# EXPERIMENTAL CIRCUIT MODEL GENERATION OF NON-UNIFORM COUPLED MULTI-CONDUCTOR STRUCTURES

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## ABSTRACT

In the paper a new method is described for the experimental circuit modeling of non-uniform coupled multi-conductor structures. The method can handle a large number of coupled conductors N since it reduces the modeling of the 2N-port to the modeling of a number easier to model 4-port structures. All electrical properties, such as reflection, transmission, backward and forward crosstalk between the conductors of the structure are included in the model. To illustrate the method, a 35-pins high density backplane connector is modeled.

## INTRODUCTION

With the increase of clock speed and miniaturization in high-speed digital circuits, the complexity of computer and telecom systems also increases. The closely spaced off-chip interconnections and the dense large pin count IC-packages are no longer negligible and can cause system failure. In order to incorporate all the effects of the passive devices, suitable circuit models are required. Recently a lot of research efforts have been spent in the experimental circuit modeling of interconnection structures and packages [1]-[4]. However all derived models are only valid at low frequencies or neglect the coupling between the different conductors or are only valid for a limited number of coupled conductors. A frequently used approach in the experimental generation of a circuit model is the global optimization of all parameters in a proposed circuit model [5]. When many parameters are involved, the optimization can be computer memory and time consuming and can suffer from convergence problems. In [6] a new theoretical method is described for the high-frequency circuit modeling of non-uniform coupled multi-conductor systems. The method is in particular very useful for the modeling of structures with many conductors N (N>100) and takes into account the coupling from one conductor to all other conductors. In this paper the method is adapted to make it practically more applicable. In [6] modeling of 2- and 4-ports were used, while in this paper we base the modeling only on 4-port characterizations. The method is also very suited for the circuit modeling of devices for which the signal/ground configuration can differ (e.g., large pin count electronic packages, multi-pins backplane connectors, ...). The problem with circuit modeling such devices is that the parameter values of the circuit model are different for each different configuration. When a traditional method (global optimization) is used to determine these parameter values, the complete modeling process must be repeated for each possible configuration. This is not the case for the new proposed modeling method. A number of basis configurations consisting of two coupled conductors are modeled. The circuit model of an arbitrary signal/ground configuration can easily be determined from the circuit models of these basis configurations. To illustrate this method, the circuit model for two different signal/ground configurations of a high-density backplane connector will be derived.

## THEORY

A structure consisting of N signal conductors and a reference conductor can be modeled by the lumped circuit model shown in figure 1. All conductors are inductively and capacitively coupled. In the figure most coupling elements are omitted for sake of clarity. Each section is completely determined by its **R**-, **L**-, **G**- and **C**-matrix. For non-uniform structures the parameter values of each section can be different. As mentioned before,

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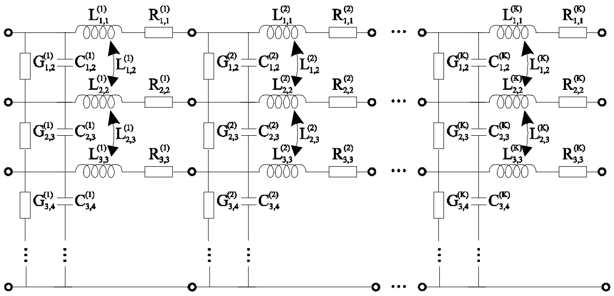

Figure1: Lumped element model of a coupled structure consisting of N signal conductors and 1 reference conductor.

determining all parameter values of the model in an optimization process leads to convergence problems, especially when starting from bad initial values. To determine the parameter values a complete new procedure is developed. For simplicity reason we assume that the coupled structures have no losses (**R**=**G**=**0**) but the method is also applicable to lossy structures.

In the first step of this procedure we reduce the 2N-port structure to a 4-port substructure by short-circuiting all conductors, except for two (conductors i and j), at both sides of the conductor with the reference conductor. Next, the obtained coupled transmission line structure is characterized by its S-parameters (or Z-parameters) and an equivalent circuit model (figure 2) is derived. The parameter values of the model are fitted to the measurements through optimization. We notice that for each section only 6 parameter values must be determined: $C^{(k)}_{m,i,i}, C^{(k)}_{m,i,j}, C^{(k)}_{m,j,j}, L^{(k)}_{m,i,i}, L^{(k)}_{m,i,j}, \text{and } L^{(k)}_{m,j,j}$. The obtained parameter values of the substructure are not the parameter values of the corresponding conductor of the 2N-port. In order to find the relation between parameter values of both models we define the **Q**-matrix as the inverse of the **L**-matrix.

$$\mathbf{Q} = \mathbf{L}^{-1} \qquad (1)$$

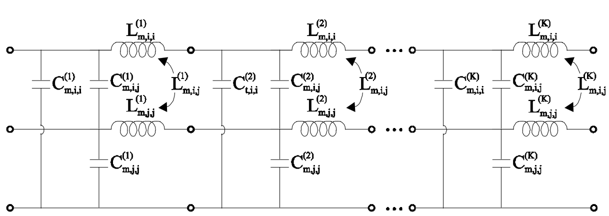

Figure 2: Lumped element model of two coupled signal conductors.

It can be shown that

$$\begin{pmatrix} \left(\mathbf{C}^{(k)}\right)_{i,i} & \left(\mathbf{C}^{(k)}\right)_{i,j} \\ \left(\mathbf{C}^{(k)}\right)_{i,j} & \left(\mathbf{C}^{(k)}\right)_{j,j} \end{pmatrix} = \begin{pmatrix} C^{(k)}_{m,i,i} + C^{(k)}_{m,i,j} & -C^{(k)}_{m,i,j} \\ -C^{(k)}_{m,i,j} & C^{(k)}_{m,j,j} + C^{(k)}_{m,i,j} \end{pmatrix}$$
$$\begin{pmatrix} \left(\mathbf{Q}^{(k)}\right)_{i,i} & \left(\mathbf{Q}^{(k)}\right)_{i,j} \\ \left(\mathbf{Q}^{(k)}\right)_{i,j} & \left(\mathbf{Q}^{(k)}\right)_{j,j} \end{pmatrix} = \begin{pmatrix} L^{(k)}_{m,i,i} & L^{(k)}_{m,i,j} \\ L^{(k)}_{m,i,j} & L^{(k)}_{m,j,j} \end{pmatrix}^{-1} \qquad (2)$$

With $\mathbf{C}^{(k)}$ and $\mathbf{Q}^{(k)}$ the element matrices of the complete 2N-port structure. This means that, by short-circuiting all conductors at both sides with the reference conductor except two, we find the diagonal elements (i,i) and (j,j) and the non-diagonal element (i,j) of the **C**- and **Q**-matrix. This step is repeated for all possible combinations of conductors i and j: (i,j) = (1,2), (1,3), ..., (N-1,N). In this way each diagonal element of both matrices is found N-1 times. Due to measurement errors and non-perfect optimizations there will be a variation among the obtained element values. In the second step of the modeling procedure we calculate the mean value of each diagonal element, we replace each diagonal element by its mean value and we repeat step 1 of the procedure. But this time, since we already know the diagonal elements of both matrices, we can use this information to reduce the number of parameters to be optimized per section from 6 to 2: $C^{(k)}_{m,i,j}$ and $Q^{(k)}_{m,i,j}$. The other parameter values of the circuit model are given by

$$C^{(k)}_{m,i,i} = \left(C^{(k)}\right)_{i,i} - C^{(k)}_{m,i,j}$$
$$C^{(k)}_{m,j,j} = \left(C^{(k)}\right)_{j,j} - C^{(k)}_{m,i,j}$$
$$L^{(k)}_{m,i,i} = \frac{\left(Q^{(k)}\right)_{j,j}}{\left(Q^{(k)}\right)_{i,i}.\left(Q^{(k)}\right)_{j,j} - Q^{(k)}_{m,i,j}} \qquad (3)$$
$$L^{(k)}_{m,i,j} = -\frac{\left(Q^{(k)}\right)_{i,j}}{\left(Q^{(k)}\right)_{i,i}.\left(Q^{(k)}\right)_{j,j} - Q^{(k)}_{m,i,j}}$$
$$L^{(k)}_{m,j,j} = \frac{\left(Q^{(k)}\right)_{i,i}}{\left(Q^{(k)}\right)_{i,i}.\left(Q^{(k)}\right)_{j,j} - Q^{(k)}_{m,i,j}}$$

In the last step of the modeling procedure we invert the **Q**-matrix to find the **L**-matrix.

In order to characterize and to model an N-conductor interconnection we need to characterize and to model $\frac{1}{2}$ N.(N-1) 4-port structures. In practice however this number can be reduced on the basis of symmetry of the considered teststructures and by neglecting the capacitive C- and Q-coupling between conductors at far

Figure 3: Test fixture for characterisation of a non-shielded backplane connector.

distance or between conductors shielded from each other. Further on, we notice that it is much more easy to characterize a large number of two coupled structures than one N-conductor structure with N large.

## RESULTS

To illustrate the method described above, we have modeled a non-shielded high-density multi-pins backplane connector (5 rows 2 mm grid Millipacs2 backplane connector of Framatome Connectors International - figure 3). The connector has 35 pins (5 rows, 7 columns). The structure is modeled with the circuit model of figure 1. 3 sections were needed to model the connector up to 5 GHz. For each section the associated **C**- and **Q**-matrix were derived. These matrices are independent of the signal/ground configuration of the connector. To find the **C**- and **Q**-matrix of the circuit model of a specific configuration, we only have to remove the rows and columns corresponding with the ground pins, no extra measurements or optimizations are required. In order to demonstrate this we have considered two different specific signal/ground configurations (figure 4). Configuration A is a 1/1 configuration. For each signal pin there is one ground pin. Configuration B is a 4/1 configuration. There is one ground pin for each four signal pins. Verification of the model is done by comparing circuit model simulations with the measured S-parameters of the connector with the specific signal/ground configuration. The results of the comparison are shown on figure 5 in time domain for configuration A and on figure 6 in frequency domain for configuration B.

From these pictures we can conclude that the agreement both in time and frequency domain between measurement and simulation is excellent for both configurations.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| A | X | M | M | X | O | O | X |
| B | O | X | X | O | X | X | O |
| C | X | O | O | X | O | O | X |
| D | O | X | X | O | X | X | O |
| E | X | O | O | X | O | O | X |

configuration A

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| A | O | O | O | O | O | O | O |
| B | O | O | O | O | O | O | O |
| C | X | X | X | X | X | X | X |
| D | M | O | O | O | O | O | O |
| E | M | O | O | O | O | O | O |

configuration B

Figure 4: Two specific signal/ground pin configurations (O: signal pin, M: monitored signal pin, X ground pin).

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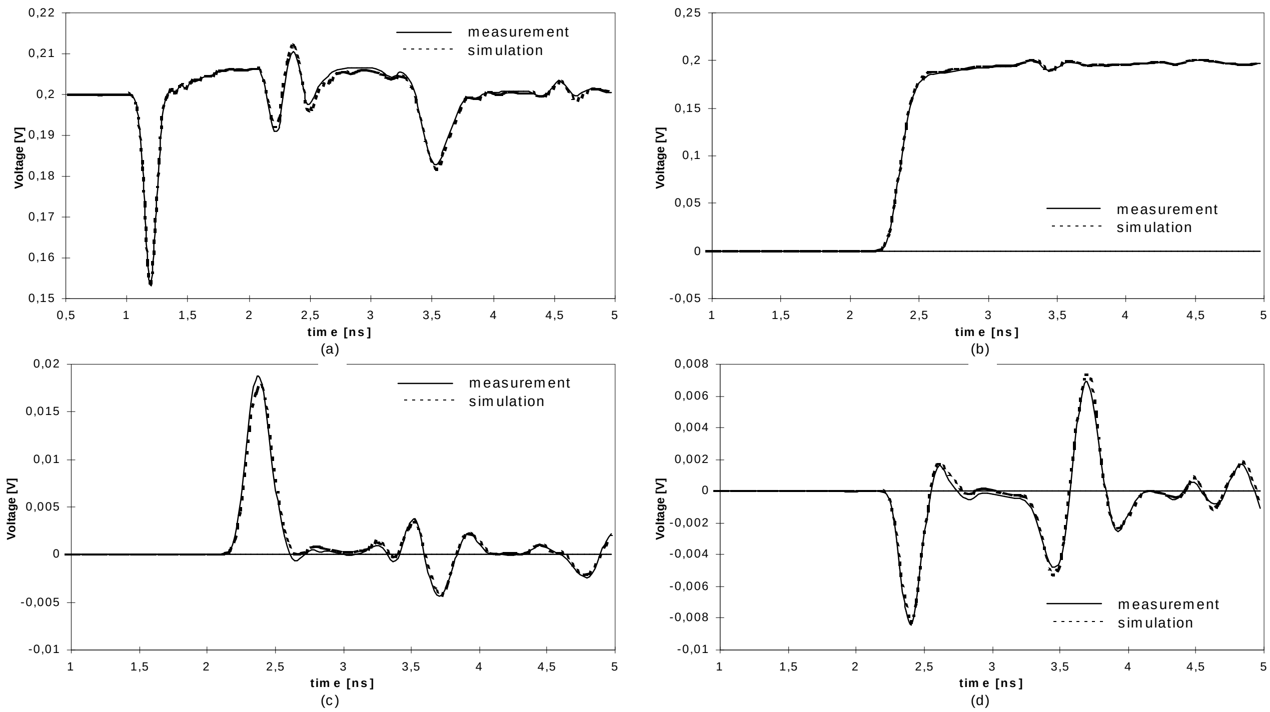


Figure 5: Time domain comparison between measurement and simulation, configuration A, rise time 100 ps, (a) reflection at pin A2, (b) transmission through pin A2, (c) backward and (d) forward crosstalk between pins A2 en A3.

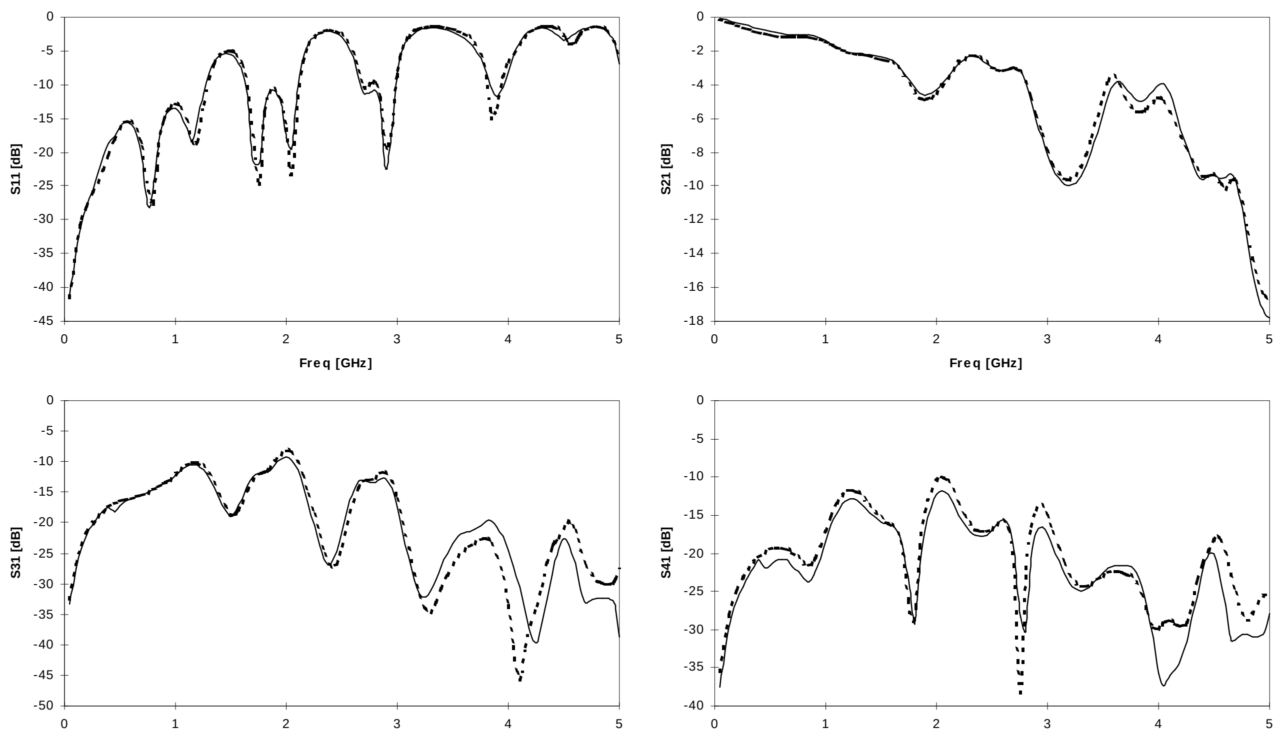


Figure 6: Frequency domain comparison between measurement and simulation, configuration B, (a) reflection at pin D1, (b) transmission through pin D1, (c) backward and (d) forward crosstalk between pins D1 en E1.