Reduced-Nonlinear Effect on Magnetic Recording Channels Using MMSE Equalizer

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ABSTRACT

This paper considers the nonlinear effect on magnetic recording channels in order to reduce the system distortion. We propose the designed minimum-mean square error (MMSE) equalizer and targets for a high density perpendicular magnetic recording to combat the nonlinear transition shift (NLTS) in a channel characterized by jitter noise and additive white Gaussian noise (AWGN). Due to the complex nature of nonlinear effects, the nonlinearity of a read-back signal is modeled by the second order Volterra model consisting of linear and nonlinear parts. The bit-error rate (BER) of the nonlinear-affected system using the designed MMSE equalizer is significantly decreased. The results show that the proposed MMSE equalizer with g_t=1 constraint can decrease the inter-symbol interference (ISI) that causes nonlinearity and also improves a system performance.

Keywords: Perpendicular Magnetic Recording, Jitter Noise Nonlinearity, Volterra Model, MMSE Equalizer.

1. INTRODUCTION

Due to the requirement of increasing areal density in magnetic recording system, the perpendicular magnetic system has outperformed the longitudinal magnetic system to overcome the limit of superparamagnetic effect [1]. However, in the high density in perpendicular magnetic system, the nonlinear distortion occurred in many forms often leads to the system performance degradation. For example, nonlinearity occurs in the write process in the form of the nonlinear transition shift (NLTS) due to the demagnetization field of the previous transition. Nowadays, hard disk drives certainly have high capacity; hence the recorded bits on the media are closely packed leading to increased inter-symbol interference (ISI), another cause of nonlinearity. As a consequence, the read-back signal includes both linear part, which is preferable data, and nonlinear part, which causes errors and degrades the system performance. The write precompensation is one efficient technique [1] to reduce a signal distortion induced by NLTS by adjusting the transition delay of write current taking into account of neighboring write bits.

However, the behavior of nonlinearity is not easy to be tackled. The bit position affected by nonlinearity is unpredictable. Various techniques have been studied in order to model the channel with nonlinearity. In [2], a Volterra equation was used to define the dibit response showing the relationship of linear and nonlinear part in the channel response based on Volterra model and the authors in [3] applied the Volterra function series to the nonlinear distortion in practice. Also, they considered some significant nonlinear part in order to identify the realistic nonlinear recording channel. In addition to [4], they used an extracted dipulse technique or pseudo random sequence method. This technique relied on the relationship between the pseudo random sequence and the read-back signal that had been affected by a head asymmetry using correlation function. In [5], they used a Golay complementary sequence for finding the dibit response due to the performance degradation by magnetoresistive (MR) and comparing with a dibit response created by feedback shift register on the both second and third order Volterra model. In [6], they designed the generalized partial response target for perpendicular magnetic recording with jitter noise and also compared the performance with various targets. Moreover, in [7] the effect of jitter noise in two different channels in magnetic recording channel was discussed. Higher-density data will always lead the higher percentages of jitter noise. The jitter noise can occur due to the noise in a thin film disc and additive noise is produced from participated media noise [8].

In this paper, we focus on a perpendicular magnetic recording and investigate the effect of the nonlinearity in write process in two channels characterized by AWGN and jitter noise. We model the nonlinear channel by the Volterra model, and then we decrease the nonlinearity by using the proposed minimum mean square error (MMSE) equalizers. We also confirm the chosen constraint that gives the MMSE by considering the MMSE of various constraints and the bit-error rate (BER) in linear and nonlinear systems in magnetic recording channels. The system performance is also analyzed by the BER of nonlinear-affected system with and without our designed MMSE equalizer.

The remainder of this paper is organized as fol-

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lows. We describe the magnetic recording channels with and without nonlinearity in Section 2. In Section 3, the MMSE equalizer is introduced and discussed. Section 4 shows the designed target and MMSE equalizer in channels that get affected from AWGN and low jitter noise. The simulation results of the performance improvement in terms of the bit-error rate (BER) are shown and discussed. Finally, the conclusion is given in Section 5.

2. MAGNETIC RECORDING CHANNELS WITH NONLINEARITY

In the recording process of hard disk drives, the data bits are encoded into the rectangular current waveforms, and then they are recorded on the media by the magnetic recording process. Afterwards, a detector will make a decision to detect these data. Since the capacity of hard disk drive is high, the wrong decision will usually happen in the write process and it can subside the performance. In this research we will focus on the nonlinearity in the write process. In practice, the read-back signal consists of linear part and nonlinear part, which cause errors and is required to be removed or mitigated.

This section introduces the linear and nonlinear channels and discusses the Volterra model to simulate a nonlinear effect of the write process.

2.1 Linear Channel

In perpendicular magnetic recording in hard disk drives, the write process starts from the data input $a_k \in \{1, -1\}$, which is encoded afterwards, then it is recorded to the media shown by 2 opposite transitions. The recording process [4] will generate a transition response corresponding to the channel input +1 to model a positive transition; likewise, a channel input -1 will be a negative transition. For perpendicular recording, the transition response can be expressed as

$$g(t) = V_p \times erf\left(\frac{2t\sqrt{ln2}}{w}\right) \tag{1}$$

where V_p is the peak value of the transition response, $erf(x)$ is the error function, which is defined as $erf(t) = \frac{2}{\pi}\int_0^t -x^2 dx$, w is the $PW50$ which is the width of $g(t)$ at half of its peak value V_p, and the normalized recording density is defined as $ND = PW50/T$, where T is the period of data bits. So, the dibit response of the system is $h(t) = g(t) - g(t-T)$. Therefore, the read-back signal can be represented by

$$r(t) = \sum a_k h(t - kT + \Delta t_k) + n(t) \tag{2}$$

where $n(t)$ is an electronics noise which is an additive white Gaussian noise (AWGN) with two-sided power spectral density. The jitter noise [6] Δt_k, is a Gaussian distribution with zero mean and variance σ_j^2, where σ_j is the percentage of bit interval, T. If we want to add $k\%$ of jitter noise, we will define σ_j to be equal to $k\%$ of bit interval.

In practical usability, the data stored in hard disk drive is intense due to its high areal density; hence the system will get affected from the ISI that normally leads to a nonlinear effect. So, a nonlinear channel in this simulation will be designed by the Volterra model.

2.2 Nonlinear Channel using Volterra Models

Since the nonlinearity of read-back signal from the recording process is not easy to be predicted or estimated, in this research, we use the Volterra model [2] to model a nonlinear channel. Volterra equations show the relationship between the linear and nonlinear structures that simultaneously occur in the write process. Moreover, the Volterra model can be written in terms of a Volterra series. Let us define $q[m] = q(mT_s)$, where T_s is the sampling interval and equals to $T_s = T_b/p$, T_b is the bit interval, and p is an integer greater than one. Given that $a_k \in \{\pm 1\}$ is an input sequence, the oversampled signal $s[m]$ can be expressed as

$$\begin{aligned} s[m] &= s^{(0)}[m] + \sum_k a_k C^{(1)}[m - kT_b] \\ &+ \sum_k \sum_{d_1=1}^{L-1} a_k a_{k-d_1} C^{(2)}_{d_1}[m - kT_b] \\ &+ \sum_k \sum_{d_1=1}^{L-2} \sum_{d_2=d_1+1}^{L-1} a_k a_{k-d_1} a_{k-d_2} C^{(3)}_{d_1,d_2}[m - kT_b] \\ &+ \ldots + \sum_k a_k a_{k-1} \ldots a_{k-(L-1)} C^{(L)}_{1,2,\ldots,L-1}[m - kT_b] \\ &+ \ldots + \left(\begin{array}{l} \sum_k \sum_{d_1=1}^{L-l+1} \cdots \sum_{d_1=d_{l-1}+1}^{L-1} a_k a_{k-d_1} \ldots a_{k-d_{l-1}} \\ C^{(l)}_{d_1,d_2,\ldots,d_{l-1}}[m - kT_b] \end{array} \right), \\ l &= \{2, \ldots, L\}, \end{aligned} \tag{3}$$

where the Volterra kernel is defined as $C^{(l)}_{d_1,d_2,\ldots,d_l}$, where $d_1, d_2, \ldots, d_{l-1}$ are bits shifted from the reference position, L is the order of a Volterra kernel, and $l = \{2, \ldots, L\}$. For the linear part, the superscript (1) of $C^{(1)}[m - kT_b]$ indicates the first Volterra kernel that only uses a single bit information and the subscript k of a_k represents the bit position. Similarly in the higher order terms, for example, in the third order, we consider every 3 bits; likewise the subscript shows the position of bit from a_k, a_{k-1}, and a_{k-2}. We can show the block diagram of Volterra model to describe recording channel with nonlinearity in Fig. 1.

From the property of the Volterra model [9], a read-back sensor's transfer function is an example of the nonlinear channel in the write process. It can be rewritten in terms of the power series as.

$$f(s) = \sum_{k=0}^{\infty} c_k s^k(m) = c_0 + c_1 s + c_2 s^2 + \ldots \tag{4}$$

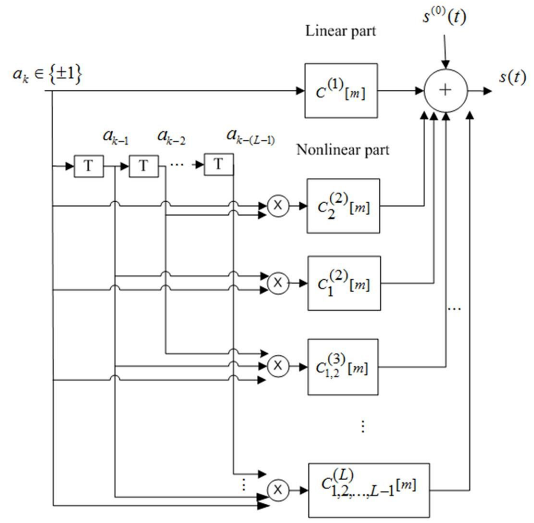

Fig.1: The Volterra model for nonlinear recording channel.

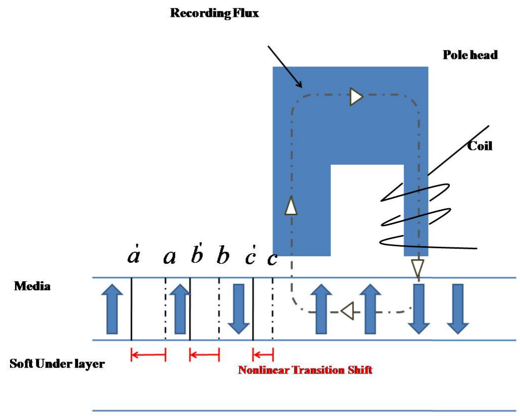

Fig.2: The effect of NLTS in the written perpendicular recording process.

where f is a nonlinear transfer function, s is the input, and $c_0, c_1, \ldots$ are constants. Then, substituting equation (3) in (4), we can see the independent term $s^{(0)}[m] = c_0$, while the first order Volterra kernel $C^{(1)}[m] = c_1 h[m]$ is the linear part, and the second order Volterra kernel, which is $C_d^{(2)}[m] = 2c_2 h[m]h[m+dT_b]$, $d = 1, 2, \ldots, L-1$, represents the nonlinear part in the recording channel.

2.3 Nonlinear Effect

The nonlinear distortion in the magnetic recording can occur in a write current because the read head of hard disk drive provides a closely located transition and is stored on a medium. Furthermore, nonlinearity in perpendicular recording has a shift in transition position to the direction of the previously written transition which occurs as the demagnetizing field of the previously written transition because the read head writing is at the current transition. The current transition decreases the demagnetization field from the previous transition because of some given magnetization. Hence, the transition is shifted previously in time and gets some magnetization. In the case of high densities, the space between transitions is closer and some transition will merge some part of other transitions together. The illustration of NLTS in the write process is shown in Fig. 2.

In the next section, we will design target and equalizer in order to decrease the effect of nonlinearity in the recording system.

3. MMSE EQUALIZER

In this work, we will use the MMSE equalizer to reduce the ISI in the system. Normally, characteristics of equalizer must closely match to the hard disk drive's channel, while the optimal target must have the frequency response mostly resembling the frequency response of the channel. In this simulation, we will use the MMSE method to design target and equalizer [6][10] due to the simple process and also suitable for using in practice. The MMSE design has many target constraints, which can be chosen to properly fit the channels.

The designed system is introduced in Fig. 3. Let a_k be an input bit, n_k is an AWGN, s_k is an incoming signal and affected by the AWGN sequence. Thus, it can be rewritten in terms of $p_k = s_k + n_k$ and $w_k = y_k - r_k$ is the error between the equalizer output y_k and a target output r_k that represents the error from the process of target and designed equalizer. The MMSE can be written in terms of the expectation equation as following.

$$\begin{aligned} E\left[w_k^2\right] &= E\left[(y_k - r_k)^2\right] \\ &= E\left[\left((s_k * f_k) - (a_k * g_k)\right)^2\right], \end{aligned} \quad (5)$$

where $*$ denotes the convolution operator and $E[\cdot]$ is an expectation operator. As a consequence, the MMSE method will calculate the coefficients of target $G(D)$ and equalizer $F(D)$ simultaneously to get the smallest mean-square error (MSE). The MSE can be computed in terms of a matrix equation from

$$E\left[w_k^2\right] = \mathbf{F}^T\mathbf{R}\mathbf{F} + \mathbf{G}^T\mathbf{A}\mathbf{G} - 2\mathbf{F}^T\mathbf{P}\mathbf{G} \quad (6)$$

where $[\cdot]^T$ represents the transpose operation of a matrix. We define $\mathbf{G} = [g_{-k} \ldots g_0 \ldots g_k]^T$ and $\mathbf{F} = [f_{-k} \ldots f_0 \ldots f_k]^T$ to be the coefficient matrices of a target $G(D)$ and equalizer $F(D)$. The matrix $\mathbf{R}$ is the autocorrelation matrix of the channel output s_k, $\mathbf{A}$ is an autocorrelation matrix of the input data a_k, and $\mathbf{P}$ is the cross correlation matrix of the channel output s_k and the input data a_k.

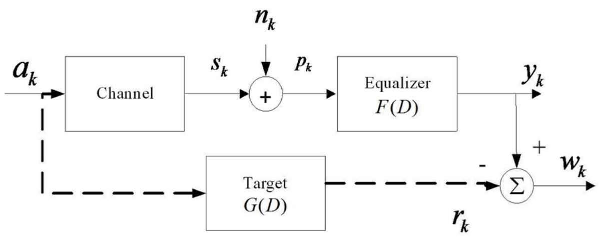

Fig.3: *Model of the designed MMSE equalizer.*

For the designed target and equalizer, we specify the target with length L and the number of taps in equalizer $N = 2K + 1$. Let λ be the Lagrange multiplication, to minimize $E[w_k^2]$ and avoid letting $\mathbf{F}{=}\mathbf{0}$ and $\mathbf{G}{=}\mathbf{0}$, we compare the effects of this system by using three constraints , the first constraint is the fixed target such as PR2 [1 2 1], the second one is a monic constraint $g_0 = 1$ that lets the first position of target matrix be equal to 1, so let $\mathbf{I} = [1, 0, \dots, 0]^T_{L\times 1}$ or can be rewritten in terms of the matrix $\mathbf{I}^T\mathbf{H} = 1$ and then substitute in this equation (6). We will get

$$E\left[w_k^2\right] = \mathbf{F}^T\mathbf{R}\mathbf{F} + \mathbf{G}^T\mathbf{A}\mathbf{G} - 2\mathbf{F}^T\mathbf{P}\mathbf{G} - 2\lambda(\mathbf{I}^T\mathbf{G} - 1), \quad (7)$$

By letting (7) equals to 0, we derive

$$\lambda = \frac{1}{\mathbf{I}^T(\mathbf{A} - \mathbf{P}^T\mathbf{R}^{-1}\mathbf{P})^{-1}\mathbf{I}}, \quad (8)$$

$$\mathbf{G} = \lambda(\mathbf{A} - \mathbf{P}^T\mathbf{R}^{-1}\mathbf{P})^{-1}\mathbf{I}, \quad (9)$$

and equalizer equation is

$$\mathbf{F} = \mathbf{R}^{-1}\mathbf{P}\mathbf{G}. \quad (10)$$

Finally, the third constraint is a $g_1 = 1$ that will define the coefficients of the second position be equal to 1 by $\mathbf{I} = [0, 1, \dots, 0]^T_{L\times 1}$ and the other matrix's coefficients can be any integer.

Therefore, we will compare the performance of all constraints by considering the MMSE in both linear and nonlinear systems. The appropriate and chosen constraint of the system must give the lowest MMSE in both linear and nonlinear channels. The results in Fig.4 compare the target and equalizer at the normalized density (ND) of 2. The numbers of equalizer taps of all constraints ranges from 3 to 19 taps. The simulation shows that the case of $g_1 = 1$ gives the lowest MMSE among all the constraints. From the MMSE graph, the linear system has a lower MMSE value than the nonlinear system as expected for all the number of taps of equalizer under consideration. Therefore, the $g_1 = 1$ constraint gives the lowest MMSE in linear and nonlinear system; hence in this experiment we will use the $g_1 = 1$ constraint to analyze the distortion of the nonlinear channel and reduce the error as well as improve the performance in the system.

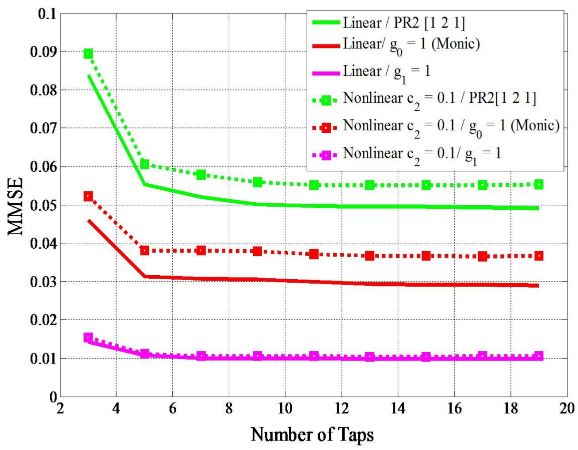

Fig.4: *The MMSE versus the number of equalizer taps in linear and the second order nonlinear channels.*

4. DESIGNED TARGET AND MMSE EQUALIZER

From the system diagram shown in Fig. 4, the oversamples received signal through the second order Volterra model without noise can be explained by

$$\begin{aligned} s(mT_s) =& s^{(0)}(mT_s) + \sum_k a_k C^{(1)}(mT_s - kT_b) \\ &+ \sum_k a_k a_{k-1} C_1^{(2)}(mT_s - kT_b) \\ &+ \sum_k a_k a_{k-2} C_2^{(2)}(mT_s - kT_b). \end{aligned} \quad (11)$$

A linear part is denoted by $C^{(1)}[m] = c_1 h[m]$ and in this work we let $c_1 = 1$, and the second order nonlinear part is referred to $C_d^{(2)}[m] = 2c_1 h[m]h[m + dT_b]$, $d = 1, 2$. The target and equalizer will use the $g_1 = 1$ constraint because this constraint gives the least MMSE value and matches the system claimed in [11]. We consider and use the second order Volterra model to generate a read-back signal that gets affected from nonlinearity, where the block diagram is shown in Fig. 5.

Due to the ability of equalizers that can decrease the error, we will compare their performances in the nonlinear system. Fig.6 shows the performance of recording system with and without an MMSE equalizer in both linear system and the second-order nonlinear system with $c_2 = 0.5$ (nonlinear density). The result shows that the BER of the system without an MMSE equalizer will give the worst performance, even though they still have a Viterbi detector.

However, the system with an MMSE equalizer with the chosen $g_1 = 1$ constraint gives the lower BER than the one with $g_0 = 1$ constraint. Consider the BER graph at BER $= 10^{-3}$, the system without MMSE equalizer has a lower SNR gain than the sys-

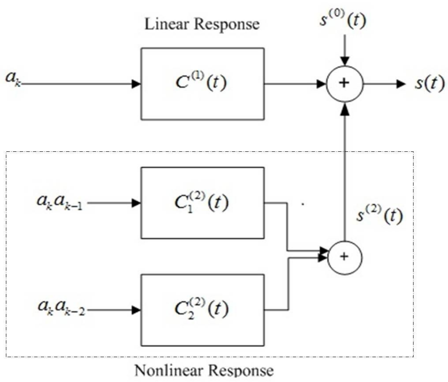

Fig.5: *The second order Volterra Model.*

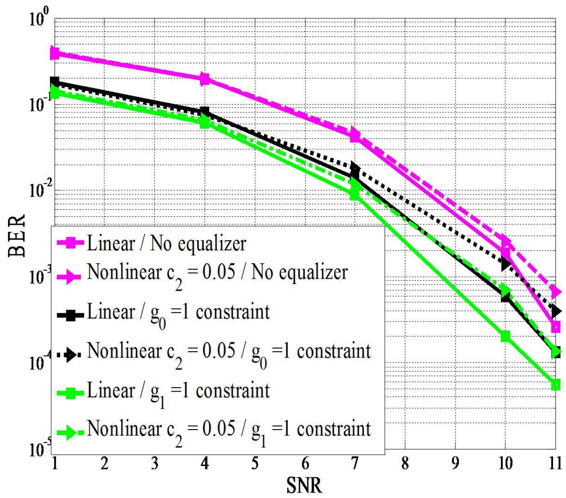

Fig.6: *The BER of the linear and nonlinear systems with and without MMSE equalizer.*

tem using the $g_1 = 1$ constraint by approximately 1 dB. From this simulation result, $g_1 = 1$ constraint is a preferred constraint for our designed MMSE equalizer.

4.1 The Additive White Gaussian Noise (AWGN)

To avoid the degradation from nonlinearity, we will decrease the ISI by using the proposed MMSE equalizer. In this simulation, we define the Volterra model described in [2] and let $SNR = 10log(E_b/N_0)$, where the average information bit energy $E_b = 1$, and the noise spectral density height $N_0 = 2\sigma^2$. Then, we compare the performance by considering the BER of both linear and nonlinear channels shown in Fig. 6. It is clearly shown in Fig. 6 that the system with effect of nonlinearity has more BER and lower performance than the linear system. The BER is getting worse when the nonlinear coefficient is getting increased. As shown in Fig.7, at the SNR = 9 dB, the BER of the nonlinear system with the nonlinear coefficient $c_2 = 0.1$ is approximately 4×10^{-3}, while the BER of the linear system is about 1.5×10^{-9}, which is slightly lower.

4.2 AWGN and Jitter Noise

In practice, not only the AWGN can degrade the system performance in the write process, but also a jitter noise can increase its BER. To model the recording system in this work, a low jitter noise is added as well as investigating the performance comparison of linear and nonlinear systems in order to observe its effect on the BER graphs. Fig. 8 shows the block diagram of the system for our simulation with the effect of lower jitter noise (Δ_t).

In this experiment, we consider and use the $g_1 = 1$ constraint that gives the lowest MMSE as shown in the previous section. Because the AWGN is correlated with the jitter noise [7], so if the effect of AWGN increases, it will be influenced by the transition of jitter noise as well. We compare performance of the system induced by various noise levels of 3%, 5%, 7%, and 9%. The target is equal to [0.4956 1.0000 0.6177] and 11-taps equalizer is [-0.0260 0.0606 -0.1061 0.1722 -0.2655 0.1890 0.8581 0.4180 -0.4032 0.2118 -0.0609]. The result in Fig. 9 shows that the performance of the linear system will be more degraded when the percentage of jitter noise is increased, and yields more errors. The linear system affected by jitter noise of 9% has the worst performance.

Moreover, in the nonlinear system, we firstly design the channel using the Volterra model as described in Section 2, and then compare the performance of the linear system. Also, we compare the effect of jitter noise that has various noise levels from 5%, 10%, 20%, 30% and 40% of bit interval. The BER graph shows that the more density of jitter noise in the write process, the more error in the process will occur and degrade the performance. These simulation results can be shown in Fig. 10 and Fig. 11, respectively. In Fig.11, the BER in both linear and nonlinear systems affected by 3% jitter noise is shown. At the BER = 10^{-3}, both linear systems with and without jitter noise give the SNR gains of about 1 dB compared with the nonlinear system with $c_2 = 0.1$.

The simulation results confirm that the jitter noise in the write process will significantly decrease the performance, even through in the linear system which has no effect with nonlinearity. The more severe noise the system gets, the more distortion will occur in the system as shown in the BER graphs.

5. CONCLUSION

In this work, we have designed the MMSE equalizer to reduce the errors that can occur from AWGN

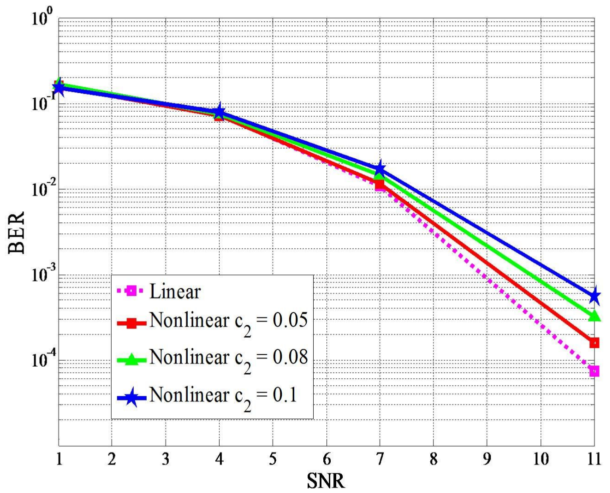

Fig.7: *The BER of linear and nonlinear system affected by AWGN.*

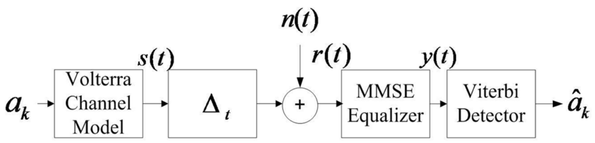

Fig.8: *The diagram of linear and nonlinear system affected by AWGN and jitter noise.*

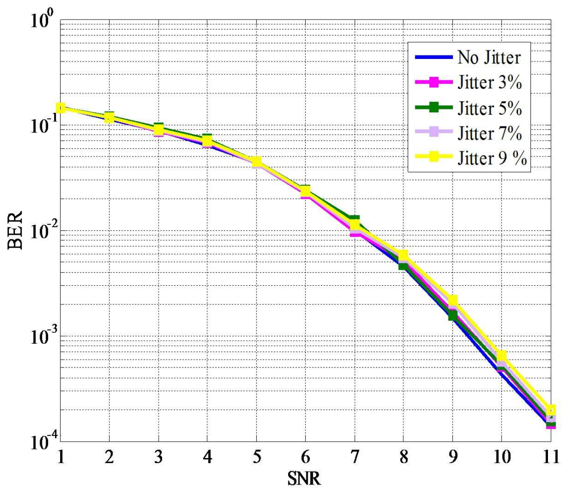

Fig.9: *The BER in the linear system affected by jitter noise.*

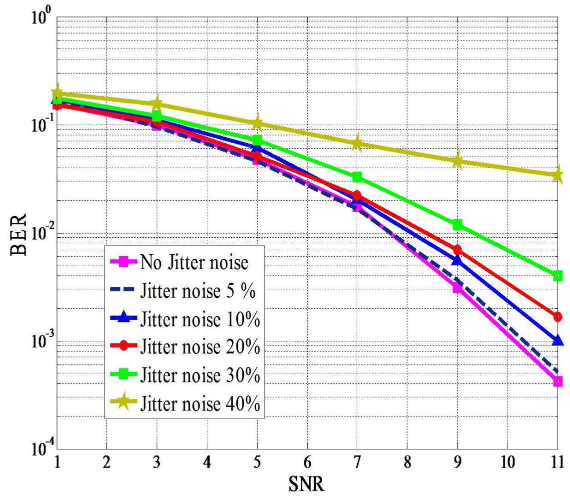

Fig.10: *The BER in the nonlinear system affected by jitter noise 5%,10%,20%,30% and 40%.*

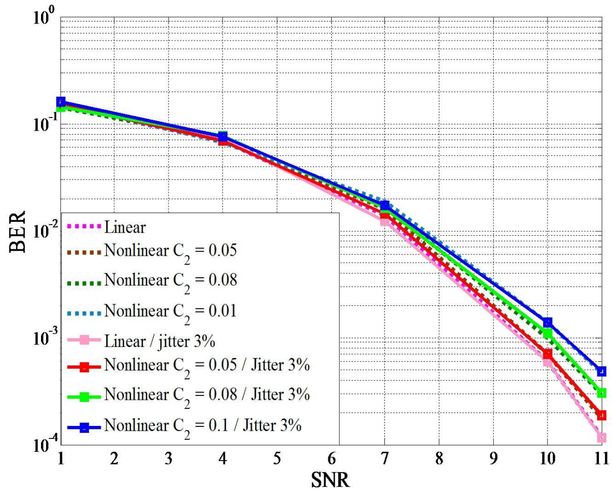

Fig.11: *The BER in the linear and nonlinear system affected by jitter noise 3%.*

and jitter noise in linear and nonlinear channels for perpendicular magnetic recordings to improve the performance of both systems. Since the effect of nonlinearity in the system is not easy to estimate and pre-compensate, so we simulate the nonlinear channel using the Volterra model, and design the MMSE equalizer with the $g_1 = 1$ constraint and choose an appropriate target to decrease errors of the system. The MMSE versus the numbers of equalizer taps graph which is set from 3 to 19 taps is shown and introduces the best constraint that can be applied in the recording system. The result shows that the $g_1 = 1$ constraint gives the lowest MMSE in both linear and nonlinear system, and is appropriate for our proposed MMSE equalizer. To be practical, we investigate the system performance with a channel characterized by both jitter noise and AWGN. With the designed MMSE equalizer, the nonlinear effect can be decreased by observing the lower BER. An analytical solution for a precompensation scheme to minimize BER that would be a good model for NLTS is still in a promising work that we will study in the future.

6. ACKNOWLEDGEMENT

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