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A Simple Method for Transmission with Reduced Crosstalk and Echo

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***Abstract*— The special ZXtalk method for completely degenerate interconnections (CDI) is capable of providing reduced echo and crosstalk in multiconductor interconnections, using few circuit elements. The paper defines the method and provides a design example showing how the termination circuits can be simplified. The paper also introduces a new type of MIMO amplifier, and explains why it is particularly suitable for the transmitting circuits used in the example. The number of circuit elements required by the ZXtalk method for CDI is finally shown to be proportional to the number of transmission channels.**

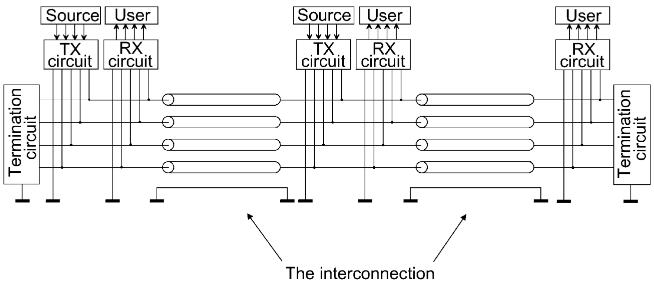

Fig. 1. An implementation of the special ZXtalk method for CDI.

I. Introduction

THIS paper describes a new method for high-data-rate signaling through a parallel link in which a reduced cross-sectional area is allocated to each transmission channel. This increase of the interconnection density is obtained using a single transmission conductor per channel and a narrow spacing between the transmission conductors. Consequently, crosstalk is expected to be the primary limiting factor in the design.

The ZXtalk method [1] [2] combines modal transmission with matched terminations. Though it does not explicitly use modal transmission, the method considered in this paper will be called the special ZXtalk method for completely degenerate interconnections (CDI), because it shares several features with the ZXtalk method. It will be defined in general terms in Sections II and III, but the paper will focus on the implementation shown in Fig. 1. The main purpose of the paper is to show that the special ZXtalk method for CDI may be implemented using few circuit elements per transmission channel, while providing low echo and crosstalk levels. Such low levels may eventually be used for further reducing the number of transmission conductors using full duplex transmission (i.e. simultaneous bidirectional signaling) [3] or a multiple level signaling scheme such as PAM-4 [4].

In Section IV, we will define an interconnection having $n = 4$ transmission conductors, and show its performances when it is used for single-ended transmission. In Section V, we will see how the termination circuit used in the special ZXtalk method for CDI may be simplified, to obtain a number of circuit element proportional to the number of channels. In Section VI, we will indicate how a new type of MIMO amplifier can be used to obtain simple transmitting circuits.

II. Properties of the Interconnection

We will consider an interconnection with n transmission conductors placed close to a reference conductor. Let us number these conductors from 0 to n, the number 0 being attributed to the reference conductor (ground). Any integer j such that $1 \le j \le n$ will be used as an index for defining the current i_j flowing on the transmission conductor j, and the voltage v_j between this transmission conductor and the reference conductor. These n currents and n voltages will respectively be called the natural currents and the natural voltages.

Since we assume that the interconnection may be described with the model of the uniform multiconductor transmission line (MTL), it is characterized with a per-unit-length (p.u.l.) impedance matrix $\mathbf{Z}$ and a p.u.l. admittance matrix $\mathbf{Y}$, both independent of z and of size $n \times n$. All the properties and definitions of the Sections II and III of [2] are applicable. Such definitions include:

- the propagation constant γ_i for a mode i, where i is an integer such that $1 \le i \le n$;
- the $n \times n$ matrix $\mathbf{Z}_C$, also called *characteristic impedance matrix*.

In this paper, we will from now on assume that the propagation constants of the different propagation modes may be regarded as equal, in a given frequency band. This for instance occurs when losses are negligible and the propagation medium is homogeneous, but we won't need these assumptions. In practice, nearly equal propagation constants may be obtained with PCB traces arranged between copper planes (multiconductor stripline). If γ is the common value of the propagation constants γ_i, we have :

$$\mathbf{YZ} = \mathbf{ZY} = \gamma^2 \mathbf{1}_n \quad (1)$$

As a consequence, the characteristic impedance matrix is given by

$$\mathbf{Z}_C = \frac{1}{\gamma}\,\mathbf{Z} = \gamma\;\mathbf{Y}^{-1} \quad (2)$$

and is therefore not diagonal.

There is no crosstalk caused by propagation between the natural voltages and between the natural currents, because natural voltages can be regarded as modal voltages and natural currents can be regarded as modal currents. It does not mean that the near-end crosstalk or the far-end crosstalk disappear when the interconnection is terminated with *n* grounded impedors (i.e. linear two-terminal circuit elements), because, as explained in Section III of [2], such terminations necessarily create crosstalk, even when pseudo-matched impedances are used.

III. The Special ZXtalk Method for CDI

The special ZXtalk method for CDI provides, in a known frequency band, *n* transmission channels each corresponding to a signal to be sent from the input of at least one transmitting circuit to the output of at least one receiving circuit (see Fig. 1). The method comprises the following steps [5]:

- proportioning the interconnection, 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 known frequency band;
- determining $\mathbf{Z}_C$ in the known frequency band;
- placing at at least one end of the interconnection a termination circuit having an impedance matrix approximating $\mathbf{Z}_C$ (i.e. a matched termination circuit);
- using one of the transmitting circuits (TX circuits), so as to obtain at its output (connected to the CDI), the generation of natural electrical variables, each being proportional to one of the input signals;
- using one of the receiving circuits (RX circuits), the input of which is connected to the CDI, so as to obtain at its output *n* output signals each corresponding to one of the transmission channels, each output signal being proportional to a single natural electrical variable among said natural electrical variables.

As defined above, the special ZXtalk method uses one transmission conductor (hence one natural electrical variable) for each channel. Contrary to the ZXtalk method mentioned in the introduction, it is not defined as a modal transmission technique, since it does not explicitly allocate a propagation mode to each transmission channel.

In this paper, we consider the case where voltages are chosen as natural electrical variables. As shown in Fig. 2, natural voltages may be produced by a transmitting circuit having *n* pairs of output terminal presenting a low series impedance. In this case, the column-vector $\mathbf{V}_T$ of the voltages across each pair

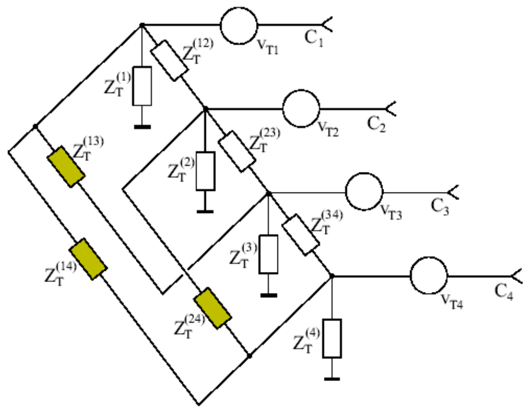

Fig. 2. A termination circuit and 4 voltage sources representing a TX circuit.

of output terminals of the transmitting circuit must be

$$\mathbf{V}_T = \pm 2\ \mathrm{diag}_n(\alpha_1,\ldots,\alpha_n)\ \mathbf{X}_I \quad (3)$$

where $\mathrm{diag}_n(\alpha_1,\ldots,\alpha_n)$ is the diagonal matrix of the non-zero proportionality coefficients α_i, where $\mathbf{X}_I$ is the column-vector of the *n* input signals $x_{I1}, \ldots, x_{In}$ applied to the TX circuit and where ± indicates that the polarity depends on the position with respect to the point of connection of the output terminals.

Since, for each channel, a RX circuit produces at its output a signal proportional to the natural voltage corresponding to this channel, we may write:

$$\mathbf{X}_0 = \mathrm{diag}_n(\beta_1,\ldots,\beta_n)\ \mathbf{V} \quad (4)$$

where $\mathbf{V}$ is the vector of the natural voltages received by the receiving circuit, where $\mathrm{diag}_n(\beta_1,\ldots,\beta_n)$ is the diagonal matrix of the non-zero proportionality coefficients β_i and where $\mathbf{X}_O$ is the column-vector of the *n* output signals $x_{O\,1}, \ldots, x_{O\,n}$ of the receiving circuit.

IV. Example for 4 Transmission Conductors

We consider a 0.3 m long interconnection for which losses may be neglected at the frequencies used for transmission, having 4 transmission conductors and a reference conductor. This interconnection is made of 4 coplanar strips centered between 2 ground planes, as defined by Kammler [6, Table VII]. We have assumed that the relative permittivity of the PCB is isotropic and equal to 4.7. We obtain

$$\mathbf{Z}_C \approx \begin{pmatrix} 68.803 & 24.149 & 10.199 & 4.510 \\ 24.149 & 67.403 & 23.685 & 10.199 \\ 10.199 & 23.685 & 67.403 & 24.149 \\ 4.510 & 10.199 & 24.149 & 68.803 \end{pmatrix} \Omega \quad (5)$$

A termination circuit having an impedance matrix equal to $\mathbf{Z}_C$ can be obtained with the $n\,(n+1)/2 = 10$ resistors shown in Fig. 2, with $Z_T^{(1)} = Z_T^{(4)} \approx 96.9\ \Omega$ and $Z_T^{(2)} = Z_T^{(3)} \approx 141.1\ \Omega$ for the grounded resistors, with $Z_T^{(12)} = Z_T^{(34)} \approx 172.7\ \Omega$ and $Z_T^{(23)} \approx 177.9\ \Omega$ for the resistors between adjacent transmission conductors, with $Z_T^{(13)} = Z_T^{(24)} \approx 2186\ \Omega$ and with $Z_T^{(14)} \approx 13900\ \Omega$. In theory, the implementation of the Special ZXtalk method for CDI with such terminations and ideal TX and RX circuits would leave no crosstalk.

When this interconnection is used for single-ended transmission, the termination is made of grounded resistors only. The designer should use optimized terminations, which may be defined as pseudo-matched impedances minimizing the maximum absolute row sum norm $\|\mathbf{P}\|_\infty$ of the matrix $\mathbf{P}$ of the voltage reflection coefficients [2, § III]. This result, for which $\|\mathbf{P}\|_\infty \approx 0.357$, is obtained with $Z_T^{(1)} = Z_T^{(4)} \approx 77.7\ \Omega$, and $Z_T^{(2)} = Z_T^{(3)} \approx 59.4\ \Omega$. With such terminations arranged at both ends, we have computed the near-end and the far-end crosstalk signals in the frequency domain from 100 kHz to 10 GHz. The highest values are shown in Fig.3.

V. Simplification of the Termination Circuits

Let us consider again the realization of $\mathbf{Z}_C$ presented above. Clearly, $Z_T^{(13)}$, $Z_T^{(24)}$ and $Z_T^{(14)}$ have little influence on the impedance of the network: it should be possible to omit them. More precisely, if we want to approximate $\mathbf{Z}_C$ with an "M-type network" comprising only grounded resistors and resistors between adjacent conductors, the remaining resistor should be computed to obtain an optimal network. An optimized M-type network may be defined as an M-type network minimizing $\|\mathbf{P}\|_\infty$. In our example, the minimum $\|\mathbf{P}\|_\infty \approx 0.021$, is obtained with $Z_T^{(1)} = Z_T^{(4)} \approx 92.7\ \Omega$ and $Z_T^{(2)} = Z_T^{(3)} \approx 135.7\ \Omega$ for the grounded resistors, with $Z_T^{(12)} = Z_T^{(34)} \approx 172.6\ \Omega$ and $Z_T^{(23)} \approx 172.4\ \Omega$ for the resistors between adjacent transmission conductors (and with $Z_T^{(13)} = Z_T^{(24)} = Z_T^{(14)} = \infty$).

We can now use such M-type terminations for implementing the Special ZXtalk method for CDI. Assuming ideal TX and RX circuits, we have computed the near-end and the far-end crosstalk signals in the frequency domain from 100 kHz to 10 GHz. The highest values are shown in Fig. 4. Perfect cancellation of crosstalk does not occur any more, but the comparison with Fig. 3 shows that a very significant reduction of echo and crosstalk has been obtained with terminations comprising only $2n-1 = 7$ resistors.

VI. Using a MIMO Series-Series Feedback Amplifier

A transmitting circuit designed according to (3) must provide two output terminals for each conductor, and each pair of output terminals must behave like a wide-band floating voltage source. The first requirement conflicts with the objective of I/O count reduction, and the second requirement cannot be achieved with known wide-band output circuits.

As shown in Fig. 1, the TX circuits may alternatively be connected in parallel with the conductors of the interconnection, showing a high parallel impedance. If $\mathbf{I}_T$ is the column-vector of the current injected by the output terminals of such a TX circuit, we should have:

$$\mathbf{I}_T = 2\,\mathbf{Z}_C^{-1}\,\mathrm{diag}_n(\alpha_1,\ldots,\alpha_n)\,\mathbf{X}_I \qquad (6)$$

Since $\mathbf{Z}_C$ is a full matrix, it looks like the linear combinations defined by (6) would require a complex circuit. If the n input signals $x_{I\,1}$, ..., $x_{I\,n}$ of $\mathbf{X}_I$ are voltages, the Authors found that (6) can be realized with a multiple-input and multiple-output (MIMO) amplifier having n inputs and n outputs, comprising a n+1 terminal feedback network.

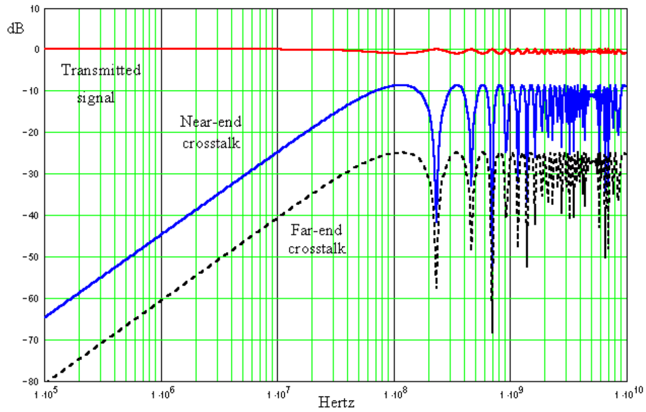

Fig. 3. Highest crosstalk signals for single-ended transmission using pseudo-matched impedances at both ends.

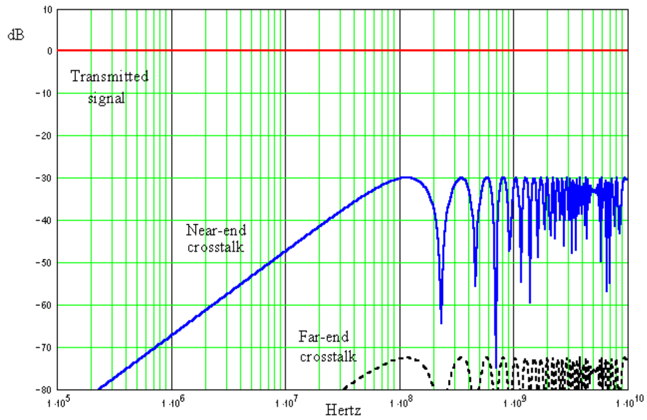

Fig. 4. Highest crosstalk signals for the special ZXtalk method implemented with a simplified termination (M-type network) at each end.

Fig. 5 shows an example of this new MIMO amplifier, having 4 signal input terminals and 4 signal output terminals, comprising 4 bipolar transistors, 4 current sources for output biasing and a feedback network made of 10 impedors. The feedback network has a terminal connected to the reference terminal, and 4 other terminals each being connected to the emitter of a transistor. The feedback network presents a non-diagonal impedance matrix $\mathbf{Z}_{FB}$, this impedance matrix being defined with respect to the reference terminal. The feedback network produces a negative feedback such that, in a known frequency band, an approximation of (6) is obtained.

Since the negative feedback used in Fig. 5 can be considered as a generalization of series-series feedback, we will refer to the new amplifier as a MIMO series-series feedback amplifier or MIMO-SSFA. In Fig. 5, each bipolar transistor could be replaced with an active device or circuit in MOS or bipolar technology. For such a circuit, the characteristics of an ideal second-generation current conveyor (CCII) [7, chapter 58] are very desirable.

As an example, we designed a MIMO-SSFA for the interconnection defined in § IV, according to the schematic diagram of Fig. 5, using NPN transistors exhibiting a f_T of 8 GHz. The design of the MIMO-SSFA consisted in the selection of an appropriate scaling of the cross-sectional area of

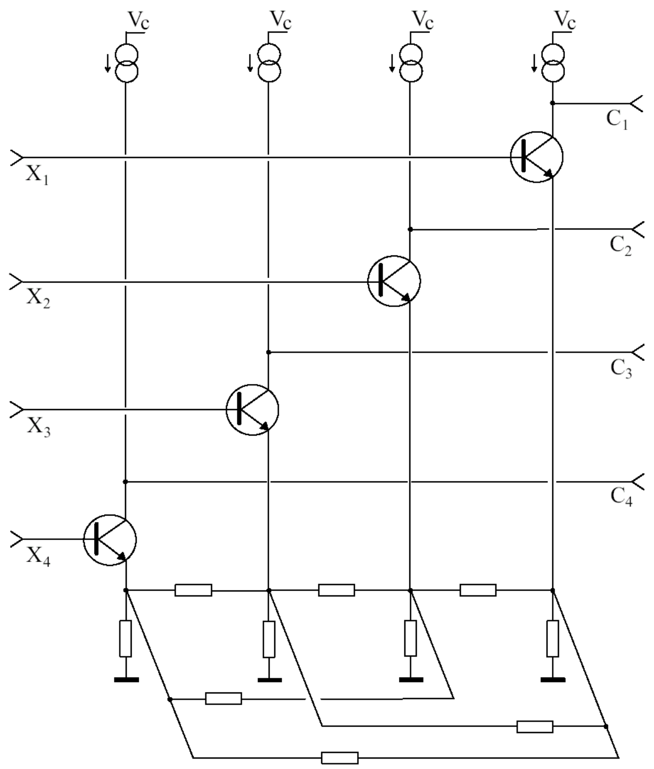

Fig. 5. A MIMO SSFA used as a transmitting circuit.

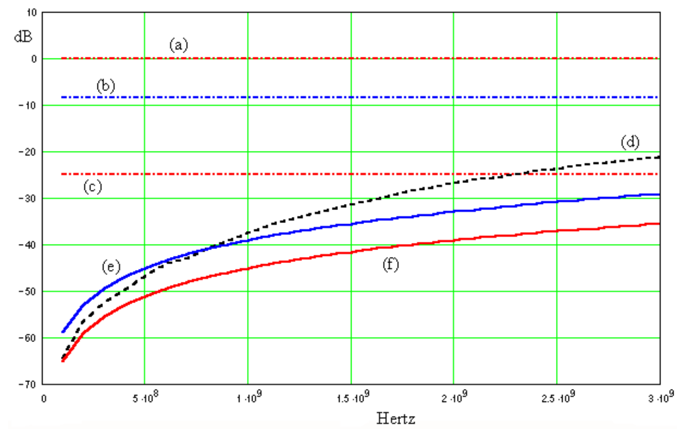

Fig. 6. Crosstalk obtained with the special ZXtalk method (d) (e) (f) and comparison with the level of wanted signal (a), and the maximum crosstalk levels of Fig. 3 (b) (c).

these transistors, and the computation of an appropriate real impedance matrix $\mathbf{Z}_{FB}$, since we wanted a feedback network merely made of resistors. Using a feedback network made of 10 resistors we obtained the simulation results shown in Fig. 6 for the signals obtained with the MIMO-SSFA connected at one end of the interconnection terminated with matched terminations: (a) is the transmission level, (b) is the maximum near-end crosstalk level obtained in Fig. 3, (c) is the maximum far-end crosstalk level obtained in Fig. 3, (d) is the near-end or far-end crosstalk level obtained with the MIMO-SSFA, between adjacent conductors, (e) is the near-end or far-end crosstalk level obtained with the MIMO-SSFA, between conductors having one conductor between them, and (f) is the near-end or far-end crosstalk level obtained with the MIMO-SSFA, between the extreme conductors. The simulation was based on the S-parameters of the bipolar transistors, other components being ideal circuit elements. Fig. 6 shows no visible echo, but crosstalk is present and increases with frequency. However, the near-end crosstalk is effectively reduced, and the far-end crosstalk is significantly reduced up to 1.5 GHz, corresponding to about $f_T/5$.

VII. Conclusion

The special ZXtalk for CDI, if it was implemented with a lossless uniform interconnection and ideal transmitting circuits, receiving circuits and termination circuits, would provide a transmission without echo and crosstalk. In the implementation considered in this paper, nearly ideal receiving circuits defined by (4) are simple to build, and we have shown that simplified termination circuits and transmitting circuits can be used to obtain an effective reduction of crosstalk and echo.

Since such simplified termination circuits and transmitting circuits are far from being ideal, this shows that a very significant improvement of the transmission characteristics can be obtained using circuits which do not accurately comply with equations (2) and (6). However, our simulation does not include all parasitics and imperfections of a practical implementation.

For n channels (i.e. for n transmission conductors), the simplified termination circuit studied in § V requires $2n-1$ resistors, and the new MIMO-SSFA of § VI comprises n active devices. Since the simplification of § V can also be applied to the feedback network of the MIMO-SSFA, we obtain, for all the circuits used in the special ZXtalk method for CDI, a total number of resistors and active parts proportional to n.

Consequently, we can state that the special ZXtalk method for CDI can be implemented at a very low cost.

Acknowledgment

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