MIMO EQUALIZATION AND CANCELLATION FOR 10GBASE-T[1]

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ABSTRACT

Traditionally equalization is performed individually for 10GBASE-T, and FEXT is treated as noise to be cancelled at the receiver. However, FEXT contains information about the symbols transmitted from remote transmitters and it can be viewed as a signal rather than noise to facilitate signal recovery. This paper proposes to use MIMO (multi-input multi output) equalization technique to deal with FEXT in 10GBASE-T. In the proposed MIMO technique, FEXT is treated as signal, which improves SNR. Instead of using long FEXT cancellers, MIMO-DFE with short length is used to remove post-cursor ISI. Our simulation results show that, by using the proposed MIMO equalization, we are able to achieve SNR (signal to noise ratio) improvement around 0.5~9dB with 13% less complexity than the traditional equalization technique in twisted-pair channel environment.

1. INTRODUCTION

The need for high data rates in LAN applications has prompted the developments of fast Ethernet standards (such as 10 Mbps and 100 Mbps) in mid 1990s, and the Gigabit Ethernet standard in 1998. More recently, the IEEE 802.3-ae standards subcommittee completed the 10 Gigabit Ethernet standard for fiber transmission (10GE Fiber). Due to the abundance and low cost of unshielded twisted pair (UTP) cables, there is great interest in developing 10 Gigabit Ethernet over copper medium (10GBASE-T) [2]. It will serve as a follow-up to the Gigabit Ethernet over copper medium (1000BASE-T) [3].

Like 1000BASE-T, 10GBASE-T performs full duplex baseband transmission over four pairs of UTP. A target 10 Gbps throughput is achieved by using eight transceivers (four at each end) to realize 2.5 Gbps data rate over each wire pair, and the full duplex data transmission on the same wire is made possible by hybrid circuits, as shown in Fig. 1. We see that, the received signal not only suffers from signal attenuation and ISI but also suffers from echo, near-end cross talk (NEXT), far-end cross talk (FEXT), and other noises such as alien NEXT (ANEXT). To meet the desired throughput and target BER (10^{-12}) requirements, the receiver has to perform a significant amount of digital adaptive filtering operations. The traditional schemes presented for 10GBASE-T in [1],[3]-[5] use four separate Feed-Forward equalizers (FFE) to individually remove pre-cursor ISI for each channel and treat FEXT crosstalk as noise to be cancelled after the FFE. To reduce the FEXT interference to a satisfactory level, three FEXT cancellers are needed for each pair of cables. Since there are four pairs of cables (four channels) in 10GBASE-T, a total of 12 FEXT cancellers are needed at the receiver side, and each of them will have 200 taps [1]. Implementing these FEXT cancellers will occupy extra silicon area and power consumption.

However, we note that, for each receiver, FEXT crosstalk inherently contains information about the symbols transmitted from the other 3 remote transmitters. In other words, each far end signal is transmitted by 4 channels, three

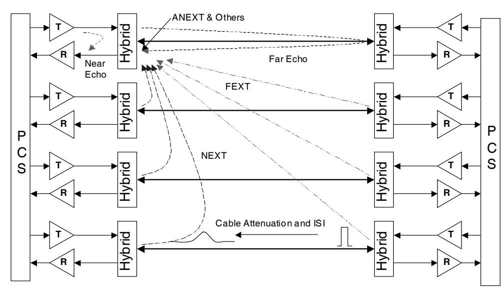

Fig. 1. 10 Gigabit Ethernet over UTP

of which are FEXT channels. Hence, it is better to exploit the far end crosstalk than simply treat it as background noise. In this paper, we treat FEXT crosstalk as signal and use MIMO equalization technique to make use of the FEXT signal. In the proposed MIMO technique, we do not need 12 FEXT cancellers at all. Instead, a MIMO-DFE architecture containing a 4×4 MIMO Feed Forward Equalizer and a 4×4 MIMO-Feedback Equalizer is used. This architecture

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has less complexity than the traditional scheme and higher SNR gain at the decision point as shown in our simulations.

The remainder of this paper is organized as follows. In section 2, a novel MIMO equalization scheme is presented and two different arrangements of Echo & NEXT cancellers are considered. Section 3 presents the simulation results in terms of SNR at the decision point for traditional SISO equalization and the proposed MIMO equalization under different channel conditions.

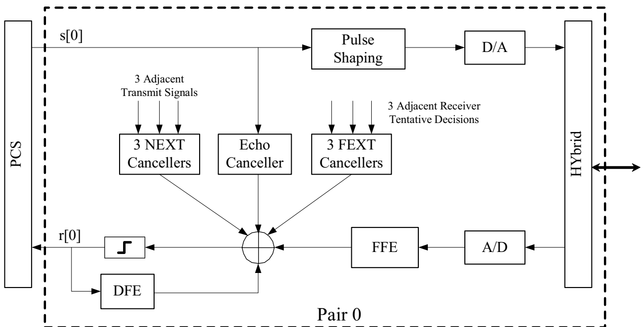

Fig. 2. Traditional 10GBASE-T transceiver block diagram

2. MIMO-DFE EQUALIZATION IN 10GBASE-T

FEXT crosstalk is typically cancelled as noise to improve SNR at the slicer. Since the tail of the FEXT crosstalk is very small, even long FEXT cancellers may not be helpful to improve SNR at the expense of high complexity. In this section, MIMO equalization technique is proposed to deal with the problem. First we model the 4 pair UTP shown in Fig. 1 as two 4 by 4 MIMO channels. Then two different structures are proposed for the MIMO equalization.

2.1. Channel Model

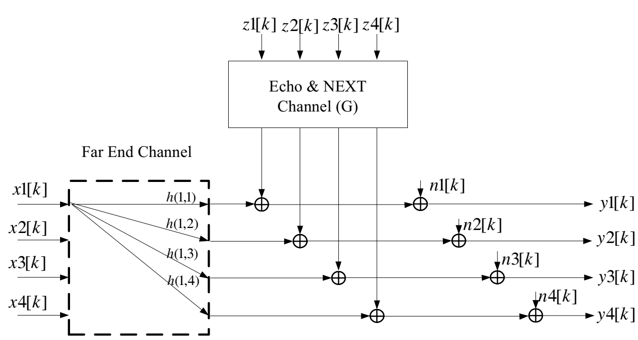

Fig. 3. Block diagram of MIMO Channel

10 Gigabit Ethernet Transmission over UTP shown in Fig.1 can be modeled as two 4×4 MIMO channels as shown in Fig. 3. These two MIMO channels can be described using a matrix $(h_{i,j})_{i=1..4,j=1..4}$ and a matrix $(g_{m,n})_{m=1..4,n=1..4}$ of time discrete impulse responses, where $h_{i,j}$ denotes the channel impulse response from the ith input to the jth output with length $v+1$. Similarly $g_{m,n}$ is the Echo & NEXT channel impulse response from the mth input to the nth output with length $l+1$. Let x_i denotes the transmitted symbol sequence from the ith far end transmitter and z_m denote the transmitted symbol sequence from the mth near end transmitter, and n_j denote background noise at the jth channel output. Then the jth channel received symbol sequence is given by

$$y_j = h_{j,j}\otimes x_j + \sum_{\substack{i=1\\ i\neq j}}^{4} h_{i,j}\otimes x_i + g_{j,j}\otimes z_j + \sum_{\substack{m=1\\ m\neq j}}^{4} g_{m,j}\otimes z_m + n_j \quad (1)$$

for $j=1,..,4$. Where $\otimes$ denotes convolution.

By grouping symbols from 4 received channel at time k into a column vector $\mathbf{y}^T(k)=[y_1(k)\quad y_2(k)\quad y_3(k)\quad y_4(k)]$, (1) can be expressed as follows:

$$\mathbf{y}(k) = \sum_{m=0}^{v} H(m)\mathbf{x}(k-m) + \sum_{p=0}^{l} G(p)\mathbf{z}(k-p) + \mathbf{n}(k) \qquad (2)$$

where $H(m)$ and $G(p)$ represent 4×4 mth far end channel coefficient matrix and pth near end channel coefficient matrix respectively. The signals $\mathbf{x}(k-m)$ and $\mathbf{z}(k-m)$ correspond to far end transmitted column vector and near end transmitted column vector at time index $k-m$. By stacking N_f successive output vector samples, (2) can be expressed in matrix form as follows:

$$\mathbf{y}(k+N_f-1:k) = \mathbf{H}\cdot\mathbf{x}(k+N_f-1:k-v) + \mathbf{n}(k+N_f-1:k) + \mathbf{G}\cdot\mathbf{z}(k+N_f-1:k-l) \qquad (3)$$

where $N_f\times(N_f+v)$ matrix $\mathbf{H}$ and $N_f\times(N_f+l)$ matrix $\mathbf{G}$ are both block Toeplitz matrices which are defined as:

$$\begin{bmatrix} H_0 & H_1 & \cdots & \cdots & H_v & 0 & \cdots & 0 \\ 0 & H_0 & & & & \ddots & & 0 \\ \vdots & & \ddots & & & & \ddots & \\ 0 & & & H_0 & H_1 & \cdots & \cdots & H_v \end{bmatrix}, \begin{bmatrix} G_0 & G_1 & \cdots & \cdots & G_l & 0 & \cdots & 0 \\ 0 & G_0 & & & & \ddots & & 0 \\ \vdots & & \ddots & & & & \ddots & \\ 0 & & & G_0 & G_1 & \cdots & \cdots & G_l \end{bmatrix}. \quad (4)$$

2.2. Joint MIMO-DFE Equalization and Cancellation

Fig. 4 shows the block diagram of the proposed joint MIMO DFE scheme. MIMO FFE is first used to remove pre-cursor ISI and exploit far end signal transmitted from FEXT channels. After FFE, Echo & NEXT interferences are easily cancelled since near end transmitted signal is usually known to the receiver at the same end. Instead of using FEXT cancellers, a MIMO DFE is used with 16 short length FIRs.

Let N_f, N_b, v_c+1 be the lengths of the feed forward filter matrix $\mathbf{W}$, feedback filter matrix $\mathbf{B}$, and Echo &

NEXT cancellers $\mathbf{C}$ respectively. Then the error vector at time k of the four channels can be represented by

$$\mathbf{e}(k) = \mathbf{W}^H \mathbf{y}(k+N_f-1:k) - \tilde{\mathbf{B}}^H \mathbf{x}(k+N_f-1:k-v) - \tilde{\mathbf{C}}^H \mathbf{z}(k+N_f-1:k-l), \quad (5)$$

where, $(.)^H$ denotes the conjugate transpose operation

$$\mathbf{W}^H = [W_0^H \cdots W_{N_f-1}^H], \; W_i = \begin{bmatrix} w_i^{(1,1)} & w_i^{(1,2)} & w_i^{(1,3)} & w_i^{(1,4)} \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ w_i^{(4,1)} & \cdots & \cdots & w_i^{(4,4)} \end{bmatrix}.$$

$$\tilde{\mathbf{B}}^H = [\mathbf{0}_{1\times\Delta_b} \quad B_0^H \quad B_1^H \quad \cdots \quad B_{N_b}^H \quad \mathbf{0}_{1\times s1}] = [\mathbf{0}_{1\times\Delta_b} \; \mathbf{B}^H \; \mathbf{0}_{1\times s1}]$$

$$\tilde{\mathbf{C}}^H = [\mathbf{0}_{1\times\Delta_c} \quad C_0^H \quad C_1^H \quad \cdots \quad C_{v_c}^H \quad \mathbf{0}_{1\times s2}] = [\mathbf{0}_{1\times\Delta_c} \; \mathbf{C}^H \; \mathbf{0}_{1\times s2}]$$

with B_i, C_i are 4×4 blocks similar with W_i, and $\mathbf{0}$ is 4×4 zero matrix. We also define $s1 = N_f + v - N_b - 1 - \Delta_b$ and $s2 = N_f + l - v_c - 1 - \Delta_c$ with Δ_b and Δ_c are the decision delays.

The MMSE solution is given by [9]

$$\begin{bmatrix} \mathbf{B}_{opt} \\ \mathbf{C}_{opt} \end{bmatrix} = \mathbf{R}^{-1}\mathbf{\Phi}(\mathbf{\Phi}^H \mathbf{R}^{-1}\mathbf{\Phi})^{-1} \quad (6)$$

where, $\mathbf{R} = \begin{bmatrix} R_{xx} - R_{xy}R_{yy}^{-1}R_{yx} & -R_{xy}R_{yy}^{-1}R_{yx} \\ -R_{zy}R_{yy}^{-1}R_{yz} & R_{zz} - R_{zy}R_{yy}^{-1}R_{yz} \end{bmatrix}$

$\mathbf{\Phi}$ is a constant matrix.

$$\mathbf{W}_{opt}^H = [\tilde{\mathbf{B}}_{opt}^H \quad \tilde{\mathbf{C}}_{opt}^H] \begin{bmatrix} R_{xy} \\ R_{zy} \end{bmatrix} R_{yy}^{-1} \quad (7)$$

$$R_{\mathbf{ee},\min} = E[\mathbf{e}(k)\mathbf{e}^H(k)] = [\tilde{\mathbf{B}}_{opt}^H \quad \tilde{\mathbf{C}}_{opt}^H] \cdot \mathbf{R} \cdot \begin{bmatrix} \tilde{\mathbf{B}}_{opt} \\ \tilde{\mathbf{C}}_{opt} \end{bmatrix} \quad (8)$$

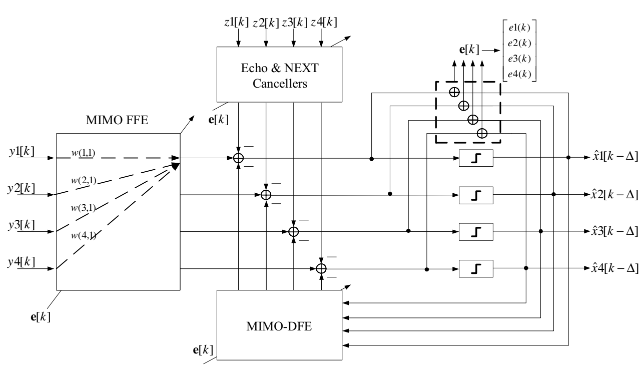

Fig. 4. Joint Cancellers and MIMO-DFE adapted structure

2.3. Separate MIMO-DFE Equalization & Cancellation

In Fig. 4, the cancellers and MIMO-DFE are jointly adapted to seek the minimal $E(\mathbf{e}^2)$, where Echo & NEXT cancellers are performed after FFE. One problem associated with this structure is that the FFE filtering will affect Echo & NEXT channel characteristics, *i.e.*, channel length or amplitude, especially when FFE filters are very long, which will result in long Echo & NEXT cancellers. To solve this problem, consider the structure in Fig. 5, where Echo & NEXT cancellers are implemented before FFE. In this arrangement, cancellers and the MIMO-DFE are independently adapted to minimize $E(\varepsilon^2)$ and $E(\mathbf{e}^2)$. However, for given Echo & NEXT cancellers, the optimal Echo & NEXT cancellers in the sense of minimizing $E(\varepsilon^2)$ may not be the one that also minimizes $E(\mathbf{e}^2)$. In other words, increasing the length of the Echo & NEXT cancellers in this case does not necessarily reduce $E(\mathbf{e}^2)$ as we want. Therefore, we are interested in comparing these two structures in 10GBASE-T. In our simulation study, we found that separate minimization structure has 0.05~0.2dB gain over jointly adapted structure with same canceller length in different channel models. It can be stated that in UTP channel, with the same Echo & NEXT complexity, the jointly adapted structure is not necessarily superior to the separately adapted structure.

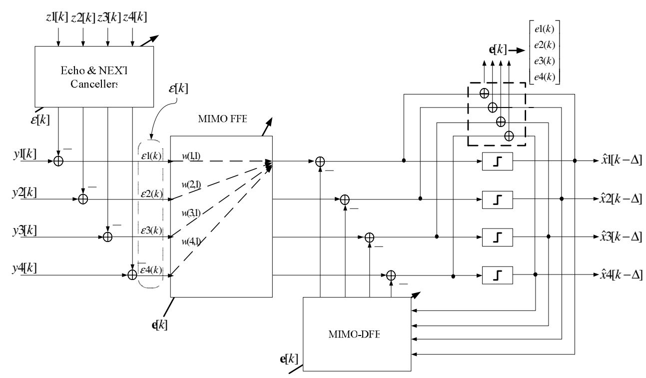

Fig. 5. Canceller separately adapted structure

3. SIMULATION RESULTS

In this section, we apply the proposed approaches to different CAT6 UTP channels with 100m and 55m. All these channel models can be obtained from IEEE 802.3an 10GBASE-T Study Group [1].

In order to give a fair comparison, parameters for traditional receiver scheme and proposed MIMO equalization scheme are set up as shown in Table I.

Table II compares the performance of the traditional scheme and the proposed MIMO equalization. We see the proposed MIMO equalization technique has 0.5~3dB SNR gain over traditional scheme with less complexity for different channel modes. Especially for short cable, by using the proposed scheme, we can have 9dB gain over the traditional approach. This is because the FEXT channel attenuation is proportional to the cable length. FEXT signals in short cables will be stronger than that in long cables. In this sense, MIMO technology will get more benefit from the FEXT signal.

Table I. Parameter Set Up

	Traditional Scheme (SISO)	Proposed Scheme (MIMO)
FFE taps	64	64
DFE taps	32	32
FEXT taps	200	32
Echo taps	500	500
NEXT taps	400	400
Total taps	2396×4 = 9584	2084×4 = 8336
Modulation	PAM-16	
AWGN	-150dBm	
TX Power	5dBm	

Table II. Decision Point SNR for Different Schemes

CAT6 (UTP)	Traditional (SISO)	Proposed (MIMO-DFE)	
		Joint	Separate
100m*	20.9 dB	23.8 dB	24.1 dB
55m*	23.1 dB	32.3 dB	32.3 dB
100m**	28.3 dB	28.8 dB	29.0 dB

* channel mode is scaled to worst case
** channel mode is the actual measure data

We also find that separate adapted structure has 0.05~0.3dB gain over jointly adapted structure with same canceller complexity in different channel models. It can be stated that in UTP channel, with the same Echo & NEXT complexity, the jointly adapted structure is not necessarily superior to the separately adapted structure.

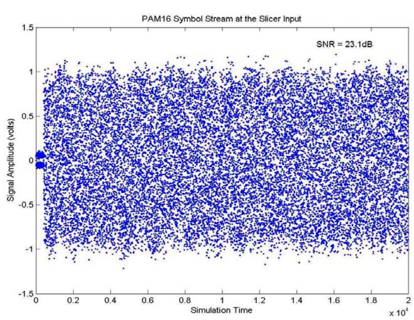

Fig. 6. Discrete time Eye diagram (Traditional SISO)

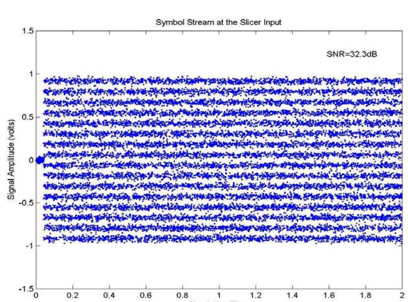

Fig. 7. Discrete time Eye diagram (Proposed Scheme)

Fig. 6 and Fig. 7 show the comparison by the discrete eye diagrams (a plot of the soft symbol decisions before the slicer) corresponding to 55m CAT6 cable in table II.

4. CONCLUSION

We have presented to use MIMO technique to deal with FEXT as signal rather than background noise in 10GBASE-T transceiver design. It is shown that, with same Echo & NEXT complexity, the jointly adapted structure is not necessarily superior to the separately adapted structure in the MMSE sense. Simulation results show that by using the proposed MIMO equalization, we are able to achieve SNR (signal to noise ratio) improvement around 0.5~9dB over the traditional equalization technique in twisted-pair channel environment while using 13% less computation complexity. The increased SNR can be used to reduce the complexity of echo and NEXT cancellers, resulting in a low complexity and low power design.

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