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Non-Crosstalk Scheme Based on Linear Combination Transformation in High-Speed Interconnects

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Abstract—Aiming at the problem of crosstalk in high-speed interconnects, a non-crosstalk scheme based on coupled transmission lines-channel transmission matrix (CTL-CTM) is proposed. In this scheme, the transmitted signals are linear combination transformed at the transmitting end of the interconnect lines where the transmission signals among the interconnect lines constitute an orthogonal mode. After the signals have synchronously transmitted to the receiving end, second linear combination transformation is performed to restore the transmitted signals. Simulation results show that this low cost circuit proposed is capable of improving the quality of eye diagram and eliminating the crosstalk obviously.

1. INTRODUCTION

With the increase in the density and rate of integrated circuit and printed circuit board (PCB), the crosstalk caused by interconnect lines has become more prominent, which has seriously restricted the development of high-speed circuits. Crosstalk is one of the four types of signal integrity problems, which badly affects the transmission performance of signals in multiple channels in high-speed interconnects [1–3].

The physical reason of crosstalk is the mutual capacitance and inductance between the attack line and the victim line. When the transmission line operates at a higher frequency (The digital signal rate is high), the rise and fall time of the signal is small. Hence severe crosstalk is generated because of the instantaneous voltage conversion, and the closer the distance between the two transmission lines is in the wiring space, the greater the mutual inductance and capacitance will be produced, in which more serious crosstalk will be caused. Crosstalk constrains high-speed signal interconnection and becomes a bottleneck problem. Many measures have been taken into account for suppressing crosstalk on the victim line, such as reducing crosstalk by suppressing electromagnetic coupling between transmission lines [4–9], but such methods have limited effectiveness and narrower application range. In addition, crosstalk is reduced from the perspective of signal transmission [10–13], which has better crosstalk cancelation effect but more complicated circuit implementation. The common purpose of two methods is to reduce the impact of crosstalk on the entire interconnect system, namely to eliminate interference from crosstalk to useful signals. Based on these, [14], constructing inverse matrix with the mathematical point to eliminate interference from crosstalk to normal signal, studied the establishment of a coupled transmission lines-channel transmission matrix on the interconnection system, in which crosstalk cancelation method that is simpler in circuit and better in effect for two coupled microstrip lines has been given. However, in the CTL-CTM established by this method, the attenuation caused by the crosstalk coupling to the local signal is not considered because the transfer function is approximated. Actually, the signal itself will cause decay since a portion of the signal energy is coupled to the adjacent lines. In order

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to overcome the inaccurate construction of diagonal elements in CTL-CTM, this paper constructs an accurate CTL-CTM matrix with considering the microstrip line transfer function and far-end crosstalk transfer function as a whole. Motivated by these, an interconnection scheme for linearly combining signals at the transmitting end and the receiving end of the interconnect lines is proposed, which is capable of achieving high-speed interconnects with non-crosstalk, simpler circuit, and lower cost.

2. INTERCONNECTED MODEL BASED ON CTL

First, the proposed architecture is shown in Fig. 1. The signals on the lines are transmitted in the same direction. The two inputs x_1, x_2 are transmitted, and $X_1(\omega), X_2(\omega)$ are corresponding to frequency domain; y_1, y_2 are received signal, and $Y_1(\omega), Y_2(\omega)$ are corresponding to frequency domain. According to the relationships between the transmission and crosstalk in the interconnect system, a transfer function can be used to describe the signal relationship among the ports. Assuming that $H(\omega)$ is the transfer function of the microstrip line and that $C(\omega)$ is a far-end crosstalk transfer function, the frequency domain relationships are defined as

$$\begin{aligned} Y_1(\omega) &= X_1(\omega)\, H(\omega) + X_2(\omega)\, C(\omega) \\ Y_2(\omega) &= X_1(\omega)\, C(\omega) + X_2(\omega)\, H(\omega) \end{aligned} \tag{1}$$

Rewrite Eq. (1) in the form of a matrix and a vector.

$$\begin{pmatrix} Y_1(\omega) \\ Y_2(\omega) \end{pmatrix} = \begin{pmatrix} H(\omega) & C(\omega) \\ C(\omega) & H(\omega) \end{pmatrix} \begin{pmatrix} X_1(\omega) \\ X_2(\omega) \end{pmatrix} \tag{2}$$

According to Eq. (2), the channel transmission matrix between two parallel coupled microstrip lines can be given by

$$\mathbf{H} = \begin{pmatrix} H(\omega) & C(\omega) \\ C(\omega) & H(\omega) \end{pmatrix} \tag{3}$$

Since the transfer function has the same physical meaning as the S-parameter in the interconnect lines, under the weak coupling and 3W rule (The distance from one center point to the other of the adjacent transmission lines is three times the line width), $H(\omega)$ and $C(\omega)$ are as shown in Eqs. (4) and (5) [15].

$$H(\omega) = S_{21} = S_{43} = \mathrm{e}^{\frac{-\mathrm{j}(\Delta\beta)l}{2}} \cos\left[\frac{(\Delta\beta)\, l}{2}\right] \tag{4}$$

$$C(\omega) = S_{41} = S_{23} = -\mathrm{j}\mathrm{e}^{\frac{-\mathrm{j}(\Delta\beta)l}{2}} \sin\left[\frac{(\Delta\beta)\, l}{2}\right] \tag{5}$$

where $\Delta\beta = \beta_\mathrm{e} - \beta_\mathrm{o}$; $\beta_\mathrm{e}, \beta_\mathrm{o}$ are respectively the even mode and odd mode propagation constants, and l is the coupled length.

Substituting Eqs. (4) and (5) into Eq. (3), the specific form of the channel transmission matrix can be written as

$$\mathbf{H} = \mathrm{e}^{\frac{-\mathrm{j}(\Delta\beta)l}{2}} \begin{pmatrix} \cos\left[\dfrac{(\Delta\beta)\, l}{2}\right] & -\mathrm{j}\sin\left[\dfrac{(\Delta\beta)\, l}{2}\right] \\ -\mathrm{j}\sin\left[\dfrac{(\Delta\beta)\, l}{2}\right] & \cos\left[\dfrac{(\Delta\beta)\, l}{2}\right] \end{pmatrix} \tag{6}$$

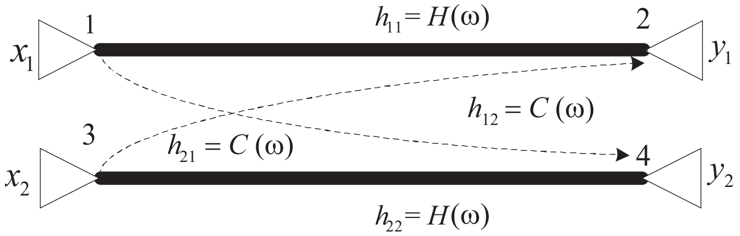


Figure 1. Channel model of two coupled microstrip lines.

3. INTERCONNECTION SCHEME OF NON-CROSSTALK

To obtain signal non-crosstalk transmission, a high-speed interconnect model without crosstalk is constructed as shown in Fig. 2. In Fig. 2, applying linear combination transformation to the signals respectively in the input and output ends of the transmission lines makes them form an orthogonal mode. After the signals are synchronously transmitted to the receiving end, the second linear combination transformation is performed, reconstructing a transmission signal. Two linear combination transformations based on the eigenvalue decomposition (EVD) form of CTL-CTM need to be constructed, and the specific process is as follows.

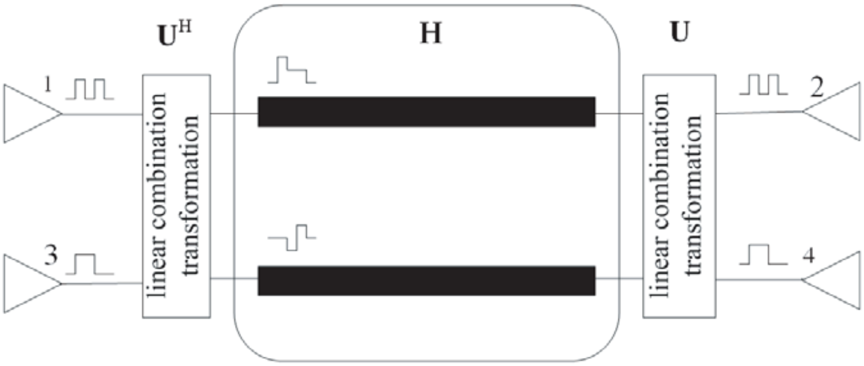


Figure 2. High-speed interconnects model of non-crosstalk.

H is a normal matrix by Eq. (6), whose EVD is decomposed as follows:

$$\mathbf{H} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^{-1} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^{\mathrm{H}} \tag{7}$$

The **Λ** matrix formed by the eigenvalues of **H** matrix is as shown in Eq. (8), and the **U** matrix composed of the eigenvectors of **Λ** matrix is as shown in Eq. (9).

$$\mathbf{\Lambda} = \begin{pmatrix} \mathrm{e}^{-\mathrm{j}(\Delta\beta)l} & 0 \\ 0 & 1 \end{pmatrix} \tag{8}$$

$$\mathbf{U} = \begin{pmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \end{pmatrix} \tag{9}$$

The linear combination transformation in Fig. 2 can be realized by Eq. (9) based on an orthogonal matrix of **U**. After transformation, the transmission signals on the two microstrip lines are as shown in Eq. (10) and are in orthogonal mode because the transmitted signals are random digital signals.

$$\begin{aligned} X_1'(\omega) &= \frac{\sqrt{2}}{2}\left[X_1(\omega) + X_2(\omega)\right] \\ X_2'(\omega) &= \frac{\sqrt{2}}{2}\left[X_1(\omega) - X_2(\omega)\right] \end{aligned} \tag{10}$$

After the linear combination transformation is performed on both the transmitted and received ends of the interconnect system, the relationship between the received and transmitted signals is

$$\begin{aligned} \begin{pmatrix} Y_1(\omega) \\ Y_2(\omega) \end{pmatrix} &= \mathrm{e}^{\frac{-\mathrm{j}(\Delta\beta)l}{2}} \begin{pmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \end{pmatrix} \begin{pmatrix} \cos\left[\frac{(\Delta\beta)l}{2}\right] & -\mathrm{j}\sin\left[\frac{(\Delta\beta)l}{2}\right] \\ -\mathrm{j}\sin\left[\frac{(\Delta\beta)l}{2}\right] & \cos\left[\frac{(\Delta\beta)l}{2}\right] \end{pmatrix} \begin{pmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \end{pmatrix} \begin{pmatrix} X_1(\omega) \\ X_2(\omega) \end{pmatrix} \\ &= \begin{pmatrix} \mathrm{e}^{-\mathrm{j}(\Delta\beta)l} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} X_1(\omega) \\ X_2(\omega) \end{pmatrix} \end{aligned} \tag{11}$$

As can be seen from Eq. (11), when the off-diagonal elements of the channel transmission matrix are zero after increasing the linear combination transform, the crosstalk is canceled. The crosstalk signal caused by the adjacent coupling does not exist in the received signal. The two coupled signals are independent, and all distortionless channel transfer functions are as shown

$$\begin{aligned} Y_1(\omega) &= X_1(\omega)\,\mathrm{e}^{-\mathrm{j}(\Delta\beta)l} \\ Y_2(\omega) &= X_2(\omega) \end{aligned} \tag{12}$$

The specific circuit implementation of non-crosstalk scheme of two parallel microstrip lines in high-speed interconnects according to Eq. (9) is shown in Fig. 3 where the specific parameters are marked. As can be seen from Fig. 3, the circuit implementation of the scheme is simple.

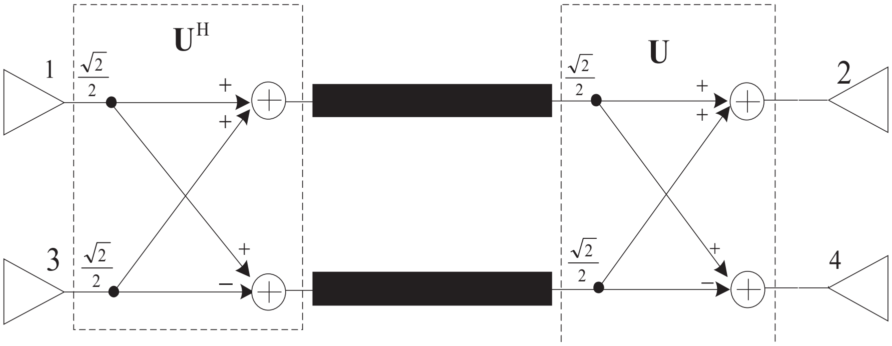


Figure 3. Non-crosstalk scheme of two parallel microstrip lines.

4. SIMULATION RESULTS AND ANALYSIS

The validity of the proposed method is simulated and verified by utilizing advanced design system (ADS) software. The MACLIN2 of TLines-Microstrip has been used to create two microstrip lines in parallel. The architecture parameters are marked as Fig. 4: width of the microstrip line $w = 20\,\mathrm{mil}$, distance between adjacent microstrip lines $s = 60\,\mathrm{mil}$ ($s = 3w$), medium height $d = 22\,\mathrm{mil}$, dielectric constant $\varepsilon_r = 4.5$, magnetic permeability $\mu_r = 1$, dielectric loss angle tangent $\tan\delta = 0.02$, and length of the microstrip line $l = 16$ inch. The conductor is copper. In addition, the characteristic impedance of microstrip line is $50\,\Omega$. The circuit is arranged as shown in Fig. 3. The transmission rate of input data through microstrip line is set as 5 G bit/s. The rise/fall time is 20 ps, and the input data are pseudo-random sequence. The eye diagrams of the receiving signal in microstrip lines are simulated.

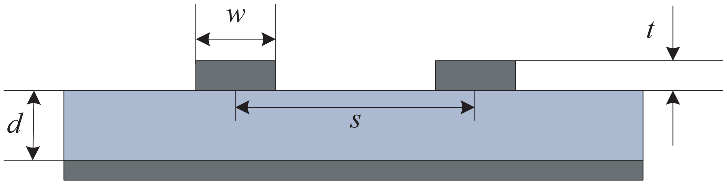
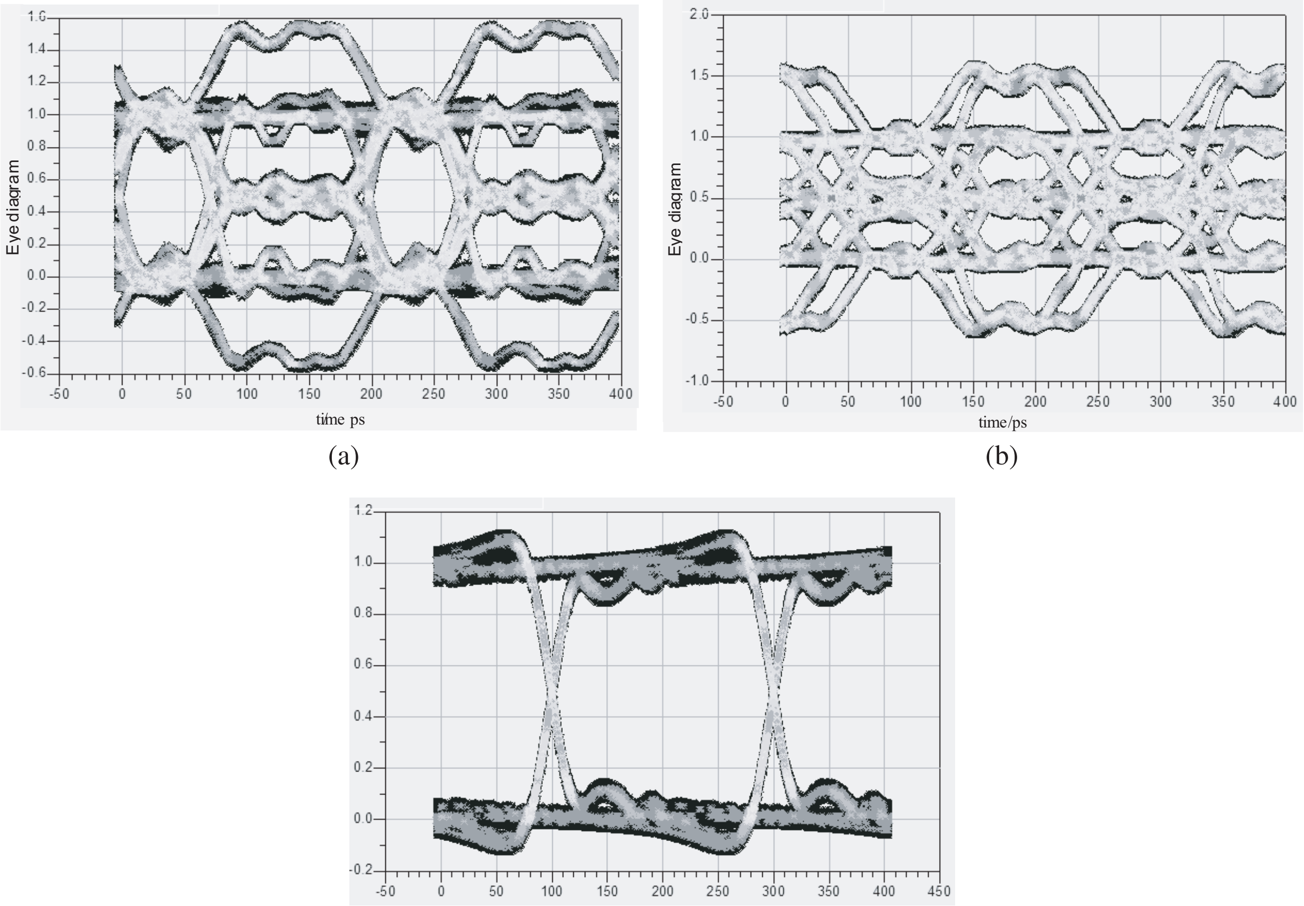


Figure 4. The structure of the coupled microstrip lines.

Since crosstalk respectively superimposed on the edge and symbol level of the victim signal will generate jitter and amplitude noise, this paper simulates the eye diagrams of the two signals in the case of synchronization and half-symbol phase difference. The results are shown in Fig. 5. In both cases, the eye diagram of received signal is basically the same after using this method, as shown in Fig. 5(c) that is compared with Fig. 5(a) and Fig. 5(b).

It can be observed that the jitter caused by the crosstalk is eliminated, and the width and height of the eye diagram are restored when the two transmitted signals are synchronized. The eye



(a) (b)

(c)

Figure 5. Comparison of eye diagrams. (a) Before using scheme (transmitting signal with synchronization). (b) Before using scheme (transmitting signal with half-symbol phase difference). (c) After using scheme.

diagram affected by the crosstalk is rarely open when the two transmitted signals have half-symbol phase difference. However, jitter and noise are eliminated after linear combination transformation transmitting.

The simulation results clarify that the proposed method is capable of achieving non-crosstalk in the high-speed interconnects, which suppresses the jitter and noise of crosstalk. At the same time, comparing the method in this paper with in [12–14] can be concluded that the circuit architecture advantage is simpler, and crosstalk cancelation effect is pretty good, easier to implement, and lower in cost under the premise of having the same signal transmission effect.

5. CONCLUSION

In this paper, a non-crosstalk scheme in high-speed interconnects has been proposed to overcome the shortcomings caused by approximating the transfer function on the microstrip line. This scheme takes advantage of the signal linear combination transformation for crosstalk cancelation to achieve high-speed signal transmission without crosstalk. The simulation results show that the quality of the eye diagram of the received signal is better, and the circuit architecture is simpler and in lower cost, which is capable of providing a technical reference for solving the crosstalk bottleneck problem in high-speed interconnects. The specific CMOS circuit implementation of this method and the crosstalk cancelation scheme between multiple transmission lines will be discussed in our future works.

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REFERENCES

1. Fan, J., X. Ye, J. Kim, et al., "Signal integrity design for high-speed digital circuits: Progress and directions," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 52, No. 2, 392–400, 2010.
2. Bogatin, E., *Signal and Power Integrity — Simplified*, Prentice Hall, New Jersey, 2009.
3. Halligan, M. and D. Beetner, "Maximum crosstalk estimation in weakly coupled transmission lines," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 56, No. 3, 736–743, 2014.
4. Lee, K., H. Jung, H.-J. Chi, et al., "Serpentine microstrip line with zero far-end crosstalk for parallel high-speed DRAM interfaces," *IEEE Transactions on Advanced Packaging*, Vol. 33, No. 2, 552–558, 2010.
5. Wu, B. and T. Mo, "Barbed transmission lines for crosstalk suppression," *Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC)*, 621–624, Singapore, May 21–24, 2012.
6. Refaie, M. I., W. S. El-Deeb, and M. I. Abdalla, "A study of using graphene coated microstrip lines for crosstalk reduction at radio frequency," *Proceedings of the 35th National Radio Science Conference (NRSC)*, 85–90, Cairo, Egypt, March 20–22, 2018.
7. Xu, J. and S. Wang, "Investigating a guard trace ring to suppress the crosstalk due to a clock trace on a power electronics DSP control board," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 57, No. 3, 546–554, 2015.
8. Huang, B., K. Che, and C. Wang, "Far-end crosstalk noise reduction using decoupling capacitor," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 58, No. 1, 1–13, 2016.
9. Balakrishnan, R., S. A. Thomas, and S. Sharan, "Crosstalk and EMI reduction using enhanced guard trace technique," *2018 IEEE Electrical Design of Advanced Packaging and Systems Symposium (EDAPS)*, 1–3, Chandigarh, India, December 16–18, 2018.
10. Pizano-Escalante, L., O. Longoria-Gandara, and R. Parra-Michel, "Crosstalk cancellation on high-speed interconnects through a MIMO linear precoding," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 61, No. 11, 3860–3870, 2013.
11. Cevrero, A., C. Aprile, P. A. Francese, et al., "A 5.9 mW/Gb/s 7 Gb/s/pin 8-lane single-ended RX with crosstalk cancellation scheme using a XCTLE and 56-tap XDFE in 32 nm SOI CMOS," *Proceedings of the Symposium on VLSI Circuits*, C228–C229, Kyoto, Japan, June 16–19, 2015.
12. Oh, T. and R. Harjani, "Adaptive techniques for joint optimization of XTC and DFE loop gain in high-speed I/O," *ETRI Journal*, Vol. 37, No. 5, 906–916, 2015.
13. Aprile, C., A. Cevrero, P. A. Francese, et al., "An eight-lane 7-Gb/s/pin source synchronous single-ended RX with equalization and far-end crosstalk cancellation for backplane channels," *IEEE Journal of Solid-State Circuits*, Vol. 53, No. 3, 861–872, 2018.
14. Wang, Y. and X. Li, "Crosstalk cancellation method based on unitary transformation of coupled transmission lines-channel transmission matrix," *Progress In Electromagnetics Research Letters*, Vol. 52, 45–50, 2015.
15. Mbairi, F. D., W. P. Siebert, and H. Hesselbom, "High-frequency transmission lines crosstalk reduction using spacing rules," *IEEE Transactions on Components and Packaging Technologies*, Vol. 31, No. 3, 601–610, 2008.