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Pseudo-Differential Links Using a Wide Return Conductor and a Floating Termination Circuit

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Abstract **— This paper introduces a new type of pseudo-differential link in which the interconnection comprises a return conductor wider than the transmission conductors, whereas conventional pseudo-differential links use a common conductor similar to the transmission conductors. We explain the principle of this signaling scheme, referred to as the ZXnoise method, and the particular properties expected from the p.u.l. impedance and admittance matrices of the interconnection. The essential feature of the ZXnoise method is that it may provide low reflections and a good protection against external crosstalk, because the return conductor in a way acts as an electromagnetic screen, which shields the transmission conductors from ground.**

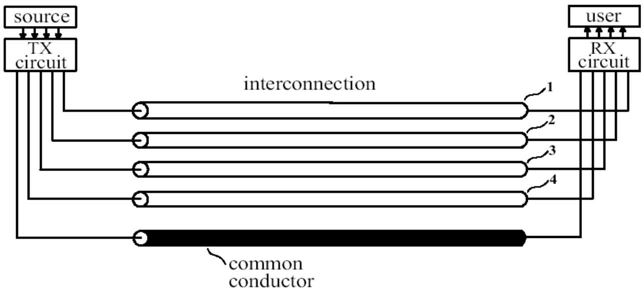
I. Introduction

This paper relates to transmission through a multiconductor interconnection, for obtaining m channels, with $m \geq 2$. Each channel may be used for transmitting analog or digital signals, from a source to a user. In this context, crosstalk between the different channels shall be referred to as *internal crosstalk*. However, there are other crosstalk phenomena which may produce noise, for instance when the interconnection and other conductors are built on the same chip or on the same printed circuit board. We shall refer to these phenomena as *external crosstalk*.

Differential links and pseudo-differential links are intended to provide a good protection against external crosstalk. A differential link providing m channels uses an interconnection having $n = 2m$ transmission conductors (TCs). The authors have recently provided an analysis of crosstalk in balanced interconnections used for differential signaling [1]. A pseudo-differential link (PDL) providing m channels [2, § 4.2.3] uses an interconnection having $n = m$ TCs and a common conductor (CC) distinct from the reference conductor (ground). A PDL is shown in Fig. 1, this link comprising an interconnection having $n = 4$ TCs. The transmitting circuit (TX circuit) receives at its input the signals of the 4 channels of the source, and the receiving circuit (RX circuit) outputs the signals of the 4 channels to the user. Protection against external crosstalk results from the following design requirement: each signal delivered to the user must be mainly determined by the voltage between one of the TCs and the CC.

II. Design Options for a Conventional PDL

In Fig. 1, there is no termination circuit, as is the case in many pseudo-differential signaling methods [2] [3] [4]. Consequently, substantial reflections of signals occur, and this implies limitations on the length $\mathcal{L}$ of the interconnection ($\mathcal{L}$ must be sufficiently small) and on the available bandwidth, since the limitation stated by Jarvis [5] applies ($\mathcal{L}$ should typically be less than one fourth of the distance traveled during the transition time).



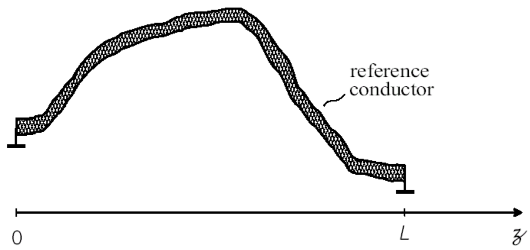


Fig. 1. A conventional pseudo-differential link (PDL) comprising an interconnection consisting of 4 transmission conductors (TCs), numbered from 1 to 4, and a common conductor (CC).

In Fig. 1, since no termination is present, there is no need to maintain a constant characteristic impedance or characteristic impedance matrix along the interconnection, and there is consequently no constraint on the manner of routing the interconnection with respect to ground. Consequently, the reference conductor is shown as an irregular geometrical shape, such that the distance between the conductors of the interconnection and the reference conductor varies as a function of the abscissa z along the interconnection.

Another conventional PDL, shown in Fig. 2, uses a termination [6]. If the designer considers that reflection are not an issue for the CC intended to deliver a reference voltage to the RX circuit, the termination only consists of the resistors R_1 to R_4, each being connected to a TC. If the designer wishes that the CC operates in the same configuration as the TCs, a resistor R_D connected to the CC is also used. If R_D is not present, the termination does not have an impedance matrix with respect to the CC, but it has an impedance matrix $\mathbf{Z}_{G1}$ with respect to the reference conductor. $\mathbf{Z}_{G1}$ is a diagonal matrix of size 4 × 4 equal to

$$\mathbf{Z}_{G1} = \mathrm{diag}_4(R_1, R_2, R_3, R_4) \tag{1}$$

where $\mathrm{diag}_n(x_1,\ldots, x_n)$ denotes the diagonal matrix of size $n \times n$ of the components $x_1,\ldots, x_n$. If R_D is present, the termination has an impedance matrix $\mathbf{Z}_{C2}$ with respect to the CC and an impedance matrix $\mathbf{Z}_{G2}$ with respect to the reference conductor. $\mathbf{Z}_{C2}$ and $\mathbf{Z}_{G2}$ are square matrices of size 5 × 5 equal to

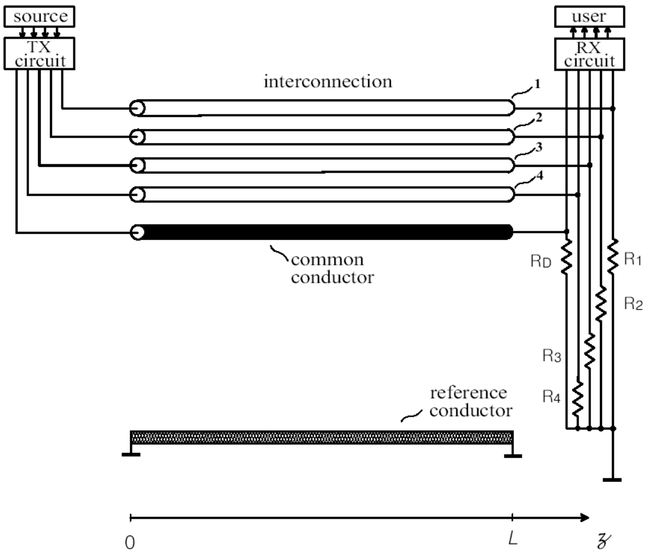


Fig. 2. A conventional PDL using a termination made of grounded resistors.

$$\mathbf{Z}_{C2} = \begin{pmatrix} R_1 + R_D & R_D & R_D & R_D & R_D \\ R_D & R_2 + R_D & R_D & R_D & R_D \\ R_D & R_D & R_3 + R_D & R_D & R_D \\ R_D & R_D & R_D & R_4 + R_D & R_D \\ R_D & R_D & R_D & R_D & R_D \end{pmatrix} \quad (2)$$

and

$$\mathbf{Z}_{G2} = \mathrm{diag}_5\left(R_1, R_2, R_3, R_4, R_D\right) \quad (3)$$

In Fig. 2, instead of being connected to ground, the resistors could be connected to a node intended to present a fixed voltage with respect to ground, for instance a power supply voltage. This technique is used in the Gunning Transceiver Logic (GTL) family [7, pp. 2-3 to 2-17], which is intended to be used in conventional PDLs.

In Fig. 2, since a grounded termination is used to avoid reflections, the interconnection must be such that it is possible to model the propagation in the interconnection using a uniform multiconductor transmission line (MTL) having $n + 2 = 6$ conductors, the MTL using as variables the n natural voltages (which are defined with respect to the reference conductor) and the n natural currents flowing on the TCs and on the CC [8]. This result is typically obtained with a geometry such that the cross section of the interconnection and the reference conductor, in a plane orthogonal to the direction of propagation, does not change over the greatest part of the length of the interconnection, in the vicinity of the TCs. In order to indicate this requirement, the reference conductor is, in Fig. 2, represented as a uniform geometrical shape, such that the distance between the conductors of the interconnection and the reference conductor does not vary as a function of z.

The termination made of grounded resistors should provide an impedance matrix not too different from the characteristic impedance matrix of said (n+2)-conductor MTL. This may happen only if the characteristic impedance matrix of this MTL is sufficiently close to a diagonal matrix, in a suitable frequency band. This implies that the TCs are in a way closer to the reference conductor than to the CC, as in the microstrip and stripline structures shown in Fig. 3.

The state of the art as regards fighting against external crosstalk requires that the routing of all TCs and of the CC must be matched [6], so that substantially equal noise voltages are obtained on all conductors of the interconnection. This seems to be achieved for the configurations shown in Fig. 3. Unfortunately, we see that, in Fig. 3, the CC (5) is close to a TC (4), but far from other TCs (1 and 2). The coupling parameters between an external conductor and a conductor of the interconnection are consequently different for the different conductors of the interconnection, and it is not possible to eliminate external crosstalk. Consequently, according to the pseudo-differential transmission schemes considered so far, there is a discrepancy between an effective protection against external crosstalk which implies that the TCs are in a way closer to the CC than to the reference conductor, and reduced reflections which imply that the TCs are in a way closer to the reference conductor than to the CC. This is why, when m is large, several CCs are needed, for instance one CC every fourth TC [3].

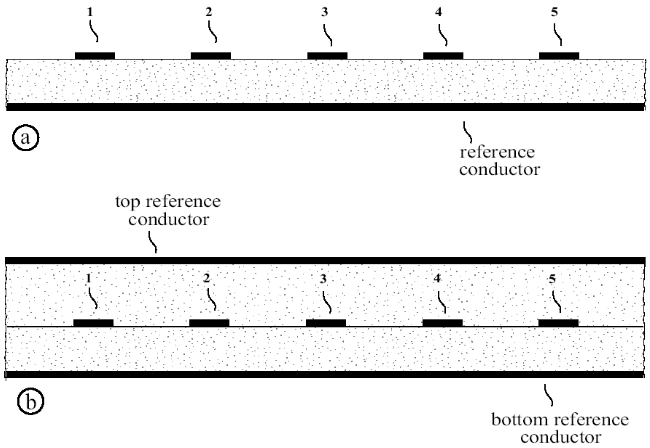


Fig. 3. Two possible cross-sections for the interconnection used in Fig. 2, where 1 to 4 are the TCs and 5 is the CC.

III. Presentation of a New Type of PDL

We will consider interconnections with $n \geq 2$ TCs, referred to as TC1 to TCn, and a return conductor (RC) distinct from the reference conductor. The new ZXnoise method is intended to provide, in a known frequency band, m transmission channels with $n \geq m \geq 2$.

For any integer j such that $1 \leq j \leq n$, at a given abscissa z along the interconnection, let us use i_j to denote the natural current of index j, that is to say the current flowing on the TCj, and let us use v_{Rj} to denote the natural voltage referenced to the RC of index j, that is to say the voltage between the TCj and the RC. We may define the column-vector $\mathbf{I}_R$ of the natural currents i_1,..., i_n and the column-vector $\mathbf{V}_R$ of the natural voltages $v_{R\,1}$,..., $v_{R\,n}$ referenced to the RC.

The designer first proportions the interconnection such that it may, in a part, denoted by B, of the known frequency band, 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, be modeled with a sufficient accuracy as a (n+1)-conductor MTL such that:

— the (n+1)-conductor MTL uses the natural voltages referenced to the RC and the natural currents as variables;
— the (n+1)-conductor MTL has uniform electrical characteristics over its length.

This implies that all conductors other than the conductors of the interconnection may be neglected when one models propagation in the interconnection and that, in particular, the reference conductor may be neglected when one models propagation in the interconnection. For instance, the two structures shown in Fig. 4 are appropriate to obtain

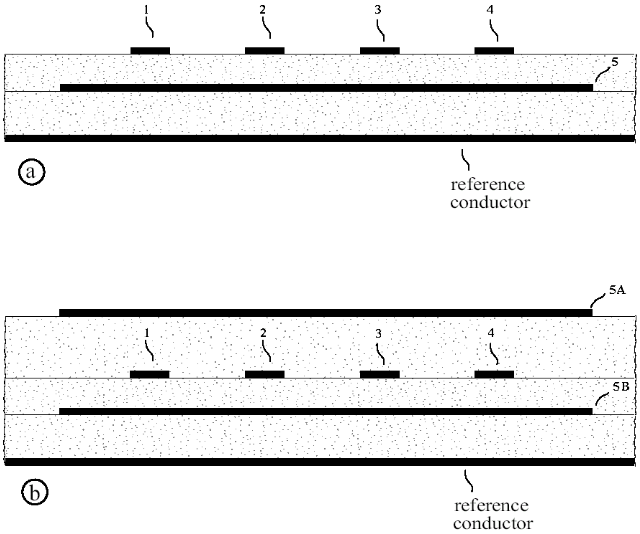


Fig. 4. Two possible cross-sections for the interconnection used in the ZXnoise method, where 1 to 4 are the TCs, where 5 is the RC in the coplanar-strips-over-return-conductor structure (*a*) and where the RC is made of the conductors 5A and 5B in the coplanar-strips-inside-return-conductor structure (*b*).

this result. In such structures, the RC in a way acts as an electromagnetic screen which shields the TCs from ground. It is possible to define, for the (n+1)-conductor MTL, at any frequency f in B, a per-unit-length (p.u.l.) impedance matrix $\mathbf{Z}_R$ and a p.u.l. admittance matrix $\mathbf{Y}_R$, and the applicable telegrapher's equations are:

$$\begin{cases} \dfrac{d\,\mathbf{V}_R}{dz} = -\mathbf{Z}_R\,\mathbf{I}_R \\ \dfrac{d\,\mathbf{I}_R}{dz} = -\,\mathbf{Y}_R\,\mathbf{V}_R \end{cases} \tag{4}$$

where $\mathbf{Z}_R$ and $\mathbf{Y}_R$ are matrices of size $n \times n$.

As shown in Fig. 5, the ZXnoise method uses at least one termination circuit, each termination circuit being floating and, at any frequency in B, approximately characterized by an impedance matrix with respect to the RC, denoted by $\mathbf{Z}_{RL}$. The matrix $\mathbf{Z}_{RL}$ is of size $n \times n$, approximately equal to a diagonal matrix, and proportioned using the characteristic impedance matrix with respect to the RC, denoted by $\mathbf{Z}_{RC}$. The classical results concerning uniform MTLs may be transposed. In particular, the theory of pseudo-matched impedances [9] gives the following results:

— the matrix of the voltage reflection coefficients of the termination circuit with respect to the RC, denoted by $\mathbf{P}_R$, is given by

$$\mathbf{P}_R = \left(\mathbf{Z}_{RL} - \mathbf{Z}_{RC}\right)\left(\mathbf{Z}_{RL} + \mathbf{Z}_{RC}\right)^{-1} \tag{5}$$

— a termination circuit such that $\mathbf{Z}_{RL}$ is a diagonal matrix may be made of n impedors (i.e. linear two-terminal circuit elements), each impedor being connected between a TC and the RC, the n impedors being easily proportioned such that all components of the matrix $\mathbf{P}_R$ have an absolute value less than a sufficiently small arbitrary value;

— it is even possible to determine a termination circuit presenting a diagonal matrix $\mathbf{Z}_{RL}$ minimizing the detrimental effects of reflections, by minimizing a suitable norm of $\mathbf{P}_R$.

The (n+1)-conductor MTL defined by (4) uses natural voltages referenced to the RC and natural currents as variables. Of course, the interconnection used in the ZXnoise method may possibly also be modeled as a (n+2)-conductor MTL. For this purpose, we define the column-vector $\mathbf{I}_G$ of the currents $i_1,..., i_{n+1}$, where the current flowing on the RC is denoted by i_{n+1}, and we define the column-vector $\mathbf{V}_G$ of the natural voltages referenced to ground $v_{G\,1},..., v_{G\,n+1}$, where for $1 \le j \le n$ the voltage between the TC number j and the reference conductor is denoted by $v_{G\,j}$ and the voltage between the RC and the reference conductor is denoted by $v_{G\,n+1}$.

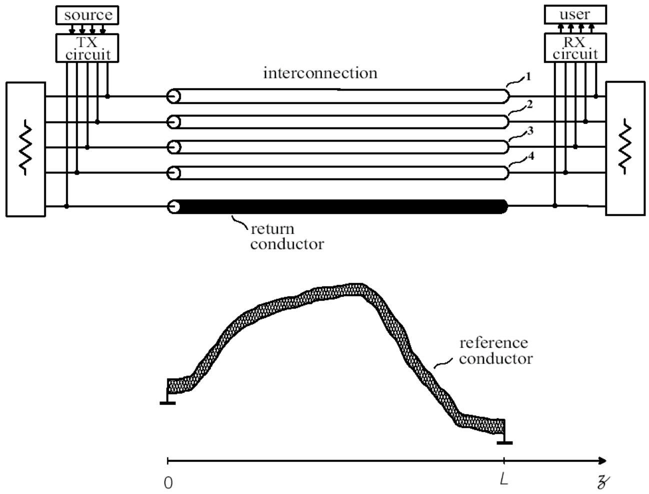


Fig. 5. A PDL implementing the ZXnoise method. At each end, the block containing the resistor symbol is a termination circuit. In some cases (e.g. unidirectional link), the termination circuit on the left is not present.

When it is possible to define, for the (n+2)-conductor MTL, at each abscissa z along the interconnection, at a frequency f in B, a per-unit-length (p.u.l.) impedance matrix $\mathbf{Z}_G$ and a p.u.l. admittance matrix $\mathbf{Y}_G$, the applicable telegrapher's equations are:

$$\begin{cases} \dfrac{d\,\mathbf{V}_G}{dz} = -\mathbf{Z}_G\,\mathbf{I}_G \\ \dfrac{d\,\mathbf{I}_G}{dz} = -\,\mathbf{Y}_G\,\mathbf{V}_G \end{cases} \tag{6}$$

In (6), the matrices $\mathbf{Z}_G$ and $\mathbf{Y}_G$ are of size $(n + 1) \times (n + 1)$. Since we assume that the interconnection may be modeled with a sufficient accuracy as a $(n + 1)$-conductor MTL, it can be shown that

$$\mathbf{Z}_G \approx \begin{pmatrix} \mathbf{Z}_R + Z_{RG}\begin{pmatrix}1\\ \vdots \\ 1\end{pmatrix}\begin{pmatrix}1 & \cdots & 1\end{pmatrix} & Z_{RG}\begin{pmatrix}1\\ \vdots \\ 1\end{pmatrix} \\ Z_{RG}\begin{pmatrix}1 & \cdots & 1\end{pmatrix} & Z_{RG} \end{pmatrix} \tag{7}$$

and

$$\mathbf{Y}_G \approx \begin{pmatrix} \mathbf{Y}_R & -\mathbf{Y}_R\begin{pmatrix}1\\ \vdots \\ 1\end{pmatrix} \\ -\begin{pmatrix}1 & \cdots & 1\end{pmatrix}\mathbf{Y}_R & Y_{RG} + \begin{pmatrix}1 & \cdots & 1\end{pmatrix}\mathbf{Y}_R\begin{pmatrix}1\\ \vdots \\ 1\end{pmatrix} \end{pmatrix} \tag{8}$$

where Z_{RG} and Y_{RG} are a p.u.l. impedance and a p.u.l. admittance which characterize the circuit comprising the RC and the reference conductor, and which may depend on the abscissa z. The equations (7) and (8) provide a description of all properties of the interconnection, with respect to transmission, echo and internal crosstalk.

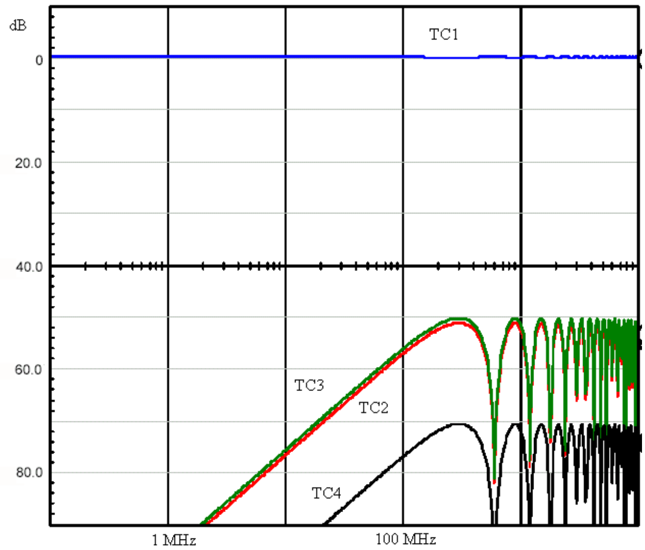


Fig. 6. Loss at the far-end for TC1 to TC4, when TC1 is excited at the near-end.

IV. Example

As an example, an interconnection intended for the ZXnoise method uses the coplanar-strips-inside-return-conductor structure shown in the drawing *b* of Fig. 4. The interconnection is built in a printed circuit board using the high-density interconnection technology (HDI), the TCs being traces of width equal to about 30 µm, the center-line to center-line spacing being 70 µm. The interconnection is proportioned in such a way that it can be modeled, with a sufficient accuracy, as a (n+1)-conductor MTL, such that

$$\mathbf{Z}_R \approx j\omega\,\mathbf{L}_R \quad \text{with}$$

$$\mathbf{L}_R \approx \begin{pmatrix} 335.7 & 24.9 & 2.1 & 0.2 \\ 24.9 & 334.7 & 24.9 & 2.1 \\ 2.1 & 24.9 & 334.7 & 24.9 \\ 0.2 & 2.1 & 24.9 & 335.7 \end{pmatrix} \text{nH / m} \tag{9}$$

and

$$\mathbf{Y}_R \approx j\omega\,\mathbf{C}_R \quad \text{with}$$

$$\mathbf{C}_R \approx \begin{pmatrix} 102.6 & -8.4 & 0.0 & 0.0 \\ -8.4 & 103.6 & -8.4 & 0 \\ 0 & -8.4 & 103.6 & -8.4 \\ 0 & 0 & -8.4 & 102.6 \end{pmatrix} \text{pF/ m} \tag{10}$$

Because of the thickness of the conductors (7.0 µm), (9) is applicable to frequencies above 50 MHz, for which losses may be neglected in the computation of $\mathbf{Z}_{RC}$. We find that $\mathbf{Z}_{RC}$ is given by

$$\mathbf{Z}_{RC} \approx \begin{pmatrix} 54.8 & 4.5 & 0.4 & 0.0 \\ 4.5 & 54.6 & 4.5 & 0.4 \\ 0.4 & 4.5 & 54.6 & 4.5 \\ 0.0 & 0.4 & 4.5 & 54.8 \end{pmatrix} \Omega \tag{11}$$

In order to compute the diagonal matrix $\mathbf{Z}_{RL}$ defined above, we chose to minimize the matrix norm $\| \mathbf{P}_R \|_\infty$ of $\mathbf{P}_R$ given by (5), this matrix norm being equal to the largest sum of the absolute values of the entries of a row [9, § III]. In this manner, we obtained

$$\mathbf{Z}_{RL} = \mathrm{diag}_4(58.8, 54.2, 54.2, 58.8)\ \Omega \tag{12}$$

for which $\| \mathbf{P}_R \|_\infty \approx 0.082$. The corresponding termination circuit is made of four resistors, each being connected between a TC and the RC. Note that, if we want to compare this termination circuit used in the ZXnoise method to the terminations used in conventional PDLs, we must compare (12) with (2), not with (1) or (3).

We have used SpiceLine [10] to create a SPICE sub-circuit modeling the interconnection as a lossless 6-conductor MTL defined by $\mathbf{Z}_G$ and $\mathbf{Y}_G$ given by (7)-(10), $Z_{RG} = j\omega$ 66.4 nH/m and $Y_{RG} = j\omega$ 469 pF/m. We could simulate a 150-mm-long PDL terminated at each end by a termination comprising the floating termination circuit defined by (12), connected to the TCs and the RC, and a damping resistor equal to $(Z_{RG}/Y_{RG})^{0.5} \approx 11.9\ \Omega$, connected between the RC and ground.

In the case where a TX circuit behaves as an ideal floating source connected between the TC1 and the RC, we obtained, at the far-end, the frequency domain transfer functions for the transmitted signal and crosstalk shown in Fig. 6. Similar results are obtained when the TX circuit is connected between another TC and the RC. The echo is very small, since no interference pattern appears in the curve TC1 of Fig. 6.

V. Conclusion

We have presented a pseudo-differential transmission scheme which provides low reflections. This ZXnoise method also provides a good protection against external crosstalk, because all TCs are near the wide RC, and because the termination circuit is floating with respect to ground. The interconnection may be formed in a rigid or flexible printed circuit board, in the substrate of a multi-chip module or hybrid circuit or inside a monolithic integrated circuit. In the ZXnoise method, the RC is used as a return path for the currents corresponding to the signals, and the position of the TCs with respect to the RC and the reference conductor is such that the RC in a way acts as an electromagnetic screen. In a conventional PDL, the function of the CC is quite different, hence the different designations.

Section IV uses an ideal TX circuit, but two device-level designs for TX circuits dedicated to the ZXnoise method are described in [11].

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