Multimode Signaling on Non-Ideal Channels

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Abstract

Simultaneous optimization of interconnect density and crosstalk poses conflicting requirements with conventional differential signaling. As an alternative, we investigate multimode signaling where n signals are transmitted by exciting all fundamental modes on a group of n closely located lines. In this paper, the channel response of multimode signaling is analyzed to demonstrate the benefits of this signaling. The misaligned channel and length mismatch sensitivity of multimode signaling are also analyzed.

I. INTRODUCTION

To maximize total bandwidth, it is desirable to route chip-to-chip interconnect at high density and exploit multi-Gb/s signaling. However, high edge rates lead to substantial crosstalk and maximum signal density is often limited to below what is manufacturable. For example, with differential lines, the inter-pair spacing might be four times higher than the spacing within the pair. Numerous signaling schemes have been investigated to reduce crosstalk including active cancellation. An interesting alternative is to exploit multiconductor transmission line theory [1], [2] in order to eliminate crosstalk. The basic concept is to use a code so that signals are transmitted using only the fundamental modes of propagation [3], [4]. Such signaling is theoretically entirely crosstalk free. In this scheme, that we refer to as *multimode signaling*, *n* signals obtained from the linear combinations of *n* fundamental modes are transmitted through a group of *n* closely located lines, called a *bundle*. In our work, we investigate the practical implementation and limitations of multimode signaling. In a recent paper [5], it was shown that inter-bundle spacing requirements are similar for n = 4 and n = 2 (i.e., conventional differential signaling) when bundles are routed in parallel. This result indicates the potential to increase overall wire density by a factor of two or more. In this paper, we report the following. First, we present a frequency domain analysis showing how to derive the required code and corresponding codec design. This is illustrated with an example. Next, we explore practical insues in implementation, including the effect of misalignment, vias, and signal skew due to length mismatch for a direct-chip-attach interconnect system. For estimating the system performance of multimode signaling, we start with deriving the channel response of multimode signaling.

II. CHANNEL RESPONSE OF MULTIMODE SIGNALING

In general, multiline channel responses can be described in the frequency domain with an $n \times n$ vector channel $\mathbf{H}(z)$, an $n \times 1$ line voltage Ψ , an $n \times 1$ source voltage \mathbf{X} , and an $n \times 1$ additive external noise \mathbf{N} , such as the noise from neighboring bundles, as

$$\Psi(z) = \mathbf{H}(z)\mathbf{X} + \mathbf{N} \tag{1}$$

where $\Psi(z) = [V_1(z), \ldots, V_n(z)]^T$ and $\mathbf{X} = [V_{1S}, \ldots, V_{nS}]^T$ with $V_i(z)$ the voltage at position z on the *i*th line and V_{iS} the *i*th source voltage. Denoting the $n \times n$ source admittance matrix as $\mathbf{Y}_{\mathbf{S}}$ and the $n \times n$ load admittance matrix as $\mathbf{Y}_{\mathbf{L}}$, the transfer function $\mathbf{H}(z)$ is given by [6]

$$\mathbf{H}(z) = (\mathbf{A} + \mathbf{B}\mathbf{Y}_{\mathbf{L}})^{-1} \cdot [(\mathbf{C} + \mathbf{D} \cdot \mathbf{Y}_{\mathbf{L}}) \cdot (\mathbf{A} + \mathbf{B} \cdot \mathbf{Y}_{\mathbf{L}})^{-1} + \mathbf{Y}_{\mathbf{S}}]^{-1} \cdot \mathbf{Y}_{\mathbf{S}}$$
(2)

where $\mathbf{A} = \cosh(\sqrt{\mathbf{Z}\mathbf{Y}}z)$, $\mathbf{B} = \sinh(\sqrt{\mathbf{Z}\mathbf{Y}}z)\mathbf{Z}_C$, $\mathbf{C} = \mathbf{Y}_C \sinh(\sqrt{\mathbf{Z}\mathbf{Y}}z)$, and $\mathbf{D} = \mathbf{Y}_C \cosh(\sqrt{\mathbf{Z}\mathbf{Y}}z)\mathbf{Z}_C$. Here \mathbf{Z} is the $n \times n$ line impedance per unit length, \mathbf{Y} the $n \times n$ line admittance per unit length, and $\mathbf{Z}_C = \mathbf{Y}_C^{-1}$ the $n \times n$ characteristic impedance of the bundle. The diagonal entries of $\mathbf{H}(z)$, $h_{ii} = \frac{V_i(z)}{V_{is}}$ represent attenuations between the ends of each line and



Fig. 1. Multimode signaling on a bundle

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Fig. 2. Channel transfer function and FEXT: (a) Cross-section of stacked stripline (n = 4), (b) conventional channel response $\mathbf{H}(z)$ with w = 2 mil and $h_s = 10$ mil, and (c) corresponding multimode signaling channel response $\mathbf{H}_m(z)$

the off-diagonal entries of $\mathbf{H}(z)$, $h_{ij} = \frac{V_i(z)}{V_{jS}}$, $i \neq j$ denote far-end crosstalk (FEXT) between *j*th source voltage V_{jS} and *i*th line voltage $V_i(z)$. Hence the cumulated FEXT coupled onto the *i*th line, FEXT_i, can be defined as

$$\text{FEXT}_{i} = \sum_{\substack{j=1\\j\neq i}}^{n} h_{ij} \tag{3}$$

To reduce FEXT_i for all the signals associated with a bundle, a pre- and post-processor are needed in the transmitter and receiver, respectively. The modified channel response $\mathbf{H}_m(z)$ including pre-processor \mathbf{T} and post-processor \mathbf{S} can be described in the frequency domain as [7]

$$\mathbf{H}_m(z) = \mathbf{S} \cdot \mathbf{H}(z) \cdot \mathbf{T} \tag{4}$$

In multimode signaling, **T** and **S** are called encoder and decoder, respectively, and can be obtained by applying multiconductor transmission line theory. According to the theory, signal transmission in a bundle can be decoupled with an encoder **T** that is a transformation matrix diagonalizing **ZY** and each column of **T** is comprised of the eigenvectors of **ZY**. This implies that effective crosstalk could be reduced by employing the encoder **T** as a pre-processor. The decoder **S** is \mathbf{T}^{-1} . As indicated by (4), FEXT may be sensitive to variation of the codec coefficients and we may derive codec coefficients that reduce FEXT when discontinuity elements are cascaded with a plain multiline response $\mathbf{H}(z)$. Fig. 1 illustrates a system diagram of multimode signaling, in which $\mathbf{d} = [d_1, d_2, \ldots, d_n]$ denotes n parallel source signals before encoding and $\mathbf{d}' = [d'_1, d'_2, \ldots, d'_n]$ are the decoded signals, expecting $\mathbf{d} = \mathbf{d}'$.

III. EXAMPLE

To see the impact of the codec on the multiline channel response, an example multiconductor transmission line system [Fig. 2(a)] is introduced that is a stacked stripline structure having four signal wires between top and bottom reference planes. The trace width w is assumed to be equal to the horizontal and vertical wire spacing. The length of the channel is 20 cm. This example channel is connected with a source admittance \mathbf{Y}_{s1} that is a 4 × 4 diagonal matrix having $[\mathbf{Y}_{s1}]_{ii} = 1/70 \ \Omega$ and a load admittance \mathbf{Y}_{L1} that is a 4 × 4 diagonal matrix having $[\mathbf{Y}_{L1}]_{ii} = 1/70 \ \Omega$ since the diagonal entries of the line's characteristic impedance matrix are 70 Ω . In general, for homogeneous dielectric media FEXT is ideally negligible under the assumption of weakly coupled lines [1, ch. 10]. But for strongly coupled striplines, FEXT becomes a function of coupling coefficient [8]. For this example, as the inductive coupling coefficient k_l is approximately 0.45 and the capacitive coupling coefficient k_c is approximately 0.35, we can consider this channel with $w/h_s = 0.2$ as strongly coupled, therefore FEXT should not be ignored. Fig. 2(b) illustrates the multiline channel response H(z) having a significant amount of FEXT. Note that at about 10 GHz the level of cumulative coupling from adjacent lines, $FEXT_i$, becomes comparable to the original signal level h_{ii} and above 15 GHz exceeds it. Fig. 2(c) is the channel response $\mathbf{H}_m(z)$ with a codec, demonstrating the benefit of multimode signaling. The encoder T_1 of this example is comprised of frequency-independent eigenvectors of ZY by exploiting a cyclic-symmetric structure of the line geometry. By including the codec (\mathbf{T}_1 and $\mathbf{S}_1 = \mathbf{T}_1^{-1}$), the resulting FEXT has been reduced significantly [Fig. 2(c)]. These example results show that for tightly coupled lines multimode signaling reduces the magnitude of FEXT as expected.

IV. SENSITIVITY ANALYSIS OF MULTIMODE SIGNALING

A. Misaligned channel

Non-idealities such as manufacturing variations, surface roughness, variation of dielectric constant with temperature and humidity, and discontinuities due to connectors and via stubs cause the channel response to deviate from the ideal response.



Fig. 3. Misaligned channel and vias: (a) Misaligned stacked stripline (n = 4), (b) vias and via stubs, and (c) S-parameter channel response with d = 0

For the stacked stripline configuration used above, layer-to-layer misalignment and via stubs are important degrading factors to be considered for the overall multimode signaling performance. Fig. 3(a) illustrates the detailed channel structure with a misalignment d relative to the lower signal layer. Each signal wire is 5 mil wide and wires are spaced 5 mil apart. Vias and via stubs are included to reflect the discontinuity effect [Fig. 3(b)]. The via stubs have a length of 80 mil and 85 mil, respectively. The overall S-parameter channel response established with near-end vias, striplines of 20 cm length, and far-end vias is demonstrated in Fig. 3(c) when d = 0. Note that in Fig. 3(c) port 5 is the far-end port corresponding to port 1 at the near end.

The sensitivity of multimode signaling with respect to misalignment has been studied with help of a circuit simulator by measuring an eye opening factor (EOF) for a 2^{12} pseudo-random bit sequence while sweeping d from 0 to 10 mil. EOF is the measured eye opening height relative to the ideal noise-free eye opening height and defined as [9]

$$EOF = \frac{(Highlevel - \sigma_H) - (Lowlevel + \sigma_L)}{(Highlevel - Lowlevel)}$$

where σ_H and σ_L denote the standard deviations of binary high and low levels. Note that the codec of multimode signaling is implemented as ideal, as defined in the previous section. According to the misalignment simulation performed at a signaling rate of 5 Gb/s, the vertical eye opening of the decoded signals is insensitive to the misalignment until *d* is shifted more than 60% of the signal line width [Fig. 4(a)]. Similar to EOF, root mean square (RMS) jitter is also increasing once *d* is greater than 60% of the signal line width [Fig. 4(b)].

B. Length mismatch

In multimode signaling, parallel signals are transmitted with linear independency between modes to reduce crosstalk. In practice, length mismatch in a bundle due to limited routing area and manufacturing variations is inevitable, resulting in



Fig. 4. Misaligned channel sensitivity for multimode signaling: (a) Eye opening factor (EOF) and (b) RMS jitter



Fig. 5. Length mismatch sensitivity for multimode signaling: (a) Simulation setup (n = 4), (b) eye opening factor (EOF), and (c) RMS jitter

degradation of the signaling performance. To demonstrate the signal skew effect due to channel length mismatch in a bundle, a simple simulation model is set up where signal 1 is delayed by a variable skew [Fig. 5(a)]. In this simulation, the signaling rate is 5 Gb/s and the line length of Fig. 3(a) with d = 0 is 20 cm. The EOF and RMS jitter measured at the output of the decoder S are illustrated in Fig. 5(b) and (c) as a function of the skew, delaying signal 1 up to 50 ps. The EOF of signal 1 has been degraded by 1.7% when the skew is 50 ps, equivalent to 0.7 cm length mismatch. Since line 3 is more coupled to line 1 than other lines in this example, the EOF of the decoded signal 3 is also reduced [Fig. 5(b)]. The RMS jitter of the decoded signals is linearly increasing with skew because the received signal 1 is applied to the decoding operation of each signal [Fig. 5(c)]. The RMS jitter observed does not exceed 8% of the bit time interval.

V. CONCLUSION

Starting with the analytical channel model of a multiconductor transmission line system, the reduction of crosstalk, in particular FEXT, has been demonstrated under the condition of tight coupling when FEXT is significant for conventional signaling. The sensitivity analysis with respect to the layer-to-layer misalignment of signal wires indicates that vertical and horizontal eye openings are affected when the misalignment is more than 60% of the signal wire width provided that the wire spacing is the same as the wire width. The analysis of channel length sensitivity of multimode signaling indicates that RMS jitter is affected by line length mismatch more than vertical eye opening. However, the amount of RMS jitter introduced in this simulation would likely be acceptable, provided the signaling system is not jitter limited.

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