Echo-Free and Crosstalk-Free Transmission in Particular Interconnections

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***Abstract*—We explore several designs for implementing the special ZXtalk method for completely degenerate interconnections, capable of providing reduced echo and internal crosstalk in multiconductor interconnections. Transmission circuits comprising a MIMO series-series feedback amplifier are adequate to obtain a wide bandwidth. The external crosstalk may also be reduced, using an additional conductor to obtain a pseudo-differential scheme.**

***Index Terms*—Crosstalk, interconnection, multiple-input multiple-output (MIMO) systems, signal integrity, transmission.**

I. Introduction

In this letter, we consider an interconnection which uses n transmission conductors to provide n transmission channels. For instance, the interconnection could be built in the substrate of a multi-chip module (MCM) or on a printed circuit board (PCB). This letter addresses the reduction of echo, internal crosstalk (i.e., crosstalk between the channels) and external crosstalk (i.e., crosstalk between channels and the outside world).

In [1] and [2], the authors have shown that a modal transmission technique called the ZXtalk method can be used to reduce echo and internal crosstalk when the interconnection behaves as a uniform multiconductor transmission line (MTL). As shown in Fig. 1, this method implements termination circuits which are matched terminations (i.e., terminations having an impedance matrix equal to the characteristic impedance matrix $\mathbf{Z}_C$ of the MTL). This ZXtalk method also uses transmitting circuits (TX circuits) and receiving circuits (RX circuits) performing linear combinations of signals, in order to allocate one propagation mode to each channel. It should be pointed out that, in general, the propagation modes of a non-degenerate MTL are not orthogonal [3], [4].

When the propagation constants of the different propagation modes may be considered as substantially equal, the MTL is said to be completely degenerate. It was initially pointed out in [5] and later (but independently) by Ciamulski and Gwarek [6] that it is possible to eliminate internal crosstalk in completely degenerate interconnections (CDI). This possibility was further discussed in Section IX of [2], as a particular case of the ZXtalk method.

In Section II below, we provide an independent definition of this special ZXtalk method for CDI, and Section III discusses the selection of the type of TX circuits and RX circuits for wide-band transmission. Section IV introduces a new scheme capable of reducing internal and external crosstalk.

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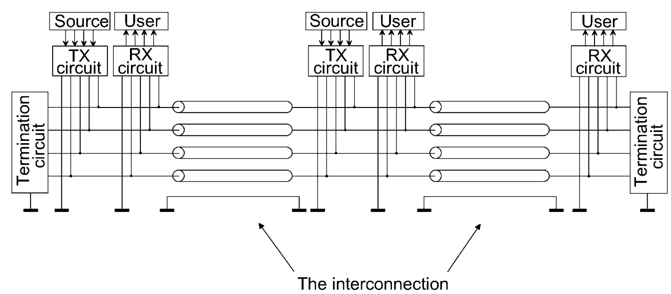

Fig. 1. ZXtalk method for reduction of crosstalk and echo.

II. Special ZXtalk Method for CDI

The special ZXtalk method uses a CDI consisting of n transmission conductors numbered from 1 to n and a reference conductor (ground). It can be implemented as shown in Fig. 1. The n currents flowing on the transmission conductors are called the natural currents, as opposed to modal currents. The n voltages between the transmission conductors and ground are called the natural voltages, as opposed to modal voltages. The special ZXtalk method for CDI provides, in a given frequency band, n channels each corresponding to a signal to be sent from the input of at least one TX circuit to the output of at least one RX circuit. The method comprises the following steps [5].

Step 1: the interconnection is proportioned, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, so as to be able to model the interconnection as a uniform MTL having substantially equal propagation constants in the given frequency band. Such a MTL is characterized by a per-unit-length (p.u.l.) impedance matrix $\mathbf{Z}$ and a p.u.l. admittance matrix $\mathbf{Y}$, both independent of the abscissa z along the MTL, and such that [2]

$$\mathbf{YZ} = \mathbf{ZY} = \gamma^2 \mathbf{1}_n \tag{1}$$

where γ is the common value of the propagation constants of the different propagation modes. Equal propagation constants for instance occur when losses are negligible and the propagation medium is homogeneous, but we won't need these assumptions since the same result may also be obtained in an inhomogeneous medium [7].

Step 2: the characteristic impedance matrix $\mathbf{Z}_C$ of the MTL in the known frequency band is computed as [2]

$$\mathbf{Z}_C = \frac{1}{\gamma}\mathbf{Z} = \gamma \mathbf{Y}^{-1}. \tag{2}$$

TABLE I
POSSIBLE DESIGNS FOR THE INTERFACE CIRCUITS

Interface	Connection	Design using natural voltages (voltage-mode signaling)	Design using natural currents (current mode signaling)
TX circuit	series (low impedance)	$\mathbf{V}_T = \pm a \ \mathrm{diag}_n(\alpha_1,\ldots,\alpha_n) \ \mathbf{X}_I$	$\mathbf{V}_T = a \, \mathbf{Z}_C \ \mathrm{diag}_n(\lambda_1,\ldots,\lambda_n) \ \mathbf{X}_I$
	parallel (high impedance)	$\mathbf{I}_T = a \, \mathbf{Z}_C^{-1} \ \mathrm{diag}_n(\alpha_1,\ldots,\alpha_n) \ \mathbf{X}_I$	$\mathbf{I}_T = \pm a \ \mathrm{diag}_n(\lambda_1,\ldots,\lambda_n) \ \mathbf{X}_I$
RX circuit	series (low impedance)	$\mathbf{X}_0 = \pm \, \mathrm{diag}_n(\beta_1,\ldots,\beta_n) \ \mathbf{Z}_C \ \mathbf{I}$	$\mathbf{X}_0 = \mathrm{diag}_n(\mu_1,\ldots,\mu_n) \ \mathbf{I}$
	parallel (high impedance)	$\mathbf{X}_0 = \mathrm{diag}_n(\beta_1,\ldots,\beta_n) \ \mathbf{V}$	$\mathbf{X}_0 = \pm \, \mathrm{diag}_n(\mu_1,\ldots,\mu_n) \mathbf{Z}_C^{-1} \ \mathbf{V}$

Step 3: a termination circuit having an impedance matrix approximating $\mathbf{Z}_C$ (i.e., a matched termination circuit) is placed at at least one end of the interconnection.

Step 4: a TX circuit delivers n natural electrical variables (i.e., natural currents or natural voltages) to the interconnection, each natural electrical variable being proportional to one of the input signals.

Step 5: a RX circuit outputs n output signals each being proportional to a single natural electrical variable.

As defined above, the special ZXtalk method for CDI uses one transmission conductor (hence one natural electrical variable) for each channel. Thus, it is not defined as a modal transmission technique, since it does not explicitly allocate a propagation mode to each channel. However, it provides a perfect cancellation of echo and internal crosstalk, in an ideal implementation [2].

The steps 4 and 5 encompass 8 possible designs each corresponding to 2 equations defining the linear combinations performed in the TX circuits and in the RX circuits. These equations [2] are summarized in Table I in which:

— we use $\mathbf{X}_I$ and $\mathbf{X}_O$ to denote the column-vector of the n input signals of a TX circuit, and of the n output signals of a RX circuit, respectively;

— we use $\mathbf{V}_T$ and $\mathbf{I}_T$ to denote the column-vectors of the voltages produced by a TX circuit connected in series with the interconnection and of the currents produced by a TX circuit connected in parallel with the interconnection, respectively;

— we use $\mathbf{I}$ and $\mathbf{V}$ to denote the column-vectors of the currents sensed by a RX circuit connected in series with the interconnection and of the voltages sensed by a RX circuit connected in parallel with the interconnection, respectively;

— the dimensionless coefficient a is equal to 1 if only one end of the interconnection is used, or to 2 if matched termination circuits are used at both ends;

— the proportionality coefficients $\alpha_i, \beta_i, \lambda_i$, and μ_i are used to take into account the gain of each interface in each channel.

— $\mathrm{diag}_n(x_1, \cdots, x_n)$ denotes the diagonal matrix of size $n \times n$ of the entries x_1 to x_n.

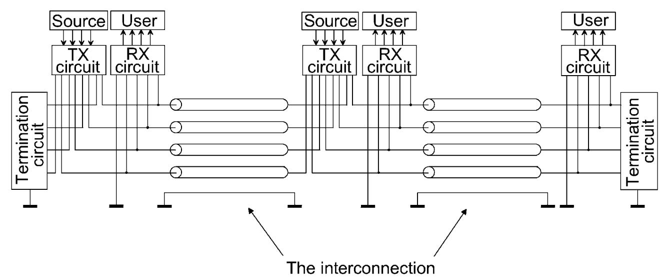

Fig. 2. Scheme using natural voltages in which no non-trivial linear combination is needed.

III. SELECTING THE TYPES OF INTERFACE CIRCUITS

Let us call "trivial" a linear combination when it is merely the product of only one signal by a coefficient. Since $\mathbf{Z}_C$ and $\mathbf{Z}_C^{-1}$ are not diagonal matrices in the cases of interest (that is to say, when a significant coupling exists between the n transmission conductors), Table I shows that two types of TX circuits and two types of RX circuits must perform non-trivial linear combinations, even though natural electrical variables are used for transmission. Using only trivial linear combinations seems desirable, because it suggests a simpler circuitry and consequently improved performances (maximum frequency of operation and accuracy). If we want to use only trivial linear combinations, Table I tells us that:

— if the natural electrical variables used for transmission are voltages (voltage-mode signaling), then the TX circuits are connected in series and the RX circuits in parallel with the interconnection, as shown in Fig. 2;

— if the natural electrical variables used for transmission are currents (current-mode signaling), then the TX circuits are connected in parallel and the RX circuits in series with the interconnection, as shown in Fig. 3.

If we consider the scheme shown in Fig. 2, we find that the TX circuits must provide n pairs of output terminals, each pair forming a low-impedance floating output. If we consider the scheme shown in Fig. 3, we find that the RX circuits must provide n pairs of input terminals, each pair forming a low-impedance floating input. If the interconnection is a set of n traces of a printed circuit board, $2n$ package leads are required for connecting an IC containing a TX circuit of Fig. 2 or a RX circuit of Fig. 3 to the interconnection. This is a first

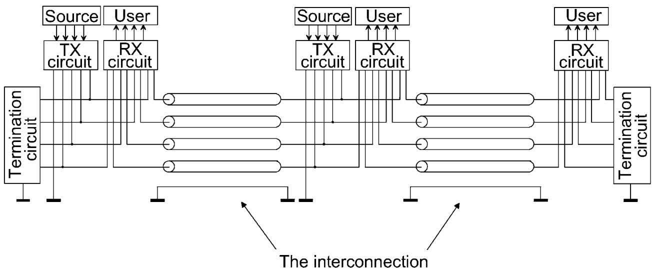

Fig. 3. Scheme using natural currents in which no non-trivial linear combination is needed.

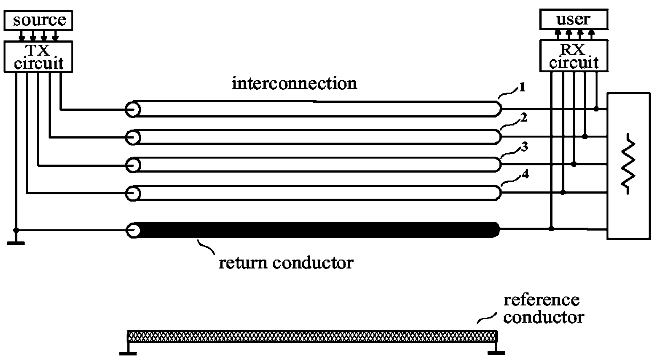

Fig. 4. Pseudo-differential link (PDL) discussed in Section IV. The block containing the resistor symbol is a floating termination circuit.

restriction. A second restriction is that the known designs for obtaining the above-mentioned floating outputs and inputs do not seem appropriate for operation well above 10 MHz. Finally, we note that both schemes are such that the signs of the signals are reversed at each side of a TX circuit. This is a third restriction if TX circuits are used elsewhere than at the ends of the interconnection, as in Figs. 2 and 3.

The problems caused by the floating ports can only be avoided if all interfaces are connected in parallel, as shown in Fig. 1. Table I tells us that, in this case:

— for voltage-mode signaling, the TX circuits perform non-trivial linear combinations determined by $\mathbf{Z}_{\mathrm{C}}^{-1}$ while the RX circuits only use trivial linear combinations;

— for current-mode signaling, the RX circuits perform non-trivial linear combinations determined by $\mathbf{Z}_{\mathrm{C}}^{-1}$ while the TX circuits only use trivial linear combinations.

Nowadays, we know that a multiple-input and multiple-output (MIMO) series-series feedback amplifier (MIMO-SSFA) [8], [9] can be used to perform such non-trivial linear combinations with a good accuracy in a wide band. It was for instance shown that a MIMO-SSFA may provide enhanced transmission up to $f_T/5$ using 8 GHz bipolar transistors.

IV. Schemes for Reducing External Crosstalk

The links shown in Figs. 1–3 are susceptible to external crosstalk because they involve the reference conductor (ground) in the propagation of signals. External crosstalk may be reduced with the following steps, which lead to a pseudo-differential link (PDL) such as the one shown in Fig. 4.

Step 6: a wide return conductor (RC) distinct from the reference conductor is used as an electromagnetic screen shielding the transmission conductors from the reference conductor, and a characteristic impedance matrix with respect to the RC, denoted by $\mathbf{Z}_{\mathrm{RC}}$, is used in the place of $\mathbf{Z}_C$, as explained in [10] for the so-called ZXnoise method. Thus, a floating termination circuit having an impedance matrix approximating $\mathbf{Z}_{\mathrm{RC}}$ is placed at at least one end of the interconnection.

Step 7: the RX circuits is such that each signal delivered to the user is mainly determined by the voltage between one of the transmission conductors and the RC.

As is the case for the ZXnoise method, the step 6 is only possible for some structures of interconnection. Unlike the ZXnoise method, the step 6 uses a floating termination circuit presenting a non-diagonal impedance matrix with respect to its terminal intended to be connected to the RC.

In Fig. 4, the RC is grounded near the TX circuit, so that it is possible to use a TX circuit producing ground-referenced signals determined by $\mathbf{Z}_{\mathrm{RC}}^{-1}$, such as a MIMO-SSFA.

V. Conclusion

We have shown how the ZXtalk method for CDI, which provides a reduction of echo and internal crosstalk, can be implemented to obtain a wide bandwidth, using the MIMO-SSFA. With the addition of a wide return conductor, the ZXtalk method for CDI may be combined with pseudo-differential signaling to obtain a protection against external crosstalk.

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