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Twelve Pseudo-Differential Transmission Schemes

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***Abstract* — By combining 4 pseudo-differential architectures with compatible types of termination circuit, we identify 12 multichannel pseudo-differential transmission schemes. Each provides a reduced external crosstalk compared to multiple single-ended links, using fewer conductors than multiple differential links.**

***Keywords* — Parallel links, chip-to-chip interconnects, signal integrity.**

I. INTRODUCTION

This paper is about pseudo-differential links (PDLs) providing $m \geq 2$ channels for sending analog or digital signals. In this context, crosstalk between the different channels shall be referred to as *internal crosstalk* and crosstalk with other circuits shall be referred to as *external crosstalk*. An m-channel PDL considered in this paper uses an interconnection having m transmission conductors (TCs) and one common conductor distinct from the reference conductor (ground) [1, § 4.2.3] [2] [3]. The m-channel PDL provides a protection against external crosstalk because the output signals of the receiving circuit (RX circuit) are mainly determined by the voltages between the TCs and the common conductor. In cases where the common conductor is used as a return path for the currents corresponding to the signals, the common conductor may be referred to as *return conductor*.

Four PDL architectures are defined in Section II. The types of termination circuits which may be used to reduce reflections are discussed in Section III. The suitability of interconnection-ground structures is addressed in Section IV. In Section V, this analysis leads us to a list of 12 pseudo-differential transmission schemes, from which the designer can select the most suitable for his analog or digital link specification, and two examples are compared.

II. FOUR PDL ARCHITECTURES

A PDL with voltage-driven common conductor (VDCC), providing $m = 4$ channels, is shown in Fig. 1. This PDL uses an interconnection having $m = 4$ TCs (numbered from 1 to 4). At the far-end of this unidirectional PDL, the termination circuit may or may not be present. At the near-end, close to the transmitting circuit (TX circuit), the common conductor is connected to a low impedance node presenting an open-circuit voltage e_{CC} and an internal impedance Z_{CC}. This node could be ground ($e_{CC} = 0$ V and $Z_{CC} = 0\ \Omega$). If bidirectional operation is desired, the architecture of Fig. 1 cannot be used since at most one low impedance node may be connected to the common conductor of a PDL, at a given time.

However, a PDL using common terminal switching circuits (SW circuits), shown in Fig. 2, is suitable for bidirectional signaling. In this type of PDL, when one of the TX circuits is in the activated state, the nearest SW circuit is in the closed state, in which it couples the common conductor to a low impedance node, while the other SW circuit is in the open state, in which it presents a high impedance to the common conductor. One or more of the termination circuits shown in Fig. 2 may or may not be present.

The PDL with VDCC (Fig. 1) and the PDL using SW circuits (Fig. 2) may use voltage-mode TX circuits or current-mode TX circuits [1] if a termination circuit is present.

A TX circuit may comprise a balancing circuit such that a constant common-mode current (CCMC) flows in the interconnection [4]. Such a TX circuit has a “common terminal” connected to the return conductor. It may be used in a

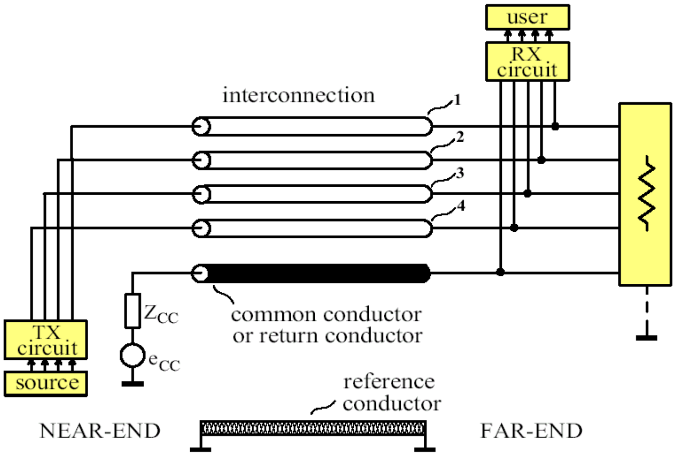

Fig. 1. Unidirectional PDL with voltage-driven common conductor or return conductor (VDCC). The block containing the resistor symbol is a termination circuit.

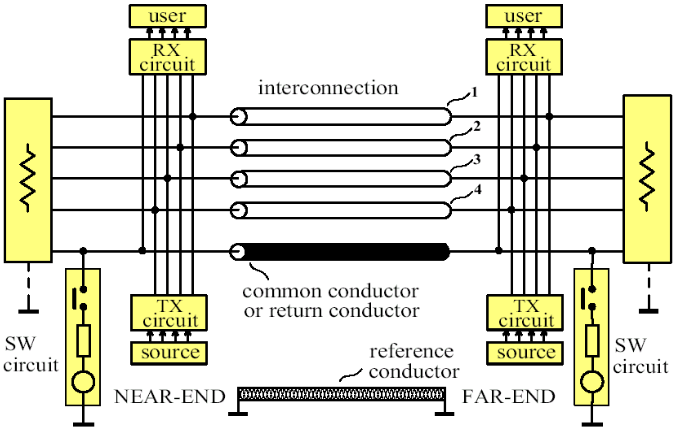

Fig. 2. Bidirectional PDL using common terminal switching circuits (SW circuits).

unidirectional PDL or in a bidirectional PDL such as the one shown in Fig. 3. Let us use i_j to denote the current flowing from the signal terminal number j of the TX circuit to the TC number j to which it is connected, and i_C to denote the current flowing from the common terminal of the TX circuit to the return conductor. The balancing circuit controls i_C in such a way that the TX circuit does not cause any significant variation of the common-mode current $i_1 + ... + i_m + i_C$. Thus, the balancing circuit provides a return path for the signal currents i_1 to i_m while not requiring a connection of the return conductor to a low-impedance node. Consequently, such TX circuits are compatible with simultaneous bidirectional transmission (i.e. full duplex signaling) in PDLs.

At this stage, we have identified four PDL architectures: PDL with VDCC, PDL using SW circuits, unidirectional PDL operating at CCMC and bidirectional PDL operating at CCMC.

III. SUITABLE TERMINATION CIRCUITS

If no termination circuit is used in a PDL, reflections of signals occur and limit the available bandwidth.

By definition, a type 1 termination circuit has an impedance matrix with respect to ground, this matrix being diagonal. Thus, a type 1 termination circuit may be made of grounded resistors, as shown in Fig. 4 for $m = 4$. The termination circuit may merely consist of the resistors R_1 to R_m connected to the TCs (TC1 to TC4 in Fig. 4). If we wish that the common conductor operates in the same configuration as the TCs, a resistor R_D connected to the common conductor (CC in Fig. 4) may also be used. Such a termination circuit uses the reference conductor for the return current produced by the currents flowing on the TCs. The reference conductor belonging to the signal path, this type 1 termination circuit will produce an unwanted coupling between other circuits using the reference conductor as a return path and the signal path.

By definition, type 2 and type 3 termination circuits are not connected to ground, such termination circuits being characterized by an impedance matrix with respect to the return conductor, denoted by $\mathbf{Z}_{RL}$. $\mathbf{Z}_{RL}$ is a matrix of size $m \times m$, $\mathbf{Z}_{RL}$ being a diagonal matrix in the case of a type 2 termination circuit, or a non-diagonal matrix in the case of a type 3 termination circuit. When a type 2 or type 3 termination circuit is used, the common conductor may be called a return conductor since it is used as a return path for the currents flowing on the TCs.

In Fig. 5, a type 2 termination circuit for $m = 4$ consists of the resistors R_1 to R_4 each connected between one of the TCs (TC1 to TC4) and the return conductor (RC in Fig. 5). In Fig. 5, we use a damping device connected between the return conductor and ground, in the form of a resistor R_D, for damping the resonances of the return conductor with respect to ground. The damping resistor R_D is not regarded as a part of the termination circuit. In Fig. 6, a type 3 termination circuit for $m = 4$ consists of the resistors R_1 to R_4 used as in Fig. 5, and of the resistors R_{12}, R_{13}, R_{14}, R_{23}, R_{24} and R_{34} each connected between two TCs. In Fig. 6, we use a resistor R_D as a damping device, as in Fig. 5.

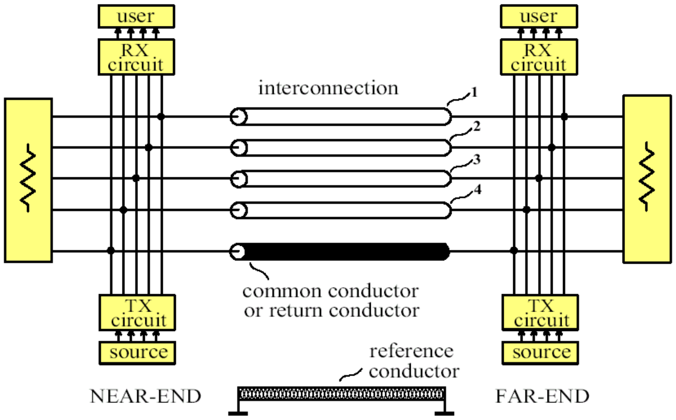

Fig. 3. Bidirectional PDL with TX circuits producing a constant common-mode current (CCMC).

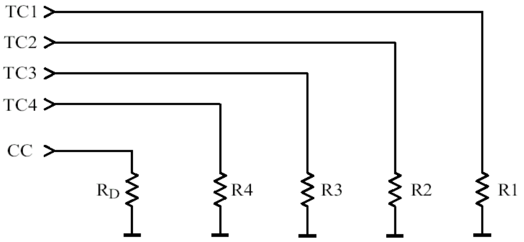

Fig. 4. A type 1 termination circuit, made of grounded resistors. CC is the common conductor.

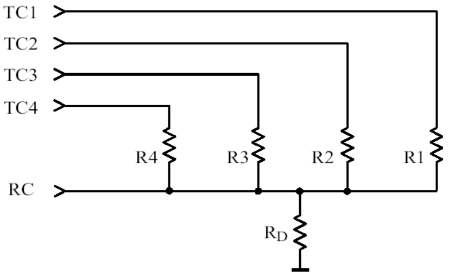

Fig. 5. A type 2 termination circuit and a damping resistor R_D. RC is the return conductor.

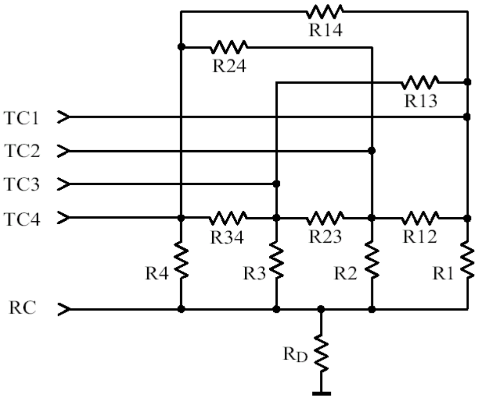

Fig. 6. A type 3 termination circuit and a damping resistor R_D. RC is the return conductor.

Since the damping device is not part of the termination circuit (it is not part of the intended signal path), type 2 and type 3 termination circuits are floating and they do not have an impedance matrix with respect to ground. Type 2 and type 3 termination circuits do not place the reference conductor in the signal path. Thus, they do not degrade external crosstalk.

In a type 3 termination circuit, the non-diagonal entries of $\mathbf{Z}_{RL}$ seem to introduce internal crosstalk. However, such termination circuits can be used to obtain a cancellation of echo and internal crosstalk, using a suitable combination of pseudo-differential signaling and one of the variants of the ZXtalk method [5].

IV. SUITABLE INTERCONNECTION STRUCTURES

The interconnection comprises the m TCs and the common/return conductor (the reference conductor is not considered part of the interconnection). The termination circuits are primarily intended to reduce reflections. Consequently, the type(s) of termination circuit which may be used in a given link depend(s) on the characteristics of the interconnection.

A type 1 termination circuit absorbs the incoming power of the signal using resistance between the TCs and ground. It will operate as intended if (condition A) the electric and magnetic fields of the signals are mainly located between the TCs and ground. In this case, the return current caused by signal propagation flows mainly in the reference conductor. This is for instance obtained in the two interconnection-ground structures shown in Fig. 7, provided that the distances between nearby conductors of the interconnection are large enough compared to the distances between each conductor of the interconnection and the reference conductor. Here, propagation takes place in the whole interconnection-ground structure, which must be modeled as a $(m + 2)$-conductor multi-conductor transmission line (MTL).

Type 2 and type 3 termination circuits (floating termination circuits) absorb the incoming power of the signal using resistance between the TCs and the return conductor. They will operate as intended if (condition B) the electric and magnetic fields of the signals are mainly confined between the TCs and the return conductor. In this case, the return current caused by signal propagation flows mainly in the return conductor. This is for instance obtained if one of the interconnection-ground structures shown in Fig. 8 is used with floating termination circuits. This is because, in Fig. 8, the return conductor may clearly behave as an electromagnetic screen and provide shielding. Thus, propagation takes place in the interconnection alone, which may be modeled as a $(m + 1)$-conductor MTL at the design stage [3] [5].

However, allocating one or more conducting layers or metallization levels to the return conductor is not necessary to meet the condition B: in Fig. 9, the return conductor is made of multiple traces which share the same layer as the TCs, so that a two-layer structure and a single-layer structure have been obtained. These structures must clearly be proportioned and used more carefully than the structures shown in Fig. 8 to obtain the desired fulfilment of the condition B.

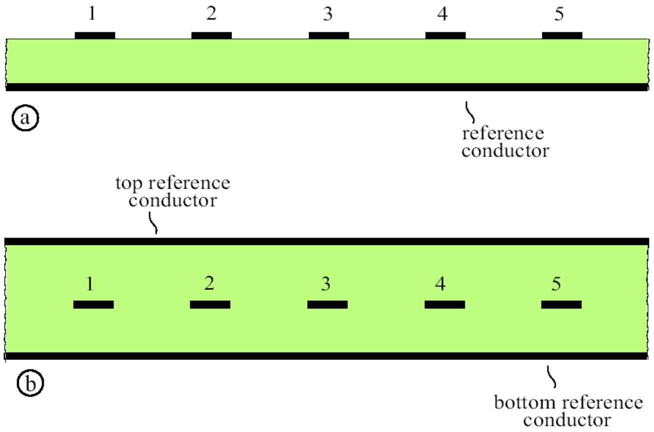

Fig. 7. Two possible cross-sections for an interconnection-ground structure used with type 1 termination circuits, where 1 to 4 are the TCs and where 5 is the common conductor.

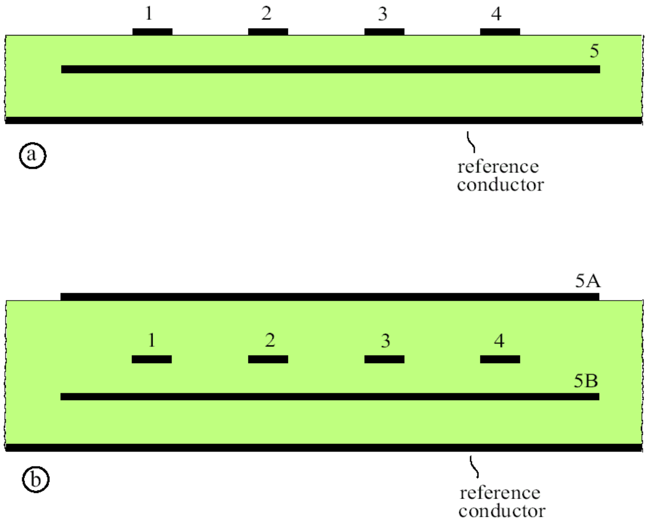

Fig. 8. Two possible cross-sections for an interconnection-ground structure used with floating termination circuits, where 1 to 4 are the TCs, where 5 is the return conductor in *a* and where the return conductor in *b* is made of 5A and 5B.

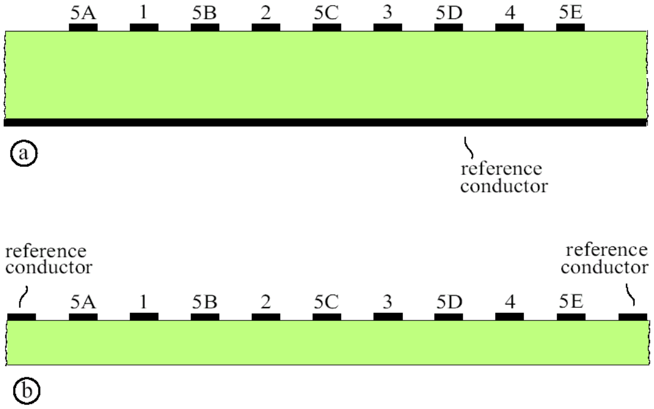

Fig. 9. Two possible cross-sections for an interconnection-ground structure used with floating termination circuits, where 1 to 4 are the TCs and where the return conductor is made of 5A to 5E, which must be sufficiently interconnected.

V. THE PSEUDO-DIFFERENTIAL TRANSMISSION SCHEMES

The table I shows the 12 realizable pseudo-differential transmission schemes, each corresponding to the combinations of a PDL architecture and a compatible type of termination circuit (type 0 referring to the absence of termination). A CCMC TX circuit needs a termination circuit which cannot be a type 1 termination circuit, because the required R_D would create internal crosstalk (this cause of internal crosstalk disappears if $R_D = 0\ \Omega$, in which case we have clearly left the realm of PDLs).

The use of one or more type 2 or type 3 termination circuits connected to an appropriate interconnection-ground structure, referred to as *ZXnoise method*, effectively reduces echo and external crosstalk [3] [5]. Type 3 termination circuits are used in PDLs combining the ZXnoise and ZXtalk methods to obtain reduced echo, internal crosstalk and external crosstalk.

The fig. 10 shows simulation results based on the exact $(m + 2)$-conductor MTL model discussed in [5], for two ideal implementations of the ZXnoise method providing $m = 4$ channels, using a 300-mm-long interconnection having the cross-section and the per-unit-length capacitance and inductance matrices described in Section IV of [5]. The first PDL uses type 2 termination circuits and the VDCC architecture. It is consequently identical to the PDL of Section IV of [5], except that it is 10 times longer. Thus, its bandwidth, limited by far-end internal crosstalk, is roughly 10 times less. The second PDL uses type 3 termination circuits and the VDCC architecture. It combines the ZXnoise and ZXtalk methods and provides three channels having very low internal crosstalk (curve B) and external crosstalk (curve C). The TX circuit and the RX circuit used in the second PDL are more complex than the ones used in the first PDL, because they must perform the linear combinations of signals inherent to the implementation of the ZXtalk method when the propagation velocities of the different modes may not be regarded as equal [5].

VI. CONCLUSION

For m channels, a PDL providing a protection against external crosstalk only uses $m + 1$ conductors instead of $2m$ conductors for m differential links. In a PDL using the ZXnoise method, the reduction of external crosstalk involves the shielding effect of the return conductor.

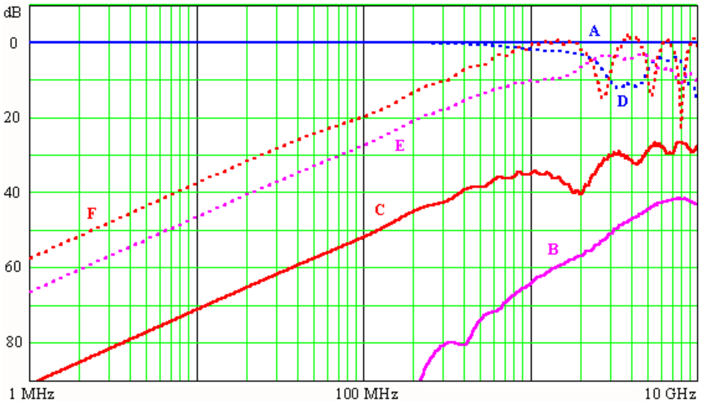

Fig. 10. Attenuations observed in two PDLs using the same 0.3 meter long interconnection. For the second PDL, measured on channel 2: attenuation of transmitted signal (curve A), lowest attenuation of far-end internal crosstalk when channel 3 or 4 are excited (curve B), attenuation of external crosstalk (curve C). For the first PDL, measured on TC number 2: attenuation of transmitted signal (curve D), lowest attenuation of far-end internal crosstalk when another TC is excited (curve E), attenuation of external crosstalk (curve F). For the curves C and F, the external crosstalk induces the same voltage on all conductors, in the TX circuit.

The Table I shows that, among the 12 possible pseudo-differential transmission schemes, 7 are new. The different transmission schemes cannot be ranked in a general way, because different specifications lead to different optimal solutions.

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TABLE I. POSSIBLE PSEUDO-DIFFERENTIAL TRANSMISSION SCHEMES

Termination circuit	Architecture of the PDL			
	VDCC (unidirectional)	SW circuit (bidirectional)	Unidirectional CCMC	Bidirectional CCMC
Type 0	Prior Art	New		
Type 1	Prior Art	New		
Type 2 (ZXnoise)	Recent [5]	New	Recent [3] [4]	New
Type 3 (ZXnoise)	Recent [5]	New	New	New