An Analytical Method of Minimizing the Crosstalk of Curved Cable and Determining the Optimal Wiring

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Abstract **─** Crosstalk is an easily occurred electromagnetic interference between adjacent cables. Previous research on crosstalk mainly focused on straight cables, and seldom works are reported for bended cables which happens most often in applications. Thus, we propose an analytic method to minimize the crosstalk between curved cables and determine the optimal wiring rules within a specified frequency range. The procedure of the proposed method can be described as the following steps: Firstly, the theoretical crosstalk model of curved cables is deduced and verified by numerical simulation. Then, an "σ area" is defined as the evaluation parameter of crosstalk effects, which is devoted to obtaining the law of S_σ with the bending degree. On this basis, an optimal wiring is presented and a physical explanation through the coupling mechanism is given. Finally, an experiment is carried out to further validate the proposed method.

Index Terms **─** Crosstalk, curved cables, σ area, optimal wiring rules.

I. INTRODUCTION

Interconnection cables are widely used to transmit energy and signals in electronic and electrical systems. The common mode current along the cable take the primary responsibility for the electromagnetic radiation, which induce the crosstalk on adjacent cables through the distribution parameters. Crosstalk between cables may lead to electromagnetic compatibility (EMC) and TEMPEST problems [1-2], so the research on the mechanism and the suppression methods of crosstalk between cables is of great significance in engineering applications.

Based on the propagation principle of crosstalk, researchers developed some interference suppression methods from three aspects: interference source, propagation path and receiver. The previous works showed that differential mode excitation gives a better case of crosstalk compared with common mode excitation [3]. Since interference source limited by circuit topology are not easy to change, many suppression techniques have been developed on propagation path and receiver, and the widely used way is changing wiring. The common methods used for guiding wiring to prevent crosstalk include keeping the cables farther apart, enlarging the angle between cables, reducing the height to ground, adding shielding layer to terminals and using guard traces [4-9], etc. In addition, some newly studies have been proposed to reduce crosstalk by using input and output configuration [10], mode velocity equalization [11], matched loads [12], the partial phase shift network [13], etc.

The research on crosstalk suppression approach should account for suppression effect, solution complexity, practical constraints and other issues. Obviously, changing wiring is still the simplest and most effective way. Some wiring rules have been used to prevent crosstalk in industrial application, but the technical rationale is not clear. This paper aims at proposing an analytical method of minimizing the crosstalk of curved cable and determining the optimal wiring. In this paper, we'll take the single core cable as example to establish the crosstalk coupling model of curved cables and study the wiring rules. Especially, in order to determine the optimal wiring between two points, we presented the definition of "σ area" on the frequency crosstalk curve to evaluate the impact of crosstalk. On this basis, an analytic method to determinate the minimum crosstalk within a specified frequency range is proposed so that an optimal wiring can be formed.

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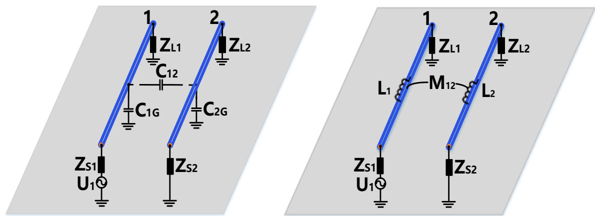
II. CROSSTALK COUPLING MODEL OF CURVED CABLE

A. Derivation of crosstalk analytic calculation

Coupling between circuits is a common electromagnetic phenomenon, and the crosstalk is a typical form of the coupling effects, as illustrated in Fig. 1.



(a) (b)

Fig. 1. Schematic for crosstalk coupling of two conductors: (a) capacitive coupling; (b) inductive coupling.

Multi-conductor transmission line (MTL) theory is often used to analyze the crosstalk between cables. The electrical behaviors of MTL equations in matrix form described in frequency domain can be given as:

$$\frac{d\hat{\boldsymbol{V}}(x)}{dx} + \hat{\boldsymbol{Z}}\hat{\boldsymbol{I}}(x) = 0, \quad (1)$$

$$\frac{d\hat{\boldsymbol{I}}(x)}{dx} + \hat{\boldsymbol{Y}}\hat{\boldsymbol{V}}(x) = 0. \quad (2)$$

For lossless transmission lines, $\hat{\boldsymbol{Z}} = j\omega\boldsymbol{L}$, $\hat{\boldsymbol{Y}} = j\omega\boldsymbol{C}$ with $\boldsymbol{L}$, $\boldsymbol{C}$ represents per-unit-length inductance matrix and capacitance matrix, respectively.

For non-uniform transmission line, the calculation formula of inductance matrix $\boldsymbol{L}$ can be defined as [14]:

$$\boldsymbol{L} = \begin{bmatrix} \frac{\mu_0}{2\pi}\ln\left(\frac{2h_1}{r_1}\right) & \frac{\mu_0}{4\pi}\ln\left(1+\frac{4h_1h_2}{s_{12}^{\ 2}}\right) \\ \frac{\mu_0}{4\pi}\ln\left(1+\frac{4h_2h_1}{s_{12}^{\ 2}}\right) & \frac{\mu_0}{2\pi}\ln\left(\frac{2h_2}{r_2}\right) \end{bmatrix}, \quad (3)$$

where, r_1 and r_2 are the radius of two adjacent cables, h_1 and h_2 are the heights to the ground, s_{12} is the spacing between two cables, μ_0 is the permeability for free space.

To solve capacitance matrix $\boldsymbol{C}$, the electric potential coefficient M is introduced, which can be written as:

$$\boldsymbol{C} = \begin{bmatrix} C_{1G}+C_{12} & -C_{12} \\ -C_{21} & C_{2G}+C_{12} \end{bmatrix} = \boldsymbol{M}^{-1}, \quad (4)$$

$$\begin{cases} M_{11} = \frac{1}{2\pi\varepsilon_0}\left(\frac{1}{\varepsilon_r}\text{In}\frac{1}{r_1} + \varepsilon_e\text{In}\frac{1}{r_1+\Delta r_1} - \text{In}\frac{1}{2h_1}\right) \\ M_{12} = S_{21} = \frac{1}{4\pi\varepsilon_0}\text{In}\left(1+\frac{4h_1h_2}{s_{12}^{\ 2}}\right) \\ M_{22} = \frac{1}{2\pi\varepsilon_0}\left(\frac{1}{\varepsilon_r}\text{In}\frac{1}{r_2} + \varepsilon_e\text{In}\frac{1}{r_2+\Delta r_2} - \text{In}\frac{1}{2h_2}\right) \end{cases}, \quad (5)$$

where, ε_0 is the permittivity for free space and ε_r the relative dielectric constant, ε_e the effective dielectric constant which can be defined by $\varepsilon_e = (\varepsilon_r - 1)/\varepsilon_r$, $\Delta\ r_1$ and Δr_2 the dielectric thickness.

By differentiating the coupled, first-order phasor MTL equations in (1), (2) with respect to line position x and substituting each other, the y can be replaced in the form of uncoupled, second-order ordinary differential equations which are coupled together. To solve these equations, it is necessary to decouple the min to n separate MTL equations with a similarity transformation [15-18]. By solving each set of separate equation, the calculated results can be transformed back to the original voltages and currents through variable transformation. Therefore, we define the relationships between the actual phasor line voltages $\hat{\boldsymbol{V}}$ and current $\hat{\boldsymbol{I}}$, and the mode voltages $\hat{\boldsymbol{V}}_m$ and currents $\hat{\boldsymbol{I}}_m$ by using the transformational matrices $\hat{\boldsymbol{T}}_V$, $\hat{\boldsymbol{T}}_I$, then we can obtain the decoupled equations of second-order MTL as follows:

$$\frac{d^2}{dx^2}\hat{\boldsymbol{V}}_m(x) = \hat{\boldsymbol{T}}_V^{-1}\hat{\boldsymbol{Z}}\hat{\boldsymbol{Y}}\hat{\boldsymbol{T}}_V\hat{\boldsymbol{V}}_m(x) = \hat{\gamma}^2\hat{\boldsymbol{V}}_m(x), \quad (6)$$

$$\frac{d^2}{dx^2}\hat{\boldsymbol{I}}_m(x) = \hat{\boldsymbol{T}}_I^{-1}\hat{\boldsymbol{Y}}\hat{\boldsymbol{Z}}\hat{\boldsymbol{T}}_I\hat{\boldsymbol{I}}_m(x) = \hat{\gamma}^2\hat{\boldsymbol{I}}_m(x). \quad (7)$$

By solving $\hat{\boldsymbol{T}}_V$ and $\hat{\boldsymbol{T}}_I$, the mode voltages and currents on the basis of the sum of forward- and backward-travelling wave can be obtained. According to the transformation relationship, they can be transformed back to the actual voltages and currents along with the transmission lines:

$$\hat{\boldsymbol{V}}(x) = \hat{\boldsymbol{T}}_V\left(\boldsymbol{e}^{-\hat{\gamma}x}\hat{\boldsymbol{V}}_m^+ + \boldsymbol{e}^{\hat{\gamma}x}\hat{\boldsymbol{V}}_m^-\right), \quad (8)$$

$$\hat{\boldsymbol{I}}(x) = \hat{\boldsymbol{T}}_I\left(\boldsymbol{e}^{-\hat{\gamma}x}\hat{\boldsymbol{I}}_m^+ - \boldsymbol{e}^{\hat{\gamma}x}\hat{\boldsymbol{I}}_m^-\right). \quad (9)$$

For uniform transmission lines, the phasor voltages and currents are related to the chain-parameter matrix, that is:

$$\begin{pmatrix} \hat{\boldsymbol{V}}(L) \\ \hat{\boldsymbol{I}}(L) \end{pmatrix} = \hat{\boldsymbol{\Phi}}(L)\begin{pmatrix} \hat{\boldsymbol{V}}(0) \\ \hat{\boldsymbol{I}}(0) \end{pmatrix} = \begin{bmatrix} \hat{\phi}_{11}(L) & \hat{\phi}_{12}(L) \\ \hat{\phi}_{21}(L) & \hat{\phi}_{22}(L) \end{bmatrix}\begin{pmatrix} \hat{\boldsymbol{V}}(0) \\ \hat{\boldsymbol{I}}(0) \end{pmatrix}, \quad (10)$$

where, the chain-parameter in (10) can be equivalent to:

$$\hat{\phi}_{11}(L) = 0.5\boldsymbol{Y}^{-1}\boldsymbol{T}_I(\boldsymbol{e}^{\gamma L} + \boldsymbol{e}^{-\gamma L})\boldsymbol{T}_I^{-1}\boldsymbol{Y}, \quad (11)$$

$$\hat{\phi}_{12}(L) = -0.5\boldsymbol{Y}^{-1}\boldsymbol{T}_I\boldsymbol{\gamma}(\boldsymbol{e}^{\gamma L} - \boldsymbol{e}^{-\gamma L})\boldsymbol{T}_I^{-1}, \quad (12)$$

$$\hat{\phi}_{21}(L) = -0.5\boldsymbol{T}_I(\boldsymbol{e}^{\gamma L} - \boldsymbol{e}^{-\gamma L})\boldsymbol{\gamma}^{-1}\boldsymbol{T}_I^{-1}\boldsymbol{Y}, \quad (13)$$

$$\hat{\phi}_{22}(L) = 0.5\boldsymbol{T}_I(\boldsymbol{e}^{\gamma L} + \boldsymbol{e}^{-\gamma L})\boldsymbol{T}_I^{-1}. \quad (14)$$

For curved non-uniform cables, non-uniformity is mainly manifested by the variation of parasitic parameters at each point along the cables. To solve crosstalk in this case, a simple method is to treat it as a discretely uniform MTL [18]. This method requires to divide a cable into cascade sections, each of them can be approximated as a uniform sub-segment with chain-parameter $\hat{\phi}_k$, as shown in Fig. 2.

Then the chain-parameter matrix of the entire non-uniform cable can be obtained by multiplying the chain-parameter matrix of each uniform sub-segments, that is:

$$\hat{\Phi}(L) = \hat{\phi}_n(\Delta x_n)\times\ldots\times\hat{\phi}_i(\Delta x_i)\times\ldots\times\hat{\phi}_1(\Delta x_1). \quad (15)$$

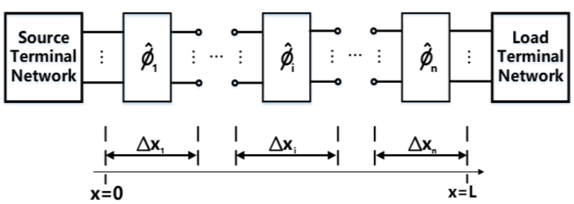


Fig. 2. Chain-parameter cascade of curved non-uniform transmission lines.

The relationship between the phasor voltages and currents of the curved non-uniform cable at both ends can also be expressed by a chain parameter matrix. With the terminal conditions in the form of Thevenin equivalents, we obtain:

$$\begin{aligned}&\left(\hat{\boldsymbol{\Phi}}_{12} - \hat{\boldsymbol{\Phi}}_{11}\hat{\boldsymbol{Z}}_S - \hat{\boldsymbol{Z}}_L\hat{\boldsymbol{\Phi}}_{22} + \hat{\boldsymbol{Z}}_L\hat{\boldsymbol{\Phi}}_{21}\hat{\boldsymbol{Z}}_S\right)\hat{\boldsymbol{I}}(0)\\ &= \hat{\boldsymbol{V}}_L - \left(\hat{\boldsymbol{\Phi}}_{11} - \hat{\boldsymbol{Z}}_L\hat{\boldsymbol{\Phi}}_{21}\right)\hat{\boldsymbol{V}}_S,\end{aligned} \quad (16)$$

$$\hat{\boldsymbol{I}}(L) = \hat{\boldsymbol{\Phi}}_{21}\hat{\boldsymbol{V}}_S + \left(\hat{\boldsymbol{\Phi}}_{22} - \hat{\boldsymbol{\Phi}}_{21}\hat{\boldsymbol{Z}}_S\right)\hat{\boldsymbol{I}}(0), \quad (17)$$

where, $\hat{\boldsymbol{Z}}_S$ and $\hat{\boldsymbol{Z}}_L$ are the impedance matrices of the near and far terminals, $\hat{\boldsymbol{V}}_S$ and $\hat{\boldsymbol{V}}_L$ the excitation source matrices of the near and far terminals, respectively. Terminal current $\hat{\boldsymbol{I}}(0)$ and $\hat{\boldsymbol{I}}(L)$ can be obtained from equations (16) and (17). Finally, we can obtain the crosstalk $\hat{\boldsymbol{V}}(0)$ and $\hat{\boldsymbol{V}}(L)$ at both ends of curved non-uniform cables through Thevenin equivalents, which will be used to derive optimal wiring rules.

B. Numerical validation of crosstalk analytic calculation

A validation model is designed to validate the calculation method above, as shown in Fig. 3. The model consists of two curved cables with a radius of 0.9mm and a dielectric thickness of 0.95 mm. The spacing is 25mm, and the height to the ground satisfies $h = 100 + 70sin\left(\pi x/1000 + \pi\right)$ mm. The aggressor cable is excited by a V_S =1V voltage over frequency (0,500MHz), all terminal impedance are 50Ω.

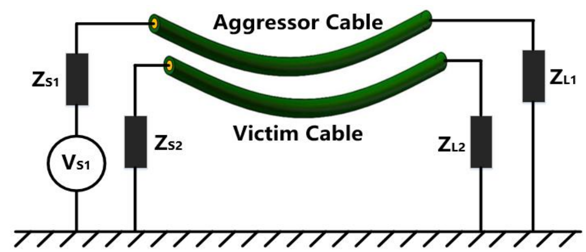


Fig. 3. Electrical connection of a two curved cables model above a ground plane

In this paper, we use a full-analysis commercial software CST based on the transmission line matrix (TLM) technique to validate the proposed method. By using 2D (TL) modeling technique, the equivalent circuit model of cables is obtained and then the crosstalk is calculated by using AC combine results solver. The AC simulation task provides three different ways for cable field coupling, and we choose the first type which ignores the radiation effects. Also, the loss effect can be set in the 2D (TL) modeling settings.

The calculated crosstalk voltages on victim cable by the proposed method and CST are drawn in Fig. 4. It can be seen that the induced voltage at near and far end of the victim cable calculated from our proposed method is well in accordance with that from CST in a wider frequency range.-However, it should be noted that there is a slight difference at higher frequency. The main reason is the difference in the extraction accuracy of the distributed parameters. Table 1 summarizes the calculation time and required memory of our method and the CST. We can see that our method consumes less memory and performs better efficiency.

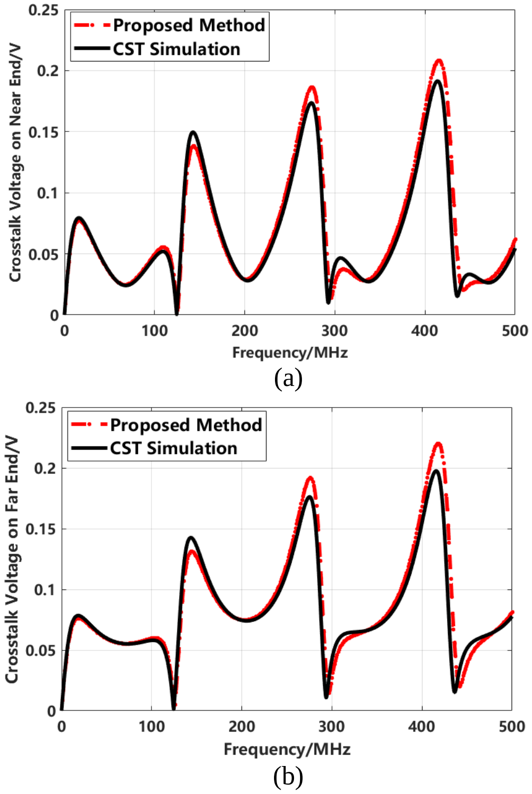


Fig. 4. Comparison of crosstalk voltage on victim cable: (a) near end; (b) far end.

Table 1: Comparison of two methods

	Proposed Method (by MATLAB)	CST Simulation
Computation Time	0.86s	2.7 Mins
Required Memory	3KB	2.08MB

III. THEORETICAL DERIVATION OF OPTIMAL WIRING RULES IN FIXED WORKING FREQUENCY

A. Definition of "σ area"

Sensitive devices often operate within a specific frequency range, and crosstalk generated in this range may cause greater harm. Therefore, the smaller the sum of crosstalk in this frequency range, the lower probability of performance degradation and breakdown happen to the interfered sensitive device. In this paper, a "σ area" is presented to evaluate the impact of crosstalk, which is defined as the area enclosed by the crosstalk waveform and the coordinate axis, as illustrated in Fig. 5, and calculated by:

$$S_\sigma = \int_{F_1}^{F_2} f(x)dx, \tag{18}$$

where, $f(x)$ is the relationship of the induced voltage and the frequency.

According to equations (3) and (4), the waveform of induced voltage is related to the values of inductance matrix and capacitance matrix, and varies with the wiring parameters, such as length, height to the ground, spacing and so on, which will lead to the variation of σ area. Therefore, we can minimize S_σ by changing the wiring of cables and obtain the best routing.

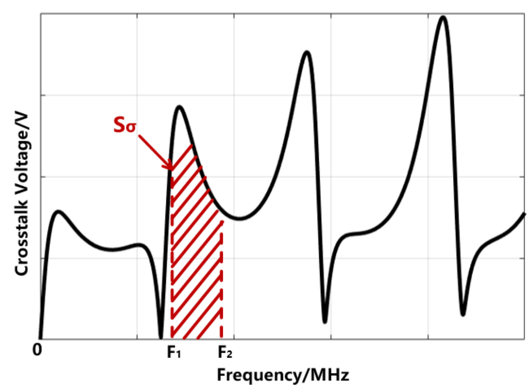


Fig. 5. Definition of "σ area".

B. Relationship between "σ area" and wiring

In applications, the interconnected cables between devices are usually in a relaxed state, as shown in Fig. 6. The cable wiring can be expressed with an approximate function as follows:

$$h = h_0 + a\sin\left(\pi x/\Delta s + \pi\right)\text{mm},$$

where, h defines the height to the ground of cable with respect to cable position$x$, h_0 the height of mounting points which means an initial height above the ground, Δs the spacing between two fixed mounting points, a the degree of bending of cable. Since h_0 and Δs usually have fixed values, the cables wiring depends mainly on the value of parameter a, and the probability can be characterized by a function of $S_\sigma(a)$.

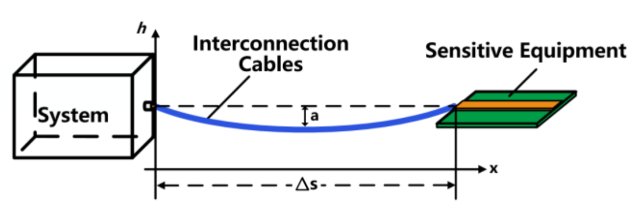


Fig. 6. Wiring of interconnection cables between devices.

Assuming h_0=80mm, Δs=500mm, and the working frequency of sensitive device ranges from 250MHz to 270MHz. The relationship curve between $S_\sigma(a)$ and parameter a can be drawn by changing a from 0 mm to 75 mm, as shown in Fig. 7. The curve shows that σ area decreases first and then increases with increased a.

As shown in Fig. 7, the value of σ area get the minimum when the parameter are aches point P, which means that the crosstalk sum value in the frequency range is minimum. Thus, it is determined that the wiring in this case is the optimal one under a given working conditions.

The optimal wiring analysis calculation process between two fixed points can be summarized as following steps:

1) Define the"σ area";

2) Draw the relation curve of S_σ about independent variables under certain conditions;

3) Determine the minimum crosstalk and optimal wiring on the basis of the above curve.

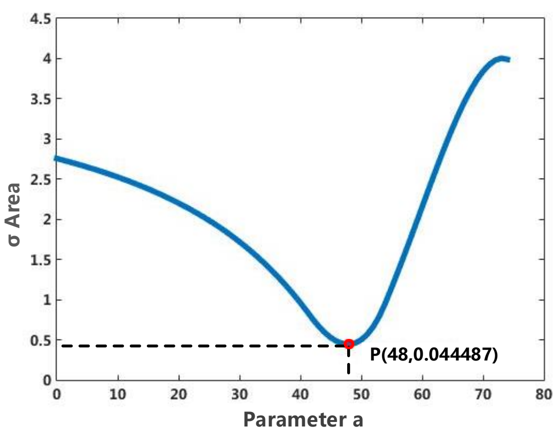


Fig. 7. Relationship between σ area and parameter a.

C. Physical interpretation of optimal wiring

The resonance point is an inherent characteristic of a system network containing inductive and capacitive components. The per-unit-length equivalent circuit for MTL, shown in Fig. 8, indicates that resonance exists among transmission lines.

When the length of transmission line is equal to half of the wavelength, the current distribution along line enhances significantly, known as generalized resonance. Letting L represents the length of transmission lines, the crosstalk voltage on the interfered lines will exhibit the same frequency rules due to the resonance of the transmission lines system in the vicinity and its multiplication of the frequency:

$$f_0=c/2L. \tag{19}$$

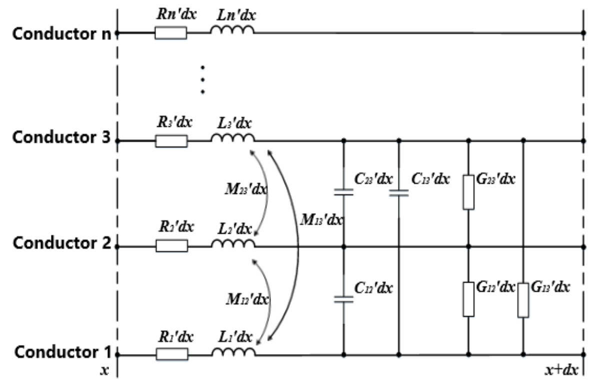


Fig. 8. The per-unit-length equivalent circuit for MTL.

So, the length of the interconnection cable will also change with the parameter a, which will cause the resonance point to move. When resonant frequency does not fall within the operating frequency, the value of σ area can be greatly reduced.

On the other hand, the value of parameter a determines the bending degree of a cable, the larger the parameter a, the smaller the height of each uniform sub-segment to the ground based on the cascade of curved cables. According to the calculation formula of capacitance matrix, the equivalent capacitance decreases as the height to the ground decreases, thus the capacitive coupling is weakened. In addition, the inductive coupling will be weakened as well due to the reduction of closed loop area enclosed by the interference circuit.

However, it doesn't mean that the larger the parameter a, the better the effect of interference rejection. There are multiple resonance points of a transmission lines system, the increasing in length will bring a new resonance point in the operating frequency range of the sensitive equipment.

IV. EXPERIMEMNTAL VALIDATION OF OPTIMAL WIRING

To validate the analytic calculation of the optimal wiring rules, we build a well-controlled cables crosstalk testing plat form by using Vector Network Analyzer as shown in Fig. 9. The core radius of tested cables is 0.9 mm, the insulation layer thickness is 0.95 mm, the spacing between two cables is 25mm and 80 mm high above a ground reference which is a finite metallic plane with a length of 1m and a width of 0.5 m, the distance between two fixed mount points is 500mm. Two cables are connected to the analyzer through SMA connectors, where the red one connected to Port1 is the aggressor cable, and the blue one connected to Port2 is the victim cable. Each terminal of the cables is matched to a 50Ω impedance.

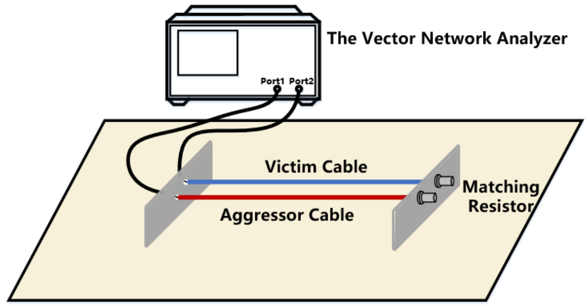
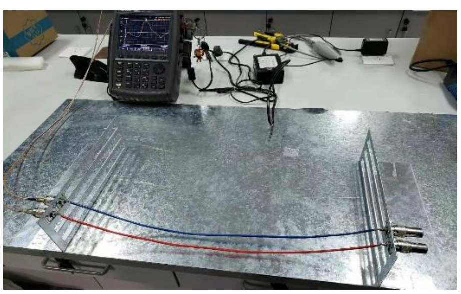


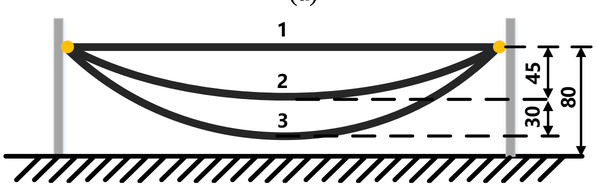
Fig. 9. Schematic diagram of two-cables coupling experiment

The output signal from Port 1 return to Port 2 via the cables and the conduction coupling path between them, so the tested cables can be regarded as a two-port network from Port 1 to Port 2. Therefore, once the S_{21} is measured, the near-end crosstalk of the victim cable can be obtained when the 1V voltage is injected into the aggressor cable.

The experimental testing device is shown in Fig. 10 (a). By increasing the length, the cables are naturally bended and sag between the two mounting points, as illustrated in Fig. 10 (b). The lengths of the cables in three groups of experiments are 500mm, 510mm, 525mm. Measurements were performed over (30KHz, 500MHz) and S_{21} of three experiments were recorded.



(a)



(b)

Fig. 10. Coupling experiments: (a) experimental test picture of S_{21}; (b) three groups of experiments.

The measured results of S_{21} with different parameter a are shown in Fig. 11. It obviously shows that the relationship between resonance points and the length of cables is in good consistent with equation (19), the longer the length, the resonant frequencies shift to the left. The resonance point of the blue solid curve is not the fundamental frequency point, but the peak point of the second waveform after the resonant points shift as the length of cables increases and the bending changes.

Table 2 shows three experimental results of σ area by calculating the region enclosed by the measured waveform of S_{21} and the coordinate axis from 200MHz to 400MHz, which demonstrates the relationship between S_σ and parameter a. When parameter a equals 45 in the No.2 experiment, the value of σ area is minimum. So compared with the analysis result, there is a consentaneous conclusion that $S_\sigma$decreases first and then increases with the increased a, and crosstalk has the minimum impact on system when a takes a value around 48. Consequently, the conclusion and the proposed calculation method of the optimal wiring can be validated through the experiments.

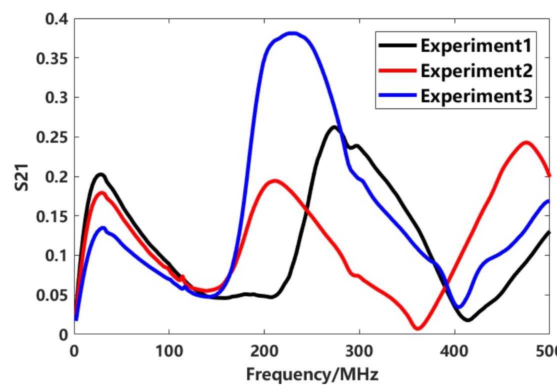


Fig. 11. Measurement waveform of S_{21} for each test.

Table 2: Calculation results of S_σ from 200 to 400MHz

Experiments	**No.1**	**No.2**	**No.3**
	a=0	a=45	a=75
S_σ	3.1262	1.8469	4.4576

V. CONCLUSION

To solve the relationship between curved cables wiring and crosstalk impacts, an analytical method to minimize curved cables crosstalk and determine the optimal wiring rules in a fixed frequency range is proposed. Firstly, a theoretical calculation model for crosstalk of curved cables is derived based on similarity transformation and chain-parameter matrix cascade, and validated by numerical simulation. Then, by defining the“σ area” to evaluate the impact of crosstalk the relation curve between crosstalk and bending degree of cables is obtained. On this basis, an optimal wiring is determined via the inflection point of the curve and a physical explanation is given by use of the generalized resonance and the crosstalk coupling mechanism. Finally, a measurements of parameter S_{21} are carried out to validate the proposed calculation method of the optimal wiring for curved cables. This work is contributed to guiding the wiring of cables in industrial application. However, the method still has some limitations. Our work takes single core cables as the object, for shielded or twisted pair cables, the calculation model needs to be further modified to analyze wiring rules due to the change of basic structure.

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