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Anti-Crosstalk Noise Performance Analysis of Multi-Symbol Transmission and Joint Crosstalk Reduction Method

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Abstract—Crosstalk between interconnected lines is considered from two perspectives in this study. From a physical space perspective, the four transmission lines are reduced to two transmission lines. Meanwhile, the replacement of signal transmission of four-channels 2PAM (Pulse Amplitude Modulation) with signal transmission of two-channels 4PAM can reduce the quantity of transmission line and increase the space between the transmission lines. Thus, it can reduce the crosstalk. Under the same signal-to-noise ratio (SNR), the change in symbol error rate (SER) after signals of four-channels 2PAM are changed to those of two-channels 4PAM is given. Results show that the latter has an advantage in anti-crosstalk compared with the former in terms of the influence of crosstalk on SER. From the signal space perspective, applying signal linear combination transformation can convert the multiplexing signals in the interconnects into orthogonal mode. This process can cancel the crosstalk. In this study, the two methods are combined to save wiring while reducing crosstalk. ADS simulation results show that the eye pattern of 4 PAM signal recovers well by saving half the number of transmission lines.

1. INTRODUCTION

In the era of big data and terabit, data and information are growing exponentially, and requirements on the data-transmission bandwidth and speed of integrated circuit system interconnection continue to increase. Interconnection has greatly hindered the development of modern integrated circuit technology. A more advanced technology requires a higher working speed of the circuit, which means more serious interconnection problems [1]. As the signal frequency becomes higher, the signal edge becomes shorter; the size of printed circuit board becomes smaller; the wiring density increases; crosstalk in interconnection becomes a more and more important problem. Reducing crosstalk has become a research hotspot [2, 3].

Two main types of crosstalk solutions exist. One category is traditional interconnection technology, in which the circuit layout, dielectric material, and parameters are optimized. Crosstalk is reduced by changing the circuit board or the physical parameters of the transmission lines to restrain electromagnetic coupling [4–7]. However, this coupling cannot be fundamentally eliminated. Therefore, the traditional interconnection technology has limited effects and can only partially reduce crosstalk. An ideal effect cannot be achieved using this method especially under high working frequency, large integration, and complex circuits. Meanwhile, the other category proposes a new interconnection technology, such as substrate integrated waveguide interconnection, substrate integration coaxial line interconnection, wireless interconnection, optical interconnection, carbon nano interconnection, and superconducting interconnection [1]. Although this method can effectively restrain crosstalk, its

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application is hampered by drawbacks, such as cost, process, and implementation complexity. In [8] and [9], several methods based on copper interconnection, such as multilevel transmission and linear combination transformation, are proposed to reduce crosstalk. Given that weak coupling is the precondition to reduce crosstalk by signal linear combination transformation, the application can only be used under the 3W rule (3W rule: The distance from one center point to the other of the adjacent transmission lines is three times of the line width). In a high-speed and high-density interconnection system, the wiring density increases, and satisfying the conditions of the 3W criterion becomes extremely difficult. The number of transmission lines should be reduced to achieve weak coupling. To ensure the data transmission capacity and unchanged bandwidth of the system, multi-symbol transmission can decrease the number of transmission lines, increase line spacing, and create conditions to realize weak coupling while simultaneously reducing crosstalk. Thus, these methods are combined in this study. As shown in Figure 1, multi-symbol transmission can satisfy the conditions in the application of the signal linear combination transformation to reduce crosstalk. The former method is combined with the latter method to jointly reduce crosstalk. This combination extends the practicability of signal linear combination transformation to reduce crosstalk.

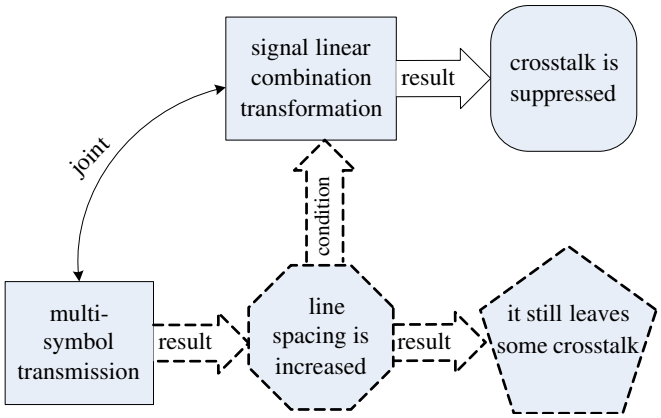


Figure 1. Diagram of joint crosstalk reduction.

2. WEAK COUPLING UNDER MULTI-SYMBOL TRANSMISSION

Crosstalk is the result of electromagnetic coupling, which is related to line spacing. Studies have shown that electromagnetic coupling and crosstalk decrease as the distance between transmission lines increases. However, restricted by product size, circuit board area, and other factors, the indefinite increase in the distance between transmission lines is impossible. Therefore, crosstalk reduction is limited. With this principle, applying multi-symbol transmission can reduce the number of transmission lines and minimize crosstalk without expanding the circuit board area [8]. This transmission is equivalent to increasing the distance between transmission lines. Strong coupling becomes weak, and crosstalk is reduced.

The PAM signal is defined as follows.

$$v(t) = a_i g_{\mathrm{T}}(t) \quad i = 1, 2, \ldots, M \quad 0 \le t \le T \tag{1}$$

where $\{a_i, i = 1, 2, \ldots, M\}$ represents the possible discrete amplitude values corresponding to the M-ary symbol, and $g_{\mathrm{T}}(t)$ refers to signal waveform.

As shown in Figure 2, the case is different from improving the bandwidth efficiency, ensuring that the system data transmission capacity, bandwidth, and area of PCB occupied by the system are not changed, and line spacing can be expanded through multi-symbol transmission by signal conversion; that is, the four-channel 2PAM signal is changed to two-channel 4PAM signal transmission. This process lessens the number of transmission lines and further expands the line spacing of the transmission lines.

In Figure 2, the original 2PAM signals $v_a(t)$ and $v_b(t)$ are transformed into one-channel 4PAM signal $v_{ab}(t)$. The original 2PAM signals $v_c(t)$ and $v_d(t)$ are transformed to one-channel 4PAM signal

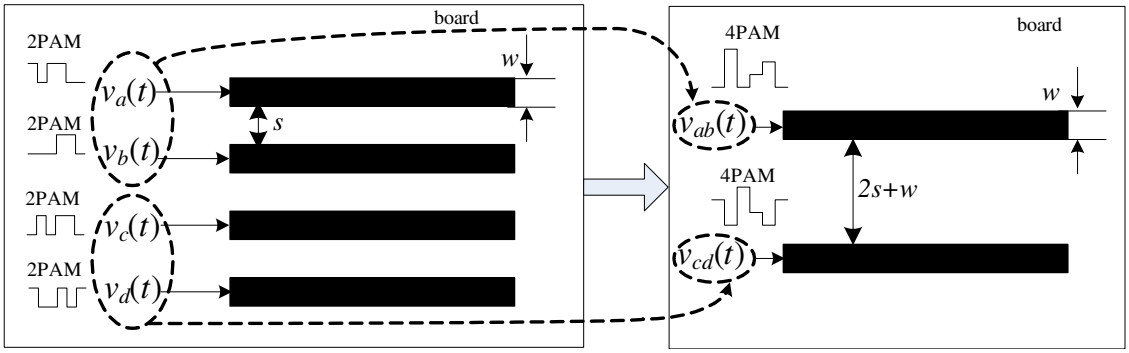


Figure 2. Four-channel 2PAM is changed into two-channel 4PAM.

Table 1. Transformation relationship.

PAM signal	Logic or level (symbol width)			
2PAM $v_a(t)$ or $v_c(t)$	0 (T_s)	0 (T_s)	1 (T_s)	1 (T_s)
2PAM $v_b(t)$ or $v_d(t)$	0 (T_s)	1 (T_s)	1 (T_s)	0 (T_s)
4PAM $v_{ab}(t)$ or $v_{cd}(t)$	$+3A$ (T_s)	$+A$ (T_s)	$-A$ (T_s)	$-3A$ (T_s)

$v_{cd}(t)$. During the transformation, the width of the code element, that is, the system bandwidth and the quantity of information remain the same. The specific transformation relationship is shown in Table 1. For example, for four transmission lines, only two transmission lines are needed after completing the transformation. The original line spacing of the transmission lines is s, while the line width of the microstrip is w. After transformation, the distance between the two adjacent lines is widened from s to $2s + w$; the line spacing is more than doubled; the coupling between the microstrips becomes weak; and crosstalk is greatly reduced.

Crosstalk can be reduced by expanding line spacing through multi-symbol transmission, but crosstalk cannot be eliminated completely. Multi-symbol transmission expands line spacing and provides conditions for the application of signal linear combination transformation to reduce crosstalk. Therefore, under the precondition of multi-symbol transmission, further crosstalk reduction requires the joint application of signal linear combination transformation.

3. ANTI-CROSSTALK NOISE ANALYSIS OF MULTI-SYMBOL TRANSMISSION

Under Gaussian white noise, crosstalk is taken as fixed interference considering the worst-case. At the receiver of the transmission line, the sampling value is y, and

$$y = a + n + v_\mathrm{c} \tag{2}$$

The values of the variables in this formula are shown in Table 2.

At this time, the SER of 2 PAM is shown in Formula (3) [10].

$$\begin{aligned} P_\mathrm{s} = {} & \frac{3}{8}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A}{\sqrt{2}\sigma}\right) + \frac{1}{4}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+v_{\mathrm{c}2}}{\sqrt{2}\sigma}\right) + \frac{1}{4}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-v_{\mathrm{c}2}}{\sqrt{2}\sigma}\right) \\ & + \frac{1}{16}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+2v_{\mathrm{c}2}}{\sqrt{2}\sigma}\right) + \frac{1}{16}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-2v_{\mathrm{c}2}}{\sqrt{2}\sigma}\right) \end{aligned} \tag{3}$$

On the basis of Formula (3) and according to the calculation formula of the SER of the multi-

symbol, the SER of 4PAM in the case of considering crosstalk is derived, as shown in Formula (4).

$$P_{\mathrm{s}}=\frac{3}{2}\left(\begin{array}{l}\frac{44}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A}{\sqrt{2}\sigma}\right)+\frac{40}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{40}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\\+\frac{31}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+2v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{31}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-2v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{20}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+3v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\\+\frac{20}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-3v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{10}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+4v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{10}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-4v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\\+\frac{4}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+5v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{4}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-5v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{1}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+6v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\\+\frac{1}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-6v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\end{array}\right) \tag{4}$$

When signals of four-channels 2PAM are changed into those of two-channels 4PAM, crosstalk will also decrease due to the expansion of the transmission line spacing. According to [8] and the definition of the parameters in Table 2, the relationship between v_{c4} and v_{c2} under the same SNR is $v_{\mathrm{c4}}=\frac{1}{6}\cdot\frac{\sqrt{5}}{5}v_{\mathrm{c2}}$.

Table 2. Values of variables in Formula (2).

——	a	n	v_{c}
2PAM	The value is $+A$, $-A$ of equal probability	Gaussian white noise with mean 0 and variance σ^2	Considering the crosstalk superposition of the attack lines on both sides, five possible values can be considered for the crosstalk on the intermediate transmission line: 0, v_{c2}, $-v_{\mathrm{c2}}$, $2v_{\mathrm{c2}}$, and $-2v_{\mathrm{c2}}$. The probability rates of occurrence are 3/8, 1/4, 1/4, 1/16, and 1/16.
4PAM	The value is $+3A$, $+A$, $-A$, $-3A$ of equal probability	Gaussian white noise with mean 0 and variance σ^2	Considering the crosstalk superposition of the attack lines on both sides, 13 possible values can be considered for the crosstalk on the intermediate transmission line: 0, v_{c4}, $-v_{\mathrm{c4}}$, $2v_{\mathrm{c4}}$, $-2v_{\mathrm{c4}}$, $3v_{\mathrm{c4}}$, $-3v_{\mathrm{c4}}$, $4v_{\mathrm{c4}}$, $-4v_{\mathrm{c4}}$, $5v_{\mathrm{c4}}$, $-5v_{\mathrm{c4}}$, $6v_{\mathrm{c4}}$, and $-6v_{\mathrm{c4}}$. The probability rates of occurrence are 44/256, 40/256, 40/256, 31/256, 31/256, 20/256, 20/256, 10/256, 10/256, 4/256, 4/256, 1/256, and 1/256.

According to the above mentioned conditions, the SER of $v_{\mathrm{c2}}=A/4$, $v_{\mathrm{c2}}=A/3$, $v_{\mathrm{c2}}=A/2$ under the same SNR is simulated with MATLAB, as shown in Figures 3 $\sim$ 5. After signals of four-channels 2PAM are changed to those of two-channels 4PAM and with the decrease in crosstalk, the latter has an advantage in anti-crosstalk compared with the former in terms of the influence of crosstalk on SER.

4. CROSSTALK REDUCTION METHOD BY THE COMBINATION OF MULTI-SYMBOL WITH SIGNAL LINEAR COMBINATION TRANSFORMATION

The derivation of the SER in the previous section lays a theoretical foundation for the application of multi-symbol transmission. Meanwhile, multi-symbol transmission creates conditions for the application

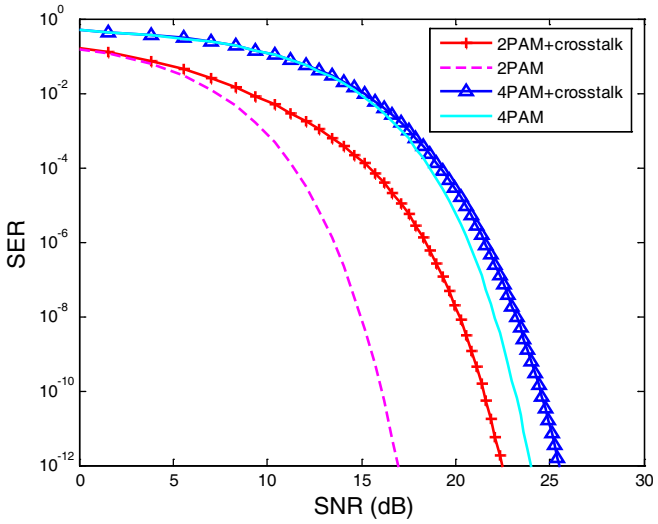


Figure 3. Simulation results of SER at $v_{c2} = A/4$.

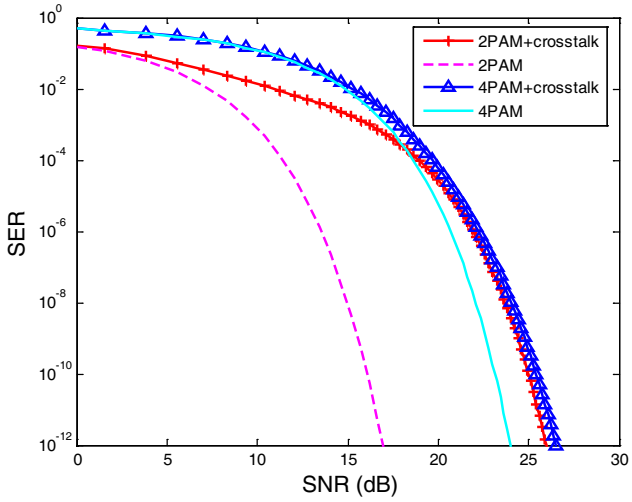


Figure 4. Simulation results of SER at $v_{c2} = A/3$.

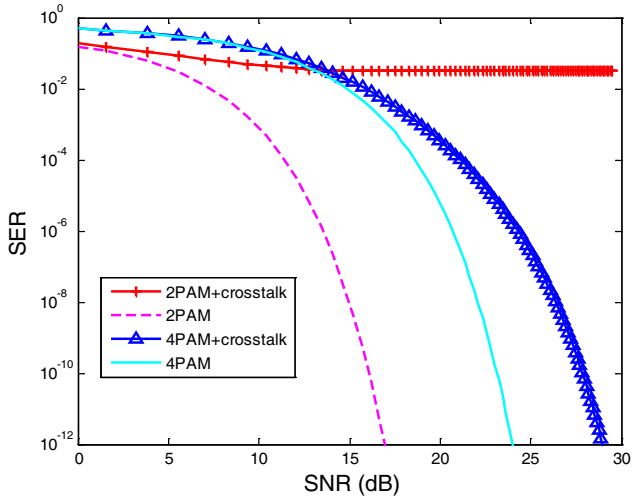


Figure 5. Simulation results of SER at $v_{c2} = A/2$.

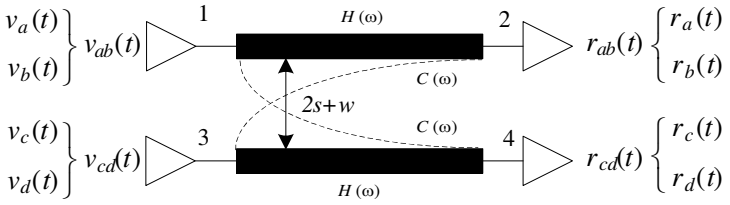


Figure 6. Crosstalk model of multi-symbol transmission.

of signal linear combination transformation to reduce crosstalk. Therefore, the combination of the two has more advantages in reducing crosstalk. As shown in Figure 6, in the two coupled transmission lines with identical parameters, the signal is transmitted in the same direction as that with four signal channels, that is, from port 1 (port 3) to the transmission loss channel of port 2 (port 4), and from port 1 (port 3) to the crosstalk signal channel of port 4 (port 2). The channel transfer function has identical

physical significance with the S-parameters [11]. Therefore, the channel transfer function $H(\omega)$ from ports 1 to 2 (or ports 3 to 4) on the microstrips is similar to S_{21}, S_{43} as follows.

$$H(\omega) = S_{21} = S_{43} \tag{5}$$

The channel transfer function from ports 1 to 4 (or ports 3 to 2), that is, the far-crosstalk function, is similar to as follows.

$$C(\omega) = S_{41} = S_{23} \tag{6}$$

Under multi-symbol transmission, line spacing increases, and weak coupling is obvious. S_{21} and S_{43} are as follows [12].

$$S_{21} = \mathrm{e}^{-\mathrm{j}(\Delta\beta)l/2} \cos\left[\frac{(\Delta\beta)\, l}{2}\right] \tag{7}$$

$$S_{41} = -\mathrm{j}\mathrm{e}^{-\mathrm{j}(\Delta\beta)l/2} \sin\left[\frac{(\Delta\beta)\, l}{2}\right] \tag{8}$$

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 of microstrip line, which are a function of frequency, and l is the coupled length.

Under multi-symbol, the frequency domain of one-channel 4PAM signal $v_{ab}(t)$ is represented as $V_{ab}(\omega)$, while that of the other one-channel 4PAM signal $v_{cd}(t)$ is represented as $V_{cd}(\omega)$. After transmission by the two coupled microstrip lines, the frequency domains of the output signal are $R_{ab}(\omega)$ and $R_{\mathrm{cd}}(\omega)$. Thus, the relationship among the output signal, input signal, and channel transfer function is represented as follows.

$$\begin{pmatrix} R_{ab}(\omega) \\ R_{cd}(\omega) \end{pmatrix} = \begin{pmatrix} S_{21} & S_{41} \\ S_{23} & S_{43} \end{pmatrix} \begin{pmatrix} V_{ab}(\omega) \\ V_{cd}(\omega) \end{pmatrix} \tag{9}$$

Given that the channel transfer function is related to the physical parameters of the transmission line, multi-symbol transmission does not change the parameters and properties of this function. Therefore, continuing the use of the CTL-CTM method is appropriate for crosstalk cancellation. Under multi-symbol transmission, line spacing increases, and weak coupling is obvious. According to [9], the above objectives can be realized when the corresponding signal linearity is carried out at the input and output ends of the coupled transmission linear combination transformation. First, the eigenvalue of CTL-CTM constituted by $H(\omega)$ and $C(\omega)$ is decomposed. The specific parameters of the signal linear combination transformation are determined based on the decomposed form. The theoretical derivation of the implementation process is shown in Equation (10), and the specific circuit implementation scheme is shown in Figure 7.

$$\begin{pmatrix} R_{ab}(\omega) \\ R_{cd}(\omega) \end{pmatrix} = \begin{pmatrix} \sqrt{2}/2 & \sqrt{2}/2 \\ \sqrt{2}/2 & -\sqrt{2}/2 \end{pmatrix} \begin{pmatrix} S_{21} & S_{41} \\ S_{23} & S_{43} \end{pmatrix} \begin{pmatrix} \sqrt{2}/2 & \sqrt{2}/2 \\ \sqrt{2}/2 & -\sqrt{2}/2 \end{pmatrix} \begin{pmatrix} V_{ab}(\omega) \\ V_{cd}(\omega) \end{pmatrix} \tag{10}$$

Equation (11) is obtained by substituting Equations (7) and (8) into Equation (10) as follows.

$$\begin{pmatrix} R_{ab}(\omega) \\ R_{cd}(\omega) \end{pmatrix} = \mathbf{I} \begin{pmatrix} V_{ab}(\omega)\, \mathrm{e}^{-\mathrm{j}(\Delta\beta)l} \\ V_{cd}(\omega) \end{pmatrix} \tag{11}$$

Equation (11) shows that the output signal has only time delay, and crosstalk is suppressed. For multi-symbol transmission, the combination of signal linear combination transformation to cancel crosstalk is effective.

5. SIMULATION AND RESULT ANALYSIS

Multi-symbol transmission lays the foundation for the use of signal linear combination transformation. ADS software simulation is used to verify the effectiveness of the joint crosstalk reduction method. According to the layout in Figure 7, two coupled microstrip lines using multi-symbol transmission are created in the schematic interface. Specific parameters are as follows: The width of the microstrip line is 40 mil. When 2PAM is transmitted, take the minimum line spacing $s = w/2 = 20$ mil. After transforming to 4PAM transmission, the line spacing is $2s + w = 80$ mil (accord to 3W rule); line length

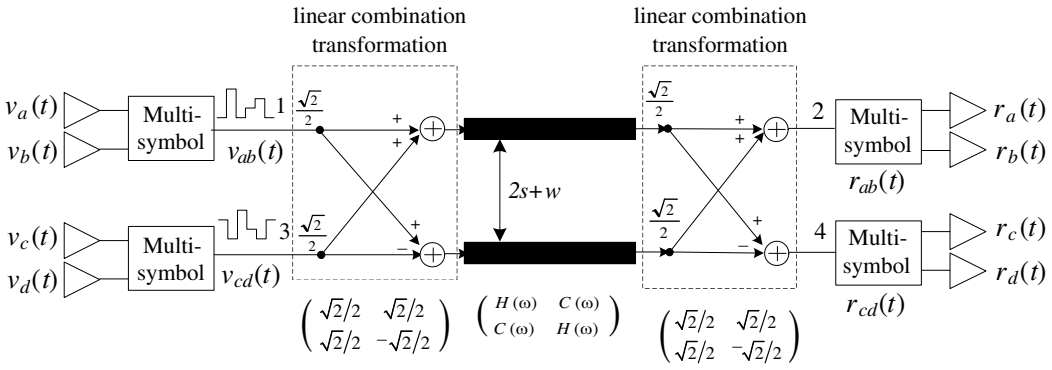
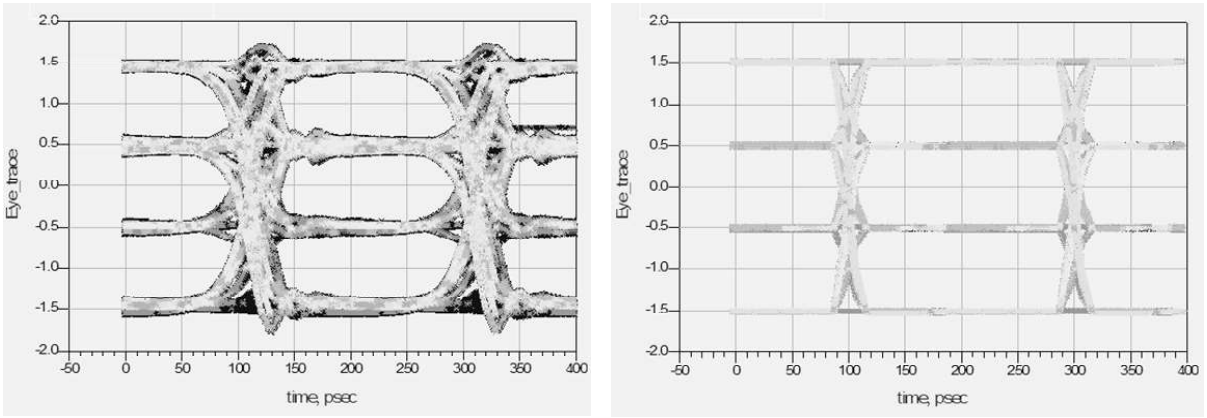
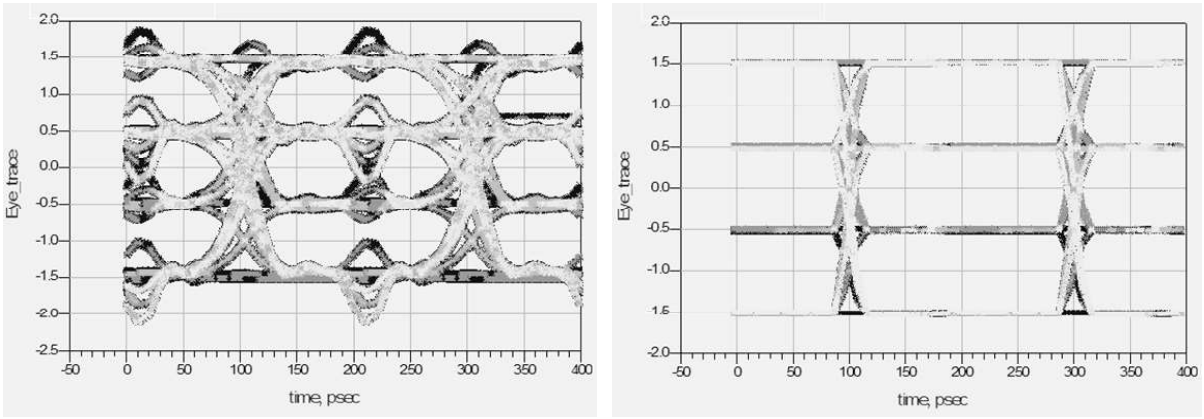


Figure 7. Combination of crosstalk reduction solution.



(a) (b)

Figure 8. Comparative simulation result (Two channels send signals synchronously): (a) The eye diagram before crosstalk cancellation; (b) The eye diagram after crosstalk cancellation.



(a) (b)

Figure 9. Comparative simulation result (Half-a-bit phase difference exists between the two-channel signals): (a) The eye diagram before crosstalk cancellation; (b) The eye diagram after crosstalk cancellation.

is 4000 mil; medium height is 22 mil; conductor thickness is $t = 2.8$ mil; relative dielectric constant $\varepsilon_r = 4.5$; relative magnetic permeability $\mu_r = 1$; dielectric loss angle tangent $\tan\delta = 0.02$. The conductor is copper, and the characteristic impedance of microstrip line is $50\,\Omega$. The transmission rate of input 4PAM random signals on fixed microstrip line is set as 5G band.

The synchronous and half-a-bit phase difference (100 ps) sending of the two-channel 4PAM signals is simulated under the eye pattern. The corresponding comparative results are shown in Figures 8 and 9. Before combining linear combination transformation to reduce crosstalk, multi-symbol transmission still has a high amount of remaining crosstalk. After using the combined crosstalk reduction method, the jitter caused by the crosstalk is eliminated when the two channels send signals synchronously, and good recovery is obtained. When the transmitted signal has half-a-bit phase difference, the jitter and noise are eliminated simultaneously, and the width and height of the eye pattern are restored. A comparison of the simulation results shows that using the linear combination transformation improves the reduction of crosstalk by 4PAM signals. In the simulation, the four-channel 2PAM signal is transformed into two-channel 4PAM signals by default. In practice, the 4PAM signal can be directly sent at the sending end of the signal, and signal transformation is not performed.

6. CONCLUSIONS

In this paper, crosstalk is reduced by combining multi-symbol with signal linear combination transformation. Multi-symbol transmission creates conditions for the application of signal linear combination transformation to attenuate crosstalk. Weak coupling is the precondition for applying linear combination transformation. Multi-symbol transmission can save transmission line, increase line spacing, and create conditions for weak coupling. Therefore, the combined process proposed to mutually reduce crosstalk has several advantages, such as decreasing the routing space and number of transmission lines.

APPENDIX A. SER DERIVATION FOR 4PAM IN THE CASE OF CONSIDERING CROSSTALK

Assume that the receiving signal on the victim line is given as

$$r = a + n + v_{\mathrm{c}} \tag{A1}$$

where a is the transmitted signal, n the Gaussian white noise, and v_{c} the induced crosstalk. Its peak values could be 0, v_{c4}, $-v_{\mathrm{c4}}$, $2v_{\mathrm{c4}}$, $-2v_{\mathrm{c4}}$, $3v_{\mathrm{c4}}$, $-3v_{\mathrm{c4}}$, $4v_{\mathrm{c4}}$, $-4v_{\mathrm{c4}}$, $5v_{\mathrm{c4}}$, $-5v_{\mathrm{c4}}$, $6v_{\mathrm{c4}}$, $-6v_{\mathrm{c4}}$. Thus, the SER on the victim line can be evaluated accordingly as follows:

$$\begin{aligned} P_{\mathrm{s}} \;=\; & P(\mathrm{e}|\, a = 3A)P(a = 3A) + P(\mathrm{e}|\, a = A)P(a = A) \\ & + P(\mathrm{e}|\, a = -3A)P(a = -3A) + P(\mathrm{e}|\, a = -A)P(a = -A) \end{aligned} \tag{A2}$$

Assuming that the signals such as "$3A$", "A", "$-3A$", and "$-A$" have an equal probability, the SER is given as

$$P_{\mathrm{s}} = \frac{P(\mathrm{e}|\, a = 3A) + P(\mathrm{e}|\, a = A) + P(\mathrm{e}|\, a = -A) + P(\mathrm{e}|\, a = -3A)}{4} \tag{A3}$$

where $P(\mathrm{e}|a = 3A)$ is the error probability of sending a signal "$3A$", and it can be evaluated as follows:

$$\begin{aligned} P\left(\mathrm{e}\,|a = 3A\right) \;=\; & P\left(\mathrm{e}\,|3A + n + v_{\mathrm{c}} < 2A\right) = P\left(\mathrm{e}\,|A + n + v_{\mathrm{c}} < 0\right) \\ =\; & P\left(n < -A\right) P\left(v_{\mathrm{c}} = 0\right) \\ & + P\left(n < -A - v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = v_{\mathrm{c4}}\right) + P\left(n < -A + v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = -v_{\mathrm{c4}}\right) \\ & + P\left(n < -A - 2v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = 2v_{\mathrm{c4}}\right) + P\left(n < -A + 2v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = -2v_{\mathrm{c4}}\right) \\ & + P\left(n < -A - 3v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = 3v_{\mathrm{c4}}\right) + P\left(n < -A + 3v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = -3v_{\mathrm{c4}}\right) \\ & + P\left(n < -A - 4v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = 4v_{\mathrm{c4}}\right) + P\left(n < -A + 4v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = -4v_{\mathrm{c4}}\right) \\ & + P\left(n < -A - 5v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = 5v_{\mathrm{c4}}\right) + P\left(n < -A + 5v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = -5v_{\mathrm{c4}}\right) \\ & + P\left(n < -A - 6v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = 6v_{\mathrm{c4}}\right) + P\left(n < -A + 6v_{\mathrm{c4}}\right) P\left(v_{\mathrm{c}} = -6v_{\mathrm{c4}}\right) \end{aligned} \tag{A4}$$

Similarly, $P(\mathrm{e}|a=A)$, $P(\mathrm{e}|a=-3A)$, and $P(\mathrm{e}|a=-A)$ are obtained.

Amplitude probability density function of Gaussian white noise is given as

$$p(n)=\frac{1}{\sqrt{2\pi\sigma^2}}\mathrm{e}^{-n^2/(2\sigma^2)} \tag{A5}$$

where σ^2 is the power of Gaussian white noise.

Substitution of the relations in Eq. (A4) through Eq. (A5) into Eq. (A3) leads to the SER expression on the victim line.

$$P_{\mathrm{s}}=\frac{3}{2}\left(\begin{array}{l}\frac{44}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A}{\sqrt{2}\sigma}\right)+\frac{40}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{40}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\\ +\frac{31}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+2v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{31}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-2v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{20}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+3v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\\ +\frac{20}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-3v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{10}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+4v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{10}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-4v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\\ +\frac{4}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+5v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{4}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-5v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)+\frac{1}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A+6v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\\ +\frac{1}{256}\cdot\frac{1}{2}\operatorname{erfc}\left(\frac{A-6v_{\mathrm{c4}}}{\sqrt{2}\sigma}\right)\end{array}\right) \tag{A6}$$

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