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An Overview of Modal Transmission Schemes

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Abstract **— We present the state of the art in the area of modal transmission used to reduce echo and internal crosstalk in a multichannel link using an untransposed multiconductor interconnection. We emphasize the difference between this approach and the more general concept of internal crosstalk cancellation. We also show how modal signaling can be extended to a category of non-uniform interconnections and how external crosstalk can be reduced in a modal transmission scheme.**

I. Introduction

This paper is about modal transmission used to reduce echo and internal crosstalk in a multichannel electrical link providing $m \geq 2$ channels. The link is linear and comprises a multiconductor interconnection, having $n \geq m$ transmission conductors (TCs) and a reference conductor or ground conductor (GC). We assume an untransposed interconnection, that is an interconnection which does not use frequent permutations of the conductors to obtain certain propagation properties. Such a link is shown in Fig. 1. The main advantages of modal signaling are that the $m - 1$ shields or wide TC-to-TC spacings used in a fast m-channel single-ended or differential link are not needed, and that only m leads are required.

Multiconductor transmission line (MTL) theory defines and investigates the propagation modes of the interconnection. It is the basis of modal transmission, since, in modal transmission, each channel is allocated to a propagation mode.

Section II provides the main definitions and notations used later. Section III is a review of modal transmission in a multichannel link using an untransposed multiconductor interconnection. Section IV presents the more general concept of internal crosstalk cancellation and emphasizes how it differs from modal transmission. Section V presents a new extension of MTL theory and modal signaling to a category of non-uniform interconnections. Section VI introduces two new techniques for the reduction of external crosstalk in a modal transmission scheme. The conclusion addresses applications.

II. Definitions and Notations

The following definitions and notations are for instance introduced in [1] and [2]:

■ *TC-to-TC coupling* collectively designates mutual capacitance between the TCs and mutual impedance between loops each comprising one of the TCs and the GC;

■ *echo* is the phenomenon by which a signal sent or received at an end of the link, in one of the channels, is followed by the reception of a delayed noise in the same channel, at the same end of the link;

■ *internal crosstalk* is the phenomenon by which a signal sent in one of the channels produces noise in another channel;

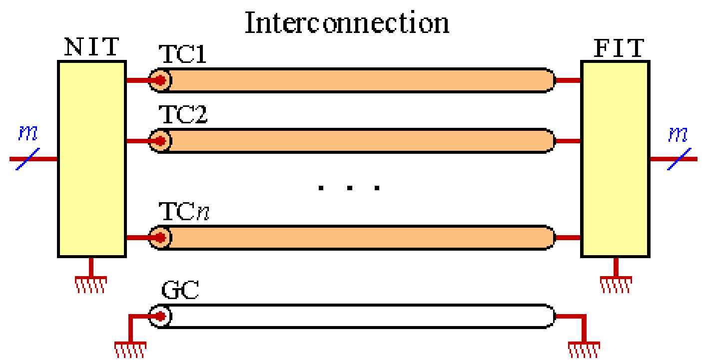

Fig. 1. A point-to-point link providing m channels, consisting of an interconnection, a near-end interface and termination device (NIT) and the far-end interface and termination device (FIT). The interconnection has n transmission conductors (TCs) and a reference conductor (GC).

■ *external crosstalk* is the occurrence of noise caused by interactions between the link and other circuits of the device in which it is built;

■ z is the curvilinear abscissa along the interconnection, the interconnection extending from $z = 0$ to $z = \mathcal{L}$;

■ $\mathbf{i}$ is the column vector of the natural currents $i_1,..., i_n$;

■ $\mathbf{v}$ is the column vector of the natural voltages $v_1,..., v_n$;

■ $\mathbf{Z}'$ is the the per-unit-length (p.u.l.) impedance matrix;

■ $\mathbf{Y}'$ is the p.u.l. admittance matrix;

■ *uniform* means independent of the abscissa z ;

■ the transition matrix from modal electrical variables to natural electrical variables are two matrices $\mathbf{S}$ and $\mathbf{T}$ satisfying

$$\begin{cases} \mathbf{T}^{-1}\mathbf{Y}'\mathbf{Z}'\mathbf{T} = \Gamma^2 \\ \mathbf{S}^{-1}\mathbf{Z}'\mathbf{Y}'\mathbf{S} = \Gamma^2 \end{cases} \tag{1}$$

where

$$\Gamma = \mathrm{diag}_n(\gamma_1, \ldots, \gamma_n) \tag{2}$$

is the diagonal matrix of order n of the propagation constants;

■ the characteristic impedance matrix $\mathbf{Z}_C$ is given by

$$\begin{aligned} \mathbf{Z}_C &= \mathbf{S}\,\Gamma^{-1}\mathbf{S}^{-1}\mathbf{Z}' = \mathbf{S}\,\Gamma\,\mathbf{S}^{-1}\mathbf{Y}'^{-1} \\ &= \mathbf{Y}'^{-1}\mathbf{T}\Gamma\mathbf{T}^{-1} = \mathbf{Z}'\,\mathbf{T}\Gamma^{-1}\mathbf{T}^{-1} \end{aligned} \tag{3}$$

■ $\mathbf{i}_M = \mathbf{T}^{-1}\,\mathbf{i}$ is the column vector of the modal currents;

■ $\mathbf{v}_M = \mathbf{S}^{-1}\,\mathbf{v}$ is the column vector of the modal voltages;

■ *reflection* is the phenomenon by which a wave propagating in a given direction produces a wave propagating in the opposite direction;

■ *matched* means having an impedance matrix equal to $\mathbf{Z}_C$, a matched termination producing no reflection.

III. Survey of Modal Signaling in untransposed interconnections

In conventional modal signaling:
— the interconnection model used to design the link is a uniform MTL model, i.e. an MTL model in which $\mathbf{Z}'$ and $\mathbf{Y}'$ are uniform;
— each of the m transmission channels is allocated to a modal electrical variable, that is a modal voltage or modal current;
— the near-end interface and termination device (NIT) and the far-end interface and termination device (FIT) shown in Fig. 1 must perform the necessary conversions, which are linear combinations defined by a transition matrix from modal electrical variables to natural electrical variables (that is $\mathbf{S}$ or $\mathbf{T}$).

An early concept of modal signaling appeared about 20 years ago as a way of eliminating crosstalk in a uniform interconnection, based on a principle stating that "there is no crosstalk between modes as there is between non-modal propagation" [3] [4]. However, this idea is incorrect, since it assumes that crosstalk is only caused by coupling during propagation, that is by TC-to-TC coupling. Let us clarify this. If an interconnection is uniform, reflections can only occur at its ends. Echo is always due to one or more reflections, but reflections can cause echo and crosstalk. A reflection may even generate crosstalk without echo, in the case of a single-ended link using diagonal matching [1, § 9] [5, § III]. Consequently, modal transmission alone does not guarantee the cancellation of crosstalk [5, § X] [6, § IX]. The inventions [3] and [4] and another early invention [7] on crosstalk elimination use the assumption that "in general, n conductors and ground have n orthogonal modes". Though orthogonal modes occur in some special cases (for instance, a balanced pair), this assertion need not be correct [1, § 7] [5, § X] [6, § V and § VI]. Unlike [3], [7] describes a link which does not use one of the available modes, the discarded mode being defined as the common-mode. Unfortunately this requirement cannot be met in general, since the common mode need not be a propagation mode of an interconnection.

A modal transmission scheme proposed some years later uses a general theory of the modes of a uniform multiconductor interconnection, based on the MTL model [5] [6] [8]. This *ZXtalk method* combines modal transmission with the use of a NIT and/or of a FIT behaving substantially as a matched termination. It takes into account the frequency dependence of $\mathbf{Z}_C$ and the possible frequency dependence of the transition matrix from modal electrical variables to natural electrical variables used to define the transmission channels. The ZXtalk method was subdivided into a *general ZXtalk method* and a *special ZXtalk method for completely degenerate interconnection* [9] [10]. Today, the latter has an improved definition and is referred to as *special ZXtalk method*; in a nutshell it encompasses the links using a decoupled interconnection, that is links in which $\mathbf{S}$ or $\mathbf{T}$ is considered to be equal to the identity matrix [1, § 15]. The definition of the former changes accordingly. In the special ZXtalk method, linear combinations of signals are not required in the NIT and FIT, so that their structure may be much simpler than the one needed for the general ZXtalk method.

Other authors have investigated various aspects of the implementation of modal transmission schemes to digital links and shown the advantages of this approach [11] [12] [13] [14] [15] [16]. Two high-speed modal chip-to-chip links have been built and described, the first one using an interconnection having $n = 4$ conductors (referred to as *a bundle*) to obtain $m = 4$ channels [17], the second one using 2 balanced pairs implementing the general ZXtalk method to obtain $m = 3$ channels, two for data and one for a source synchronous clock [18] [19].

The theory used in the definition of the ZXtalk method emphasizes the concept of total decoupling, because it provides an independent propagation of each eigen-voltage with the associated eigen-current. New results on total decoupling and an important assumption commonly used in the design of a modal link have recently been established [2]. This assumption (now a proven result) is that an approximate model of an interconnection built in a PCB or MCM, which accurately takes high-frequency losses into account, can use a characteristic impedance matrix and a transition matrix from modal electrical variables to natural electrical variables which are computed as if losses were not present. This property is very important for practical implementations, because it entails that the linear combinations performed by the NIT and FIT can be frequency independent and that the termination circuit in the NIT and/or FIT can be a network of resistors.

IV. Internal Crosstalk Cancellation Schemes

Modal signaling may be viewed as a variation of the general and old crosstalk cancellation concept of noise subtraction [20]. In noise subtraction, for given NIT and FIT, the signal at an end of TC*i* caused by an excitation of TC*j* is determined in the form of a transfer function or time-domain response, which is usually measured but could also be computed. The knowledge of these transfer functions or time-domain responses is then used to eliminate internal crosstalk using signal processing performed in the NIT and/or in the FIT. An advantage of this approach is that it is not based on a uniform MTL model. This comes at a price: in general, this noise subtraction concept leads to intensive real-time computations when the interconnection is not electrically short, because the transfer functions are strongly frequency dependent and also strongly dependent on the interconnection length. Some new signaling schemes applicable to an arbitrary nonuniform interconnection use this type of crosstalk cancellation [21] [22] [23] [24].

In the meaning of Section III, modal signaling is a special case of this general concept where the signal processing requirements are much lighter because the signal processing is based on modal transforms which are mildly frequency dependent (due to losses) and independent of the interconnection length. The ZXtalk technique is a special case of modal signaling in which the signal processing requirements are minimal because matched terminations are used to remove reflections and a high-frequency lossless model can be used for the synthesis of frequency-independent circuits in the NIT and FIT. Thus, simple high-speed low-cost analog circuits can be used for signal processing.

V. An Extension of Modal Signaling

Up to now, our definitions of modal signaling and of the ZXtalk method are based on a uniform MTL model. It is in many cases not possible to build a uniform interconnection, for instance when the interconnection spans over several substrates having different dielectric constants. If the interconnection can be modeled as a MTL which need not be uniform, the second order differential equations derived from the telegrapher's equations are

$$\begin{cases} \dfrac{d^2\mathbf{v}}{dz^2} - \dfrac{d\,\mathbf{Z}'}{dz}\mathbf{Z}'^{-1}\dfrac{d\,\mathbf{v}}{dz} - \mathbf{Z}'\,\mathbf{Y}'\;\mathbf{v} = \mathbf{0} \\ \dfrac{d^2\,\mathbf{i}}{dz^2} - \dfrac{d\,\mathbf{Y}'}{dz}\mathbf{Y}'^{-1}\dfrac{d\,\mathbf{i}}{dz} - \mathbf{Y}'\,\mathbf{Z}'\;\mathbf{i} = \mathbf{0} \end{cases} \tag{4}$$

where we have assumed that $\mathbf{Z}'$ and $\mathbf{Y}'$ are differentiable. At each abscissa z, we can assume that $\mathbf{Z}'\,\mathbf{Y}'$ is diagonalizable, so that there exist two invertible matrices $\mathbf{T}$ and $\mathbf{S}$ complying with (1) and (2). However, $\mathbf{T}$, $\mathbf{S}$ and Γ depend on z and need not be continuous functions of z, so that it is in general not possible to consider that $\mathbf{T}$ and $\mathbf{S}$ define a modal transform leading to a simple solution of (4). We can formally define, at a given abscissa z, a vector of the modal voltages $\mathbf{v}_M = \mathbf{S}^{-1}\,\mathbf{v}$ and a vector of the modal currents $\mathbf{i}_M = \mathbf{T}^{-1}\,\mathbf{i}$, and a characteristic impedance matrix $\mathbf{Z}_C$ by (3).

The TCs of the non-uniform interconnection may in some cases be proportioned such that $\mathbf{S}$ and $\mathbf{Z}_C$ are uniform. For instance, in the case of a balanced pair, the symmetry entails that $\mathbf{S}$ may be chosen uniform, and the width and spacing of the conductor give a full control over $\mathbf{Z}_C$ in the case where losses are negligible.

If we assume that $\mathbf{S}$ and $\mathbf{Z}_C$ are uniform, we can use a uniform $\mathbf{T}$ given by the Theorem 3 of [2]. Using this $\mathbf{T}$, we get

$$\begin{cases} \dfrac{d^2\,\mathbf{v}_M}{dz^2} - \Gamma^2\mathbf{v}_M = \dfrac{d\,\Gamma}{dz}\,\Gamma^{-1}\,\dfrac{d\,\mathbf{v}_M}{dz} \\ \dfrac{d^2\,\mathbf{i}_M}{dz^2} - \Gamma^2\,\mathbf{i}_M = \dfrac{d\,\Gamma}{dz}\,\Gamma^{-1}\,\dfrac{d\,\mathbf{i}_M}{dz} \end{cases} \tag{5}$$

The matrices Γ and $d\,\Gamma/dz$ being diagonal, (5) is decoupled, so that we have achieved a modal decomposition applicable to the non-uniform MTL. The solution of (5) is

$$\begin{cases} \mathbf{v}_M = \exp\left(-\int_0^z \Gamma du\right)\mathbf{v}_{M0+} + \exp\left(\int_0^z \Gamma du\right)\mathbf{v}_{M0-} \\ \mathbf{i}_M = \exp\left(-\int_0^z \Gamma du\right)\mathbf{i}_{M0+} + \exp\left(\int_0^z \Gamma du\right)\mathbf{i}_{M0-} \end{cases} \tag{6}$$

where $\mathbf{v}_{M\,0+}$, $\mathbf{v}_{M\,0-}$, $\mathbf{i}_{M\,0+}$ and $\mathbf{i}_{M\,0-}$ are z-independent vectors depending on the boundary conditions at $z = 0$ and $z = \mathcal{L}$. We will not further develop the theory of this link. However, it can be proven that the solution (6) has properties which are analogous to the total decoupling defined for a uniform MTL model.

Consequently, the ZXtalk method can be extended to an interconnection which may be modeled as a non-uniform $(n + 1)$-conductor MTL such that $\mathbf{S}$ and $\mathbf{Z}_C$ are substantially uniform [25].

VI. Mitigation of External Crosstalk

Modal signaling does not reduce external crosstalk. The dominant source of external crosstalk is usually common-mode coupling at the near-end or at the far-end. It typically happens in the line drivers or line receivers of an IC, because of ground bounce or power bounce.

The transmitting circuit (TX-circuit) shown in Fig. 2 and the receiving circuit (RX-circuit) and termination circuit shown in Fig. 3 provide a protection against common-mode coupling to an implementation of the ZXtalk method [26] [27]. The chip containing the TX-circuit of Fig. 2 and the chip containing the RX-circuit and termination circuit of Fig. 3 each have n signal terminals (ST1 to STn) and a common terminal (CT). For any integer j such that $1 \le j \le n$, the STj is connected to the TCj of an off-chip interconnection, and the CT is connected to the off-chip (substrate) ground. The CT and the chip ground do not share any lead of the chip. In the chip, the CT is not connected to the chip

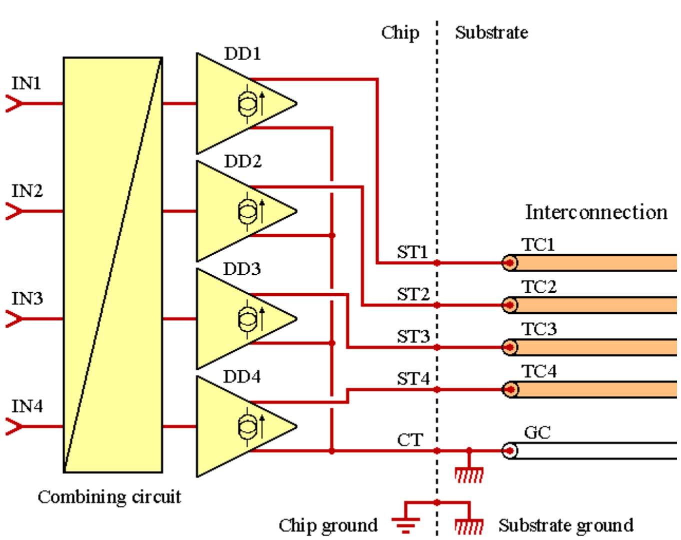

Fig. 2. A pseudo-differential TX-circuit for the ZXtalk method or another modal signaling scheme.

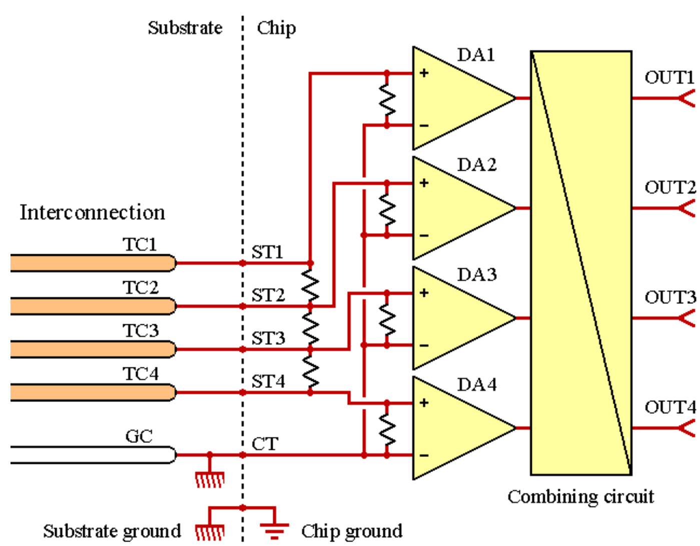

Fig. 3. A pseudo-differential RX-circuit and an on-chip M-type termination circuit for the ZXtalk method.

ground, even though it is externally coupled to the chip ground via the substrate ground. This configuration minimizes common impedances. The combining circuits shown in Fig. 2 and Fig. 3 are used to perform the linear combinations defined by the modal transform. They are not necessary for the special ZXtalk method. For brevity, we shall consider that the schematics diagrams of Fig. 2 and 3 are self-explanatory. We note that it is possible to consider that Fig. 2 shows a pseudo-differential TX-circuit, and that Fig. 3 contains a pseudo-differential RX-circuit.

However, the configurations shown in Fig. 2 and Fig. 3 do not relate to a pseudo-differential link, since in this case the interconnection would comprise a common conductor. Pseudo-differential signaling also provides a good protection against external crosstalk. It has been shown that pseudo-differential signaling can be combined with the ZXtalk method to reduce internal crosstalk and external crosstalk [10] [28].

VII. CONCLUSION

In this paper, we have reviewed modal signaling schemes and we have presented some improvements to them.

A bend in the plane of the TCs of a balanced pair produces some mode conversion. A bend in the plane of a planar arrangement of more than two TCs produces more mode conversion. Mode conversion being a limiting factor of modal signaling, modal links using a large number of TCs are more relevant to configurations where bends are not prevalent. Another factor playing against the widespread use of modal links other than differential serial links is the lack of standardized interface. There are many types of links for which these factors are immaterial, for instance in the substrate of an MCM or in flex top-side bridges between MCMs [29] [30]. In such applications, modal signaling can easily be used to increase the wiring density and reduce costs.

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