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Crosstalk Cancellation Method Based on Unitary Transformation of Coupled Transmission Lines-Channel Transmission Matrix

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Abstract—Crosstalk is one of the bottlenecks for high-speed circuits to increase its rate and density. In order to make tradeoff between complexity and effect of the crosstalk cancellation circuit, a crosstalk cancellation method based on unitary transformation is proposed. In the method, two unitary matrixes are obtained by Singular Value Decomposition (SVD) of coupled transmission lines-channel transmission matrix (CTL-CTM), and then according to the form of the unitary matrixes, the crosstalk canceling circuits are built at both ends of the transmission line, which could transform the CTMes into unit ones and crosstalk would be cancelled out. Circuit simulation results show that at the signaling rate of 5 Gbit/s, jitter performance of eye diagram improves 85% and vertical performance improves 77.5%, which means the method achieves better crosstalk canceling effect with lower circuit cost.

1. INTRODUCTION

In high-speed circuits, electromagnetic wave coupling between closely spaced signal lines limits interconnect performance, which has become a bottleneck to improve the rate of circuits [1, 2]; thus, minimizing the crosstalk among integrated signal transmission lines, such as micro strip lines, has become an important goal in design of high-speed circuits. Crosstalk, which is the transfer of an unwanted signal from one trace or circuit to its adjacent ones, is one of the major challenges in today's signal integrity for high-speed, high-density circuits. In practice, the crosstalk distorts communication signals and deteriorates the quality of digital and analog signals. It is found that crosstalk exists everywhere inside an integrated circuit, such as inside chips, printed circuit boards (PCB), interconnect packages, or any non-shielded high density integrated circuits [3, 4]. Consequently, investigation for crosstalk minimization is an important task in design of high-speed, high density circuits.

Crosstalk takes place mainly due to the mutual coupling, e.g., mutual capacitance and mutual inductance, for any arbitrary two adjacent transmission lines. Currently, crosstalk is suppressed mainly from the physical structure of circuit board and transmission line [5–11], but the effect of these methods is limited. In mobile communication systems, MIMO (multi-input and multi-output), which employs multiple antennas at the transmitter to transmit signals independently and receives the signal with multiple antennas to recover it, is used to describe an abstract mathematical model of multi-antenna wireless communication system. Based on MIMO concept, T. Oh [12, 13] proposed a method with crosstalk cancellation (XTC) equalizer to cancel crosstalk, which is similar to the space division multiplexing that separates independent data by eliminating the interference from other antennas. However, the circuit design is relatively complicated.

From another point of view, the channel transmission matrix (CTM) of coupled transmission lines (CTL) can be obtained. Since CTM shows the relationship between output and input signals on the CTL, CTM was transferred into unit matrix through signal processing, and then output signals are

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equal to input ones, which made crosstalk completely eliminated. The construction of CTL-CTM is investigated and using singular value decomposition (SVD) method, crosstalk cancellation is proposed based on the unitary transformation of CTL-CTM. The mathematics analysis of CTL-CTM shows the SVD method helps the formation of unit matrix. As a result, the realization process of crosstalk cancellation is to first construct CTL-CTM, which experiences SVD to obtain the unitary matrixes, and then according to the form of the unitary matrixes, the crosstalk canceling circuits are built at both ends of the transmission line. The circuit simulation results show that at the signaling rate of 5 Gbit/s, jitter performance of eye diagram improves significantly and the method is simple and easy to apply in actual circuit.

2. MATHEMATICS ANALYSIS

In high-speed, high-density circuits, the crosstalk is inevitable due to the electromagnetic coupling. The crosstalk between two adjacent transmission lines is shown in Figure 1. A signal is injected into one end of the line, and then the voltage noise is measured on the two ends of the adjacent line. The end nearest the signal source is labeled as "the near end crosstalk", while the end far from the signal source is labeled as "the far end crosstalk", which is in the "forward" direction to the signal transmission direction. The near end is in the "backward" direction to the signal transmission direction.

From point of signal transmission, the n CTLs in Figure 2(a), because of the existence of far crosstalk, the relationship between the output signal and the input signal can be represented with vectors and matrixes as

$$\hat{\mathbf{V}} = \mathbf{HV} \tag{1}$$

where $\hat{\mathbf{V}}$ is the vector of output signal, $\hat{\mathbf{V}} = (\hat{v}_1, \hat{v}_2, \ldots, \hat{v}_n)$, $\mathbf{V}$ the vector of input signal, $\mathbf{V} = (v_1, v_2, \ldots, v_n)$, and $\mathbf{H}$ a $n \times n$ matrix.

The $\mathbf{H}$ is defined as CTL-CTM and expressed as Formula (2).

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \ldots & h_{1n} \\ h_{21} & h_{22} & \ldots & h_{2n} \\ \vdots & \vdots & & \vdots \\ h_{n1} & h_{n2} & \ldots & h_{nn} \end{bmatrix} \tag{2}$$

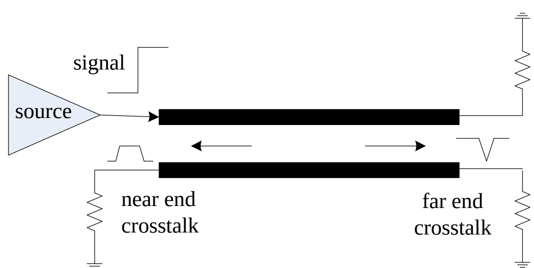


Figure 1. Near crosstalk and far crosstalk.

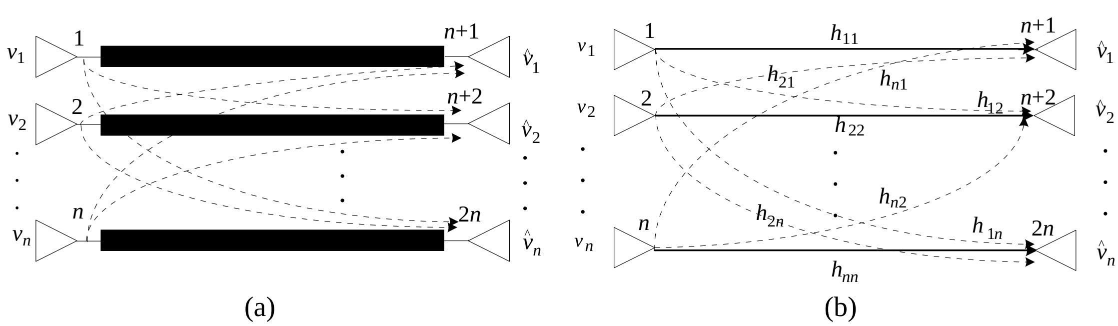


Figure 2. Relationship between input and output of CTL signals. (a) Model of CTL. (b) Model of signals with the elements in matrix H.

According to Formula (1), the elements in matrix $\mathbf{H}$ indicate the relationship between output and input of CTL signals. As to the CTL in Figure 2(b), the relationship between output signal on transmission line i and input signal on other transmission line is written as follow

$$\hat{v}_i = h_{1i}v_1 + h_{2i}v_2 + \ldots + h_{ni}v_n \tag{3}$$

where $\hat{v}_i$ $(1 \leq i \leq n)$ is the output signal on transmission line i, v_i $(1 \leq i \leq n)$ the input signal on transmission line i, and h_{ij} $(1 \leq i,\, j \leq n)$ the elements in matrix $\mathbf{H}$.

Similarly, if the ports of CTL are named according to Figure 2, where ports $1, 2, \ldots, n$ are defined as input ones and $n+1$, $n+2$, $\ldots$, $2n$ are output ones, according to the definition of the S-parameter, the relationship between output signal of transmission line i and input signal of other transmission line expressed by S-parameters would be given in the port matching case as below

$$\hat{v}_i = S_{n+i1}v_1 + S_{n+i2}v_2 + \ldots + S_{n+in}v_n \tag{4}$$

where $\hat{v}_i$ $(1 \leq i \leq n)$ is the output signal on transmission line i, v_i $(1 \leq i \leq n)$ the input signal on transmission line i, and S_{ij} $(1 \leq i, j \leq n)$ the elements in matrix $\mathbf{S}$.

From (3) and (4), also in the port matching case, the relationship between the elements in matrix $\mathbf{H}$ and S-parameters is described as follow:

$$h_{ji} = S_{n+ij} \quad (1 \leq i,\, j \leq n) \tag{5}$$

Because crosstalk between CTLs is mutual, $\mathbf{H}$ would be a symmetric matrix if transmission line parameters are all same.

3. PROPOSED METHOD

Crosstalk cancellation method based on unitary transformation of CTL-CTM in two transmission lines case is given here. Figure 3 shows two parallel microstrip transmission lines with consistent parameters. Here, $\mathbf{H}$ is expressed with S-parameter as Formula (6).

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} S_{31} & S_{41} \\ S_{32} & S_{42} \end{bmatrix} \tag{6}$$

In weak coupling case, where secondary crosstalk is ignored. According to [14], elements in $\mathbf{H}$ are

$$S_{31} = S_{42} = 1 \tag{7}$$

$$S_{41} = S_{32} = -j\Delta kl \tag{8}$$

where $\Delta k \approx \frac{\omega}{2Z_0}(L_{12} + C_{12}Z_0^2)$, l is the length of transmission line.

Substituting (7) and (8) to (6), we have

$$\mathbf{H} = \begin{bmatrix} 1 & -j\Delta kl \\ -j\Delta kl & 1 \end{bmatrix} \tag{9}$$

According to the SVD method of matrix, solving the eigenvalues and eigenvector of HH^H and H^HH, the SVD form of $\mathbf{H}$ would be obtained as Formula (10).

$$\mathbf{H} = \mathbf{U}\mathbf{A}\mathbf{V}^H \tag{10}$$

Figure 3. Two parallel microstrip lines with consistent parameters.

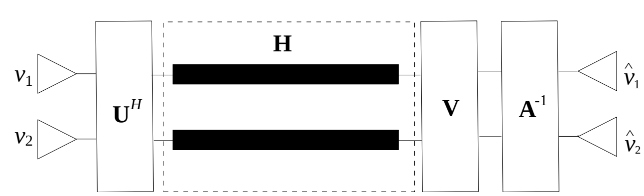


Figure 4. Crosstalk cancellation model based on unitary transformation.

where $\mathbf{A}$ is a diagonal matrix; $\mathbf{U}$ and $\mathbf{V}$ are unitary matrixes, and

$$\mathbf{A} = \begin{bmatrix} 1 - j\Delta kl & 0 \\ 0 & 1 + j\Delta kl \end{bmatrix} \tag{11}$$

$$\mathbf{V} = \mathbf{U} = \begin{bmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \end{bmatrix} \tag{12}$$

According to the character of unitary matrix, $\mathbf{U}^{-1} = \mathbf{U}^H$ and $(\mathbf{V}^H)^{-1} = (\mathbf{V}^{-1})^{-1} = \mathbf{V}$, and observing the form of Formula (10), it is found that if left multiplying matrix $\mathbf{U}^H$ and right multiplying matrix $\mathbf{V}$ by matrix $\mathbf{H}$ respectively, the channel transmission matrix would become a diagonal one.

$$\mathbf{U}^H\mathbf{H}\mathbf{V} = \mathbf{U}^H\mathbf{U}\mathbf{A}\mathbf{V}^H\mathbf{V} = \mathbf{A} \tag{13}$$

Namely

$$\mathbf{U}^H\mathbf{H}\mathbf{V} = \begin{bmatrix} 1 - j\Delta kl & 0 \\ 0 & 1 + j\Delta kl \end{bmatrix} \tag{14}$$

From Formula (13), if unitary transformations such as matrix $\mathbf{U}^H$ and $\mathbf{V}$ are taken at input and output part of CTL separately, matrix $\mathbf{H}$ can be changed into diagonal one. After making appropriate signal processing for each transmission line respectively, $\mathbf{H}$ will be varied into unit matrix. That means output signals are equal to input ones and crosstalk is canceled out. Therefore, the method using unitary transformation for crosstalk cancellation can be shown in Figure 4, which is also suitable for the case of multiple coupled transmission lines.

4. SIMULATION RESULTS

Some simulations are done to verify the proposed method. Two parallel microstrip transmission lines α and β on PCB are created in the layout interface of Advanced Design System (ADS) software. The parameters are: $w = 40\,\text{mil}$, $s = 40\,\text{mil}$, $h = 22\,\text{mil}$, $t = 2.8\,\text{mil}$, $\tan\delta = 0.02$, $\varepsilon_r = 4.6$, $\mu_r = 1$, $l = 16\,\text{in}$, the metal is copper, and the characteristic impedance of microstrip lines Z_0 is about $50\,\Omega$. The layout of simulation circuit, the port settings and parameters are defined and shown in Figure 5. What's more, the impedance matching has been setting. Because the elements in matrix $\mathbf{U}^H$ and matrix $\mathbf{V}$ are constant, the circuit could be easy constructed according to Formula (12). The total transfer matrix would be $\mathbf{A}$ after circuit structure $\mathbf{U}^H$ and V are added, then from the formers of $1-j\Delta kl$ and $1+j\Delta kl$, which are non-zero elements in $\mathbf{A}$, we can know that adding circuit structure $\mathbf{U}^H$ and $\mathbf{V}$ is equivalent

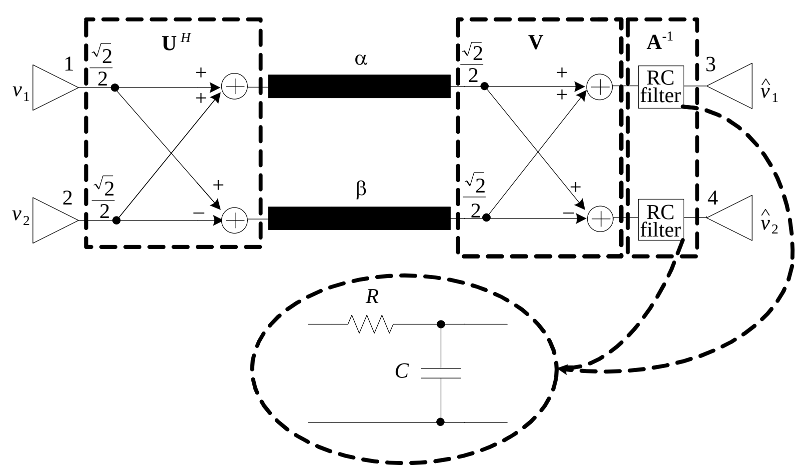
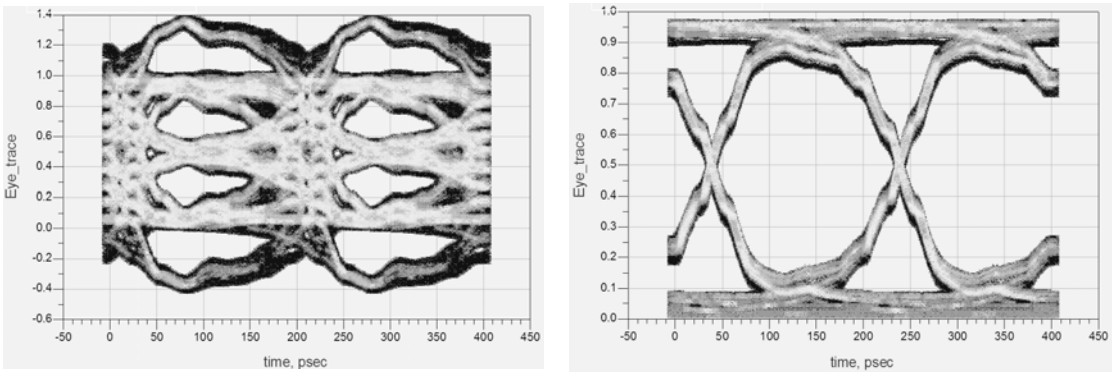


Figure 5. Layout of simulation circuit.



(a) (b)

Figure 6. Eye diagram for 5 Gbit/s NRZ signals in 2 W distances. (a) Eye diagram before using the propsed method. (b) Eye diagram after using the proposed method.

Table 1. The comparison of performance of eye diagram between two crosstalk cancellation methods at 5 Gbit/s.

Method		**Jitter (ps)**	**Vertical eye diagram [E/H (mv, mv)] [12]**	**Jitter improvements**	**Vertical improvements**
In this paper	before	92.5% UI	0	85%	77.5%
	after	7.5% UI	77.5%		
The MIMO-XTC	before	85.0% UI	7.3%	67%	58.2%
	after	18.0% UI	65.5%		

to superimpose higher frequency signal on each signal independently. So the task of back class $\mathbf{A}^{-1}$ is to filter the signals superimposed by front class. Considering the realization of circuit, two set of RC filter circuits are chosen to complete the function.

The simulation results are shown as eye diagram in Figure 6. Only diagrams of $\hat{v}_2$ are given here because $\hat{v}_1$ and $\hat{v}_2$ are very similar. The eye diagram of $\hat{v}_2$before and after adding matrixes $\mathbf{U}^H$, $\mathbf{V}$, and $\mathbf{A}^{-1}$ are illustrated in Figures 6(a) and (b) respectively. The jitter decreases from 185 ps to 15 ps (from 92.5% UI (unit interval) to 7.5% UI) and the distortion reduces greatly, which is measured with two drive signals rates of 5 Gbit/s, rising and falling time of 20 ps. Comparing the eye diagram in reference [13] with Figure 6, it can be seen that the proposed method has a better performance on offsetting jitter and noise. The comparing results with MIMO-XTC method are shown in Table 1, which indicates that jitter improvements are increased by 18% and vertical eye diagram improvements are increased by 19.3%. At the same time, the circuit structure of the proposed method is much simpler than that in reference [13].

5. CONCLUSIONS

Crosstalk is one of the bottlenecks in high-speed circuits for rate and density increasing. The conception of CTL-CTM and a crosstalk cancellation method using unitary transformation based on SVD of CTL-CTM are proposed. Simulation results indicate that the method not only does well in offsetting shaking and noise caused by crosstalk but also is easy in circuit design. The crosstalk cancellation method based on the unitary transformation of CTL-CTM could realize greater effect of crosstalk suppressing with lower costs because there is no more limited conditions such as parallel transmission lines, spacing of lines with 2 W Standard, etc., so it could be widely applied. However, the proposed method would increase the cost of circuit, so tradeoff should be made between the cost and effect in reality.

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