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New Neural Network Based Nonlinear and Multipath Distortion Equalizer for FTTA Systems

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SUMMARY A new Neural Network Equalizer (NNE), employing multilayer feedforward neural network, is proposed as a compensation method for nonlinear and multipath distortion that arises from FTTA (Fiber To The Air) system. If a signal in a channel is affected by nonlinear distortion, the conventional Decision Feedback Equalizer (DFE) finds difficulty in perfect compensation of it. To compensate for nonlinear distortion as well as multipath distortion, an equalizer, employing neural network, is investigated. A new neural network equalizer, yielding a cubic function as unit output function, is proposed in order to compensate the nonlinear distortion effectively. We also propose an initial weights of neural network for preventing from local minimum. Computer simulation results show that the compensation performance of the new NNE is superior to the conventional DFE and the conventional NNE.

key words: *digital communication, nonlinear distortion, multipath, equalizer, neural network, QAM*

1. Introduction

There has been an increasing demand on interactive systems which provide various services such as video on demand (VOD), virtual mall, interactive video game, and software distribution of application programs, and give users a mobile computing environment [1]. Wideband microcellular communication system has been studied in order to realize these services. However, the implementation of microcellular system requires the huge number of radio base stations (RBSs) transmitting and receiving RF signals and the effective connections among RBSs.

Fiber to the air (FTTA) system has attracted the attention to solve these problems [4]. In FTTA system, RBS and a control station (CS) are connected by optical fibers and radio signals are transmitted over the fiber-optic connections. As for the structure of FTTA system, RBS only requires an optic to electric converter (O/E) and an electric to optic converter (E/O), and the other functions such as RF modulation and demodulation, frequency assignment, and so on can be performed at the CS. The FTTA system gives flexible use of RBS for various kind of services with low cost.

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Unlike the advantage of the FTTA system, it is confronted with a difficulty of the nonlinear distortions due to E/O and O/E converters. Particularly, a multilevel Quadrature Amplitude Modulation (QAM) signal is greatly affected by a nonlinear distortion, because of the major fluctuation for the amplitude of the signal [5]. For this reason, the compensation of nonlinear distortion is essential to realize the FTTA system as well as the compensation of multipath distortion due to a radio channel.

As the compensation method of the multipath distortion, adaptive equalizer, based on adaptive algorithms such as least mean square (LMS), is generally employed. Distinctively, decision feedback equalizer (DFE), composing of finite impulse response (FIR) part by transversal filter and infinite impulse response (IIR) part, its feedback signals are decision signals, is practically employed as a compensator for the multilevel QAM signal in multipath channel. Although DFE is effective in compensating for the multipath distortion, it is no longer effective to the compensating for the nonlinear distortion.

As nonlinear distortion compensation methods, pre-distortion method, which is compensating for the distortion before nonlinear devices, and post-distortion method, compensating for the nonlinear distortion at the receiver, are introduced. The post-distortion method is capable of the compensation that is highly adaptive for the practical nonlinear distortion, compared with the pre-distortion method, coming up with the prediction of the nonlinearities existing in channel. Particularly, the post-distortion method is an effective method for a system, employing radio transmission such as digital mobile communications. The various compensation methods based on post-distortion has been proposed in references [6]–[9].

Recently, as a new compensation method, Neural Network Equalizer (NNE) has been proposed to compensate for nonlinear distortion [10]–[14]. Unfortunately, as previously reported, the applicability of Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK) and M-ary Phase Shift Keying (M-ary PSK) is investigated supposedly as the modulation method, furthermore, the study for the influence of linear distortion, generated in a multipath channel, has not been started. As a system employing multilevel QAM such as 16QAM and 64QAM, a method, which the neural network is applied to pre-distorter, is reported [15]. However, there is no study on NNE which can handle multilevel QAM signal. Furthermore, no NNE which can compensate for both nonlinear and multipath distortions arising at FTTA system, has been reported.

Generally, the conventional NNE employs a sigmoidal function as an unit output function [12]. However, in FTTA system employing multilevel QAM, it can not effectively compensate for nonlinear distortion due to O/E and E/O, because nonlinear distortion due to O/E and E/O has similar characteristics of the sigmoidal function. Furthermore, the NNE which employs back propagation (BP) algorithm for the training is often trapped into a local minimum, depending on the initial values of the weights, and does not converge to the optimum points. When a neural network is trapped into a local minimum, it does not perform well. Therefore, a new unit function and effective initial weights are needed to improve a compensation performance for nonlinear distortion in multilevel QAM signal.

In this paper, we propose a new NNE, which can compensate for nonlinear and multipath distortions of FTTA system employing multilevel QAM. The proposed NNE is composed of a multilayer neural network with BP algorithm, and feedforward and decision feedback tapped delay lines. The output signals of the feedforward and the feedback delay lines are applied to the neural network and compensation is performed.

In order to improve the compensation performance, the proposed NNE employs a cubic function as an new unit output function of neural network. And in order to prevent from trapping into a local minimum, we also propose a new initial weights decision method for NNE.

We analyze the compensation performance of the proposed NNE using computer simulation and show that the proposed NNE is an effective compensation technique for nonlinear and multipath distortions in FTTA system.

The paper is followed by three other sections. Section 2 explains the system model that is applied as a simulation. Section 3 explains the structure of NNE and the adaptive algorithm. The last section describes the result of the simulation.

2. System Model

Figure 1 shows FTTA system model considered in this paper.

The transmission data in multilevel QAM format is filtered in square-root roll-off filter, and sent to each base station through optical fiber where the signal is affected by nonlinear distortion due to E/O and O/E converters. Then the signal is transmitted to the

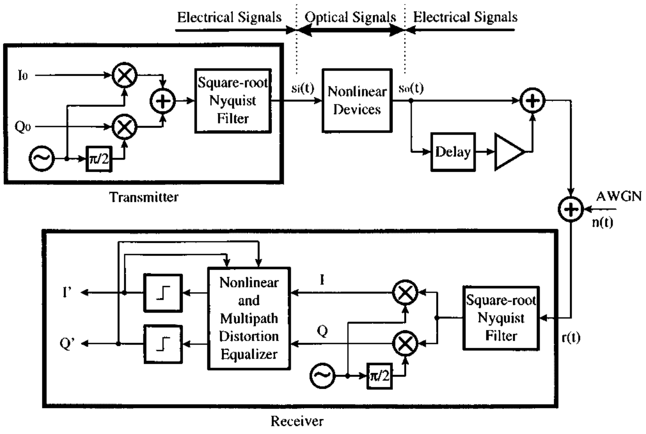

Fig. 1 System model.

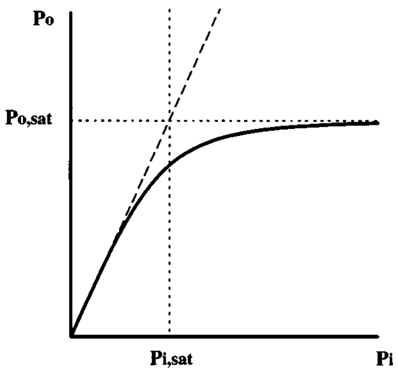

Fig. 2 Saturation of the average output power caused by nonlinear device.

mobile radio terminals through a multipath channel. At the mobile terminal, the received signal, which is distorted by multipath and additive Gaussian noise, is applied to the equalizer after it is filtered in the square-root roll-off filter. The equalizer compensates for nonlinear and linear distortion due to the E/O, O/E and multipath channel, and the received data is finally obtained through the QAM decision element.

Let us suppose that the AM/AM conversion characteristics of the nonlinear device is modeled as

$$A_o = \frac{A_i}{(1+A_i^{2p})^{1/2p}}, \tag{1}$$

where A_i and A_o are the amplitude of the input and output of the nonlinear device, respectively. A parameter $p>0$ shows the smoothness of the transmitter from the linear region to the limited region. Assume that the nonlinear device has no AM/PM conversion. An example of the AM/AM characteristics is shown in Fig. 2.

The operating point of the amplifier is expressed as the back-off. The input back-off (IBO) and the output back-off (OBO) are defined as:

$$IBO = 10\log_{10}\frac{P_{i,sat}}{P_i} \qquad (2)$$

and

$$OBO = 10\log_{10}\frac{P_{o,sat}}{P_o}, \qquad (3)$$

where P_i and P_o show the average power at the input and output of the nonlinear device, respectively. $P_{o,sat}$ is the saturation output power and $P_{i,sat}$ is the input power corresponding to the saturation point shown in Fig. 2.

The radio propagation channel is modeled as a 2-ray multipath channel, where the received signal has a desired signal and a delayed signal components. The received signal is given by

$$r(t) = s_o(t) + a s_o(t-\tau)e^{j\theta} + n(t), \qquad (4)$$

where $r(t)$ is the received signal, $s_o(t)$ is the output signal at the nonlinear device in the equivalent low-pass expression, and $n(t)$ is the complex Gaussian noise component. Also, a, θ, and τ is the path loss, phase, and delay time of the delayed signal as relative to the desired signal.

3. A New Neural Network Equalizer

The Neural Network is composed of 'unit' and 'link.' The unit is equivalent of neuron in biological nerve system, while the link corresponds to synapse. Several types of neural networks such as multilayer feedforward neural network, and recurrent neural network are proposed as an equalizer in [11], [12]. Particularly, since multilayer feedforward neural network has a powerful and simple learning algorithm called back propagation (BP) algorithm, it has been applied to the field of character recognition and audio voice recognition. In this section, we propose a new NNE based on multilayer feedforward neural network in order to compensate for both multipath and nonlinear distortions.

The structure of the proposed NNE is shown in Fig. 3. This NNE is composed of the feed forward (FF) tapped delay line, the decision feedback (DF) tapped delay line, and the multilayer feedforward neural network. The in-phase (I) and the quadrature (Q) components of the received signal are fed into FF. The output of the FF and DF are applied to the multilayer feedforward neural network, which has 3 layers, namely, input layer, hidden layer and output layer. The output of the neural network (NN) is applied to the decision element, and the output I′ and Q′ are then fed into DF. The weights of the links are given by BP algorithm.

The operation of each unit in the NNE is shown in Fig. 4. The input signals to each unit are the output signals from the other units, combined by links. As for

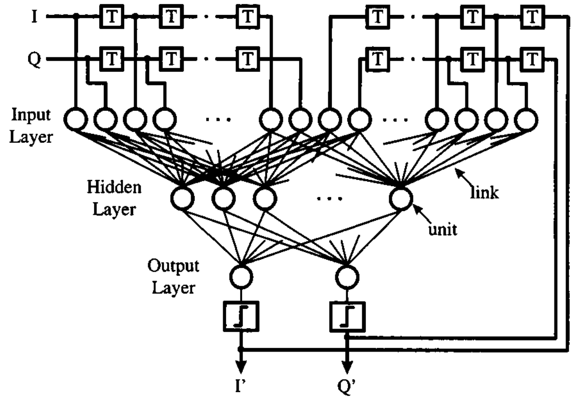

Fig. 3 Multilayer feedforward neural network equalizer.

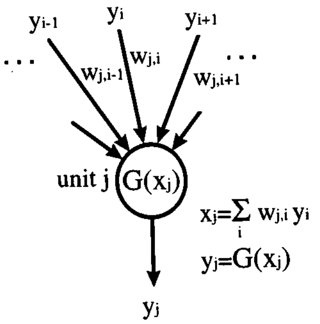

Fig. 4 Unit model.

multilayer feedforward neural network, the signals, which are input to the units in hidden layer, are the output signals of input layer units. Also, the signals, which are input to the units in output layer, are the output signals of hidden layer units. As shown in Fig. 4, y_i shows the output signal of unit i, $w_{j,i}$ shows weight of a link from unit i to unit j and y_j shows the output signal of unit j. $G(x)$ is an output function of a unit and generally has the nonlinear characteristics. y_j is given by

$$y_j = G\left(\sum_i w_{j,i} y_i\right). \qquad (5)$$

Since $G(x)$ is a nonlinear function, it can be seen that the I/O of a unit shown in Eq. (5) has nonlinear characteristics. In neural network, the desired nonlinear characteristics can be realized by the nonlinear characteristics of a unit and the weight of a link, combining with a unit. In the proposed NNE, two output layer units corresponding to the in-phase and quadrature phase components are appeared. Suppose the output function of units in input layer and output layer employs the linear function, namely, $G(x) = x$.

The weights must be updated to be adaptive to compensate the distortion so that the error between the input and output of decision element can be minimized. BP algorithm is employed to choose the weights. In BP algorithm, the error evaluation function E given by

$$E=\frac{1}{2}\sum_{j}|d_j-z_j|^2 \quad (6)$$

is minimized by steepest descent method. In Eq. (6), z_j is the output of neural network, in other words, it is the output signal of an output layer unit; and d_j is a teacher signal, or the output of the decision element. The update formula of the weight by BP algorithm becomes

$$w_{j,i}(n+1)=w_{j,i}(n)+\eta\delta_j(n)y_i(n). \quad (7)$$

where η, which is a small and positive constant, is the updating coefficient. Also, $w_{j,i}(n)$ is the weight from unit i to unit j, and $y_i(n)$ is the output signal of unit i. $\delta_j(n)$ is the error signal that is generated in unit j. The error signal is giving by

$$\delta_j(n)=\begin{cases}(d_j(n)-y_j(n))\,G'\Big(\sum_j w_{j,i}(n)\,y_i(n)\Big), & \\ \quad\text{unit j belongs to the Output Layer} & \\ G'\Big(\sum_i w_{j,i}(n)\,y_i(n)\Big)\sum_k \delta_k(n)\,w_{k,j}(n), & \\ \quad\text{otherwise.} & \end{cases} \quad (8)$$

where $d_j(n)$ is a teacher signal and $G'(x)$ is the derivative for x in the output function $G(x)$. The known training signal is used as a teacher signal while the NNE is in acquisition and the output of the decision element is used as a teacher signal for tracking.

The conventional neural network, sigmoidal function defined as

$$G(x)=\frac{1-e^{-x}}{1+e^{-x}} \quad (9)$$

is used as an output function. For employing the BP algorithm, it is required that the output function has a derivative, because the BP algorithm has to evaluate Eqs. (7) and (8). Although Eq. (9) has a deriative, the sigmoidal function could not be suitable for the compensation of the nonlinear distortion characterized by Eq. (1), because the functions (1) and (9) have similar characteristics. To solve this problem, the proposed NNE employs a new output function whose characteristics is similar to the inverse function of Eq. (1). The following cubic function given by

$$G(x)=x^3+x \quad (10)$$

is supposed as the output function of the proposed NNE.

The stability of the network with a cubic function becomes lower than that with a sigmoidal function, because $G(x)$ becomes infinity with x increases. Since Eq. (10) still has a deriative, the BP algorithm can be applied to the proposed NNE with the cubic function.

The details of the simulation result are shown in the next section. As specified in the next section, we verify the compensation performance of the proposed NNE in compared with the conventional DFE and the conventional NNE, employing sigmoidal function.

4. Result

We show computer simulation results of the proposed NNE in this section. Tables 1 and 2 show the system parameters to demonstrate the performance. We investigate the three equalizers; the conventional DFE, the conventional NNE, employing the sigmoidal function, and the proposed NNE using the cubic function. First of all, in order to get the initial weights, we train the NNE at two environments. At the first case, the NNE is trained in a noiseless channel without multipath and nonlinear distortion. And at the other case, the NNE is trained in a noiseless channel without multipath but with nonlinear distortion. We call the first one Type A and the later one Type B, respectively. We use about 30,000 symbols to get the initial weights. The NNE is then operated at the usual environment. At the training, we use a known training sequence of 30,000 symbols, corresponding to 6 ms, and then measure the symbol error rate.

The symbol error rate performance against E_b/N_0 in 16QAM case is shown in Fig. 5. The input back-off corresponds to IBO $=-0.87$ dB and the delayed phase of delayed signal corresponds to 0 degree. As Fig. 5 shows, the conventional DFE and NNE compensate the distortion to a certain extent, compared with one before equalization; nevertheless, the proposed NNE (B) shows the best characteristics

Table 1 System parameters.

Modulation		16QAM/64QAM	
Channel Width		6MHz	
Bit Rate		20Mbps/30Mbps	
Nyquist Filter		Root Rolloff Filter (α*=0.15)	
Nonlinear	Smoothing Factor (p)	3.0	
	Input Back-off (IBO)	-0.87dB/1.84dB	
Equalizer	conventional DFE	FIR	3 taps (I,Q respectively)
		IIR	5 taps (I,Q respectively)
	conventional NNE	Input Layer	16 units **
		Hidden Layer	14 units
		Output Layer	2 units
	proposed NNE	Input Layer	16 units **
		Hidden Layer	14 units
		Output Layer	2 units

* α : Roll-off Factor
** correspond to 3 taps FIR and 5 taps IIR (I,Q respectively)

Table 2 Initial weights of conventional/proposed NNEs.

NNE(A)	Initial weights of NNE are trained by using non-distorted signals.
NNE(B)	Initial weights of NNE are trained by using nonlinear distorted signals.

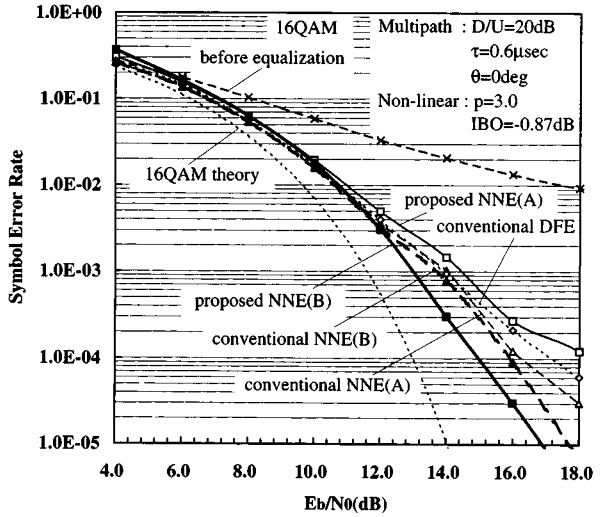

Fig. 5 Comparison of symbol error rates achieved by conventional DFE, conventional NNE and proposed NNE. (Initial weights of NNE are trained by non-distorted signals(A)/nonlinear distorted signals(B), 16QAM)

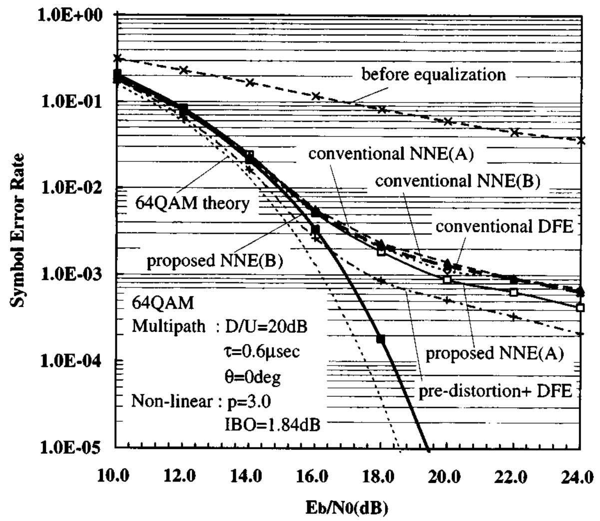

Fig. 6 Comparison of symbol error rates achieved by conventional DFE, pre-distortion+DFE, conventional NNE and proposed NNE. (Initial weights of NNE are trained by non-distorted signals(A)/nonlinear distorted signals(B), 64QAM)

among the three equalizers.

The symbol error rate performance in 64QAM case is shown in Fig. 6. In Fig. 6, the proposed NNE (B) can improve the performance in compared with other equalizers. A difference of performance in 64QAM is more notable than that of 16QAM. Especially, it is noted that the pre-distortion method (pre-distortion+DFE) is less effective than the proposed NNE(B) at the range $E_b/N_0 > 18$ dB. This result verifies the applicability of this equalizer to multiple level digital modulation. Furthermore, the proposed NNE(B) gives 4 dB better performance than the proposed NNE (A) at the symbol error rate of

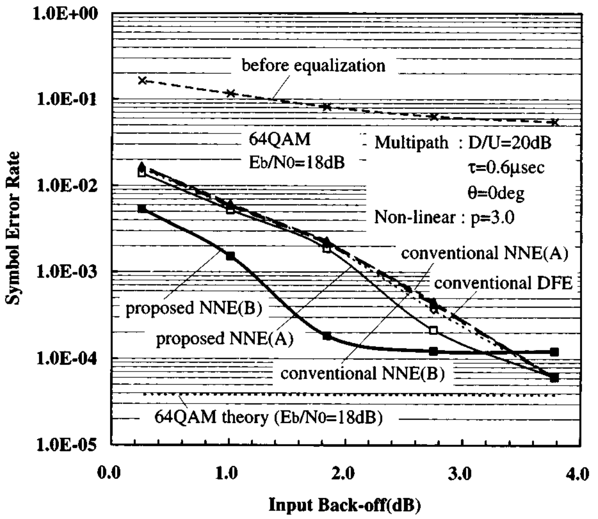

Fig. 7 Comparison of performance dependence on IBO achieved by conventional DFE, conventional NNE and proposed NNE. (Initial weights of NNE are trained by non-distorted signals (A)/nonlinear distorted signals (B), 64QAM)

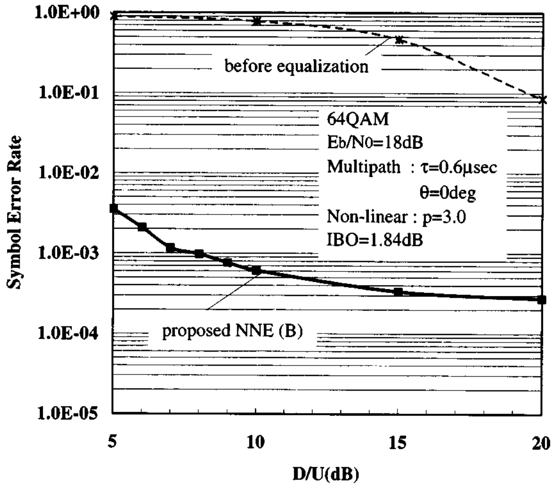

Fig. 8 SER performance against D/U. (Initial weights of NNE are trained by nonlinear distorted signals (B), 64QAM)

1.0e-3. This result leads that an arrangement of the initial values of the weights can further improve the performance.

The compensation performance against the input back-off is shown in Fig. 7. In the simulation, we choose the initial weights as those of the NNE trained at IBO= 1.84 dB. As shown in Fig. 7, the proposed NNE(B) gives the best compensation performance among three equalizers in a wide range, IBO is equal to near 0 dB to 3.0 dB. This results shows the proposed NNE (B) is not sensitive to the back-off. In order to mitigate the degradation due to nonlinear distortion, the O/E and E/O should be operated at the large back off region. However, the large back off implies the decrease in C/N at the optical link. Therefore, for FTTA system, we should operate the O/E and E/O at the smaller input back off. Accordingly, the superiority of the proposed NNE (B) to the others in the range of IBO=0 dB to 3.0 dB is significant.

Another measurement for D/U, delay time (τ) and delayed phase (θ) of delayed signal is performed to verify an influence on the compensation performance of the proposed NNE(B) in 64QAM. Figure 8 shows the symbol error rate performance against D/U, where τ=0.6 μsec, θ=0 deg, IBO=1.84 dB and E_b/N_0 =18 dB. In a wide range of D/U, the proposed NNE (B) can compensate nonlinear distortion and multipath distortion well.

The symbol error rate performance against the time delay is shown in Fig. 9, where θ=0 deg, IBO= 1.84 dB and E_b/N_0=18 dB. In this measurement, we investigate two cases. One is a case of D/U=10 dB, and the other is a case of D/U=20 dB. In both the cases, the proposed NNE(B) is performed well in the range of τ=0 μsec to 1.0 μsec, and, especially at the case of D/U=20 dB, its performance is not sensitive to the time delay of delayed signal.

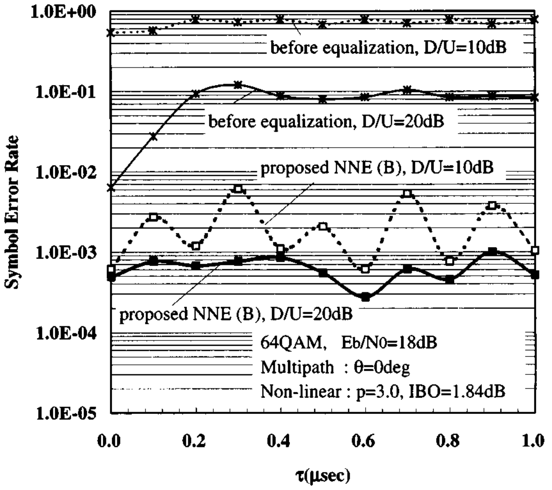

Fig. 9 SER performance against the delay time of multipath signals. (Initial weights of NNE are trained by nonlinear distorted signals (B), 64QAM)

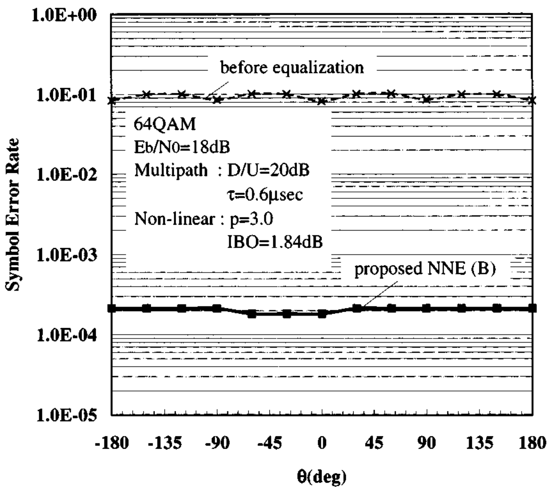

Fig. 10 SER performance against the phase of multipath signals. (Initial weights of NNE are trained by nonlinear distorted signals (B), 64QAM)

The symbol error rate for the delayed phase of delayed signal is shown in Fig. 10, where D/U=20 dB, τ=0.6 μsec, IBO= 1.84 dB and E_b/N_0=18 dB. As shown in Fig. 10, the phase of delayed signal affects no influence in the compensation performance of the proposed NNE(B).

5. Conclusion

In this paper, we have proposed a new NNE as a compensation method for nonlinear and multipath distortion due to FTTA system, and investigated the symbol error rate performance of the proposed equalizer. This simulation result indicates that this new NNE put a cubic function as the unit output function and achieves the effective compensation for nonlinear/linear distortion of multilevel QAM signal by arranging the initial values of the weights. Particularly, as for 64QAM, the proposed NNE verifies a remarkable superiority of compensation performance by the simulation. This superiority is more than any other equalizers such as the conventional DFE, and the conventional NNE, employing sigmoidal function as the unit output function.

In this paper, the performance of the proposed NNE is investigated only in the limited cases. To verify the compensation performance of the proposed NNE in the mobile computing environment, further investigation including the multipath fading environment should be required. Also, it is necessary to investigate the effect of the intermodulation distortion among the adjacent channels.

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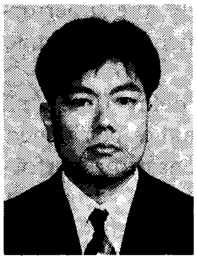

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