nvari2=0.0002;%% Noise variance for RIN noise
c=100*10^6; %% Bit rate of the signal
B=1.00*10^7; %% Bandwidth of the signal considering 30 dB=1000 s/n ratio from the
formula c=Blog2(1+s/n)
fs=4.0*10^7; %% Frequency sampling rate greater than 2B
Ts=1/fs;
forder=8;
N=10000;
t=[0:Ts:10000*Ts];
sg=sin(2*pi.*t.*t/N/N*8);
wreal=randn(1,forder);
   nth=fix(rand+0.5);
   ns=fix(rand+0.5)*2*sqrt(nvari1)-sqrt(nvari1);
   nr=fix(rand+0.5)*2*sqrt(nvari2)-sqrt(nvari2);
additivenoise=nth+ns+nr;
```


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```
ref=conv(additivenoise,wreal);
primary=sg+ref(1:length(sg));
fref=additivenoise*refgain;
lambda=1; %5Technically this is lambda inverse
w(1,:)=zeros(1,forder);
init=100;
rinv=diag(ones(1,forder)*init); % zero pad so we can start the filter at 0 and notthrow of
the index
frefpad=[zeros(1,forder-1) fref];
start=flops;
for n=1:N; % offset n so we can start tha correct value of zero padded fref
   m=n+forder-1;
   frefblock=frefpad(m-forder+1:1:m)';
   refp(n)=w(n,:)*(frefblock);
   output(n)=primary(n)-refp(n);
   k=lambda*rinv*frefblock/(1+lambda*frefblock'*rinv*frefblock);
   w(n+1,:)=w(n,:)+k'*output(n); % Out put used as an error signal
   rinv=lambda*rinv-lambda*k*frefblock'*rinv;
end;
work=flops-start;
w(length(w),:);
figure;
```


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```
hold on
for ii=1:forder;
   plot(w(:,ii),'r');
end;
figure;
subplot(3,1,1);
plot(primary);axis([0 length(primary) min(primary) max(primary)]);
title('Primary signal');
subplot(3,1,2);
plot(output);axis([0 length(primary) min(sg)-.1 max(sg)+.1]);
title('Filtered output');
subplot(3,1,3);
plot((ref(1:length(refp))-refp).^2);     axis([0     length(primary)     min(primary)-.1
max(primary)+.1]);
title('Mean squared Error');



%% signal to noise ratio calculation after and before filter


sv=2*forder;
sw=length(sg);
SNRpre=norm(sg(sv:sw))/norm(ref(sv:sw)); %% Noise before filtering
```


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```
SNRpre=10*log10(SNRpre);

SNRpost=norm(sg(sv:sw))/norm(sg(sv:sw)-output(sv:sw));%% Noise after filtering

SNRpost=10*log10(SNRpost);



figure; hold on

plot(10*log10(output*10^3),SNRpost,'k');

xlabel('output power P_o(dBm)')

ylabel('signal to noise ratio (SNR) in (dB)')

title('SNR after noise removed');

figure; hold on

plot(10*log10(output*10^3),SNRpre,'g');

xlabel('Output power P_o(dBm)')

ylabel('signal to noise ratio(SNR) in (dB)')

title('SNR before noise removed');
```


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