EFFECT OF DRIVER PARAMETERS AND LINE TERMINATION ON THE EMI BEHAVIOUR OF DIFFERENTIAL SIGNALLING

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ABSTRACT

The influence of driver-asymmetries and termination imbalance on the common-mode and differential-mode frequency spectra is studied. Both asymmetries are included into one parameter denoted as current-imbalance frequency-depended factor. This allows direct quantification of the total parasitic voltage on the ground plane of a PCB, which is a measure for unwanted electromagnetic radiation. A comparison with conventional single-ended trace routing shows degradation of EMI behaviour of differential signalling under realistic conditions.

1 INTRODUCTION

One of the main electromagnetic interference (EMI) problems on digital high-speed printed boards (PCBs) is the radiation from currents on peripheral conductive structures due to the voltage drop across the parasitic ground-plane inductance. The currents on the external structures are small in comparison to the functional differential-mode currents on the traces, but due to the large extent of the external current path, e.g. cables connected to the PCB, the radiation may dominate the differential-mode contribution from the whole system. Differential signalling is often used for routing high-speed signals to prevent such EMI problems. Due to the field cancellation of the two tightly coupled and oppositely directed trace currents, radiation is considerably reduced. The total benefit of differential signalling depends on several things, such as the PCB layout, splits in the ground plane, the differential-driver symmetry, the equivalent propagation trace length and the symmetry of the impedance termination.

A study of the differential and single trace with arbitrary trace position, with splits in the ground plane and the effect of current imbalance is presented in [1]. In this paper, the effect of the skew between the differential signals and the influence of imperfect impedance termination are investigated in terms of the resulting differential- and common-mode voltage frequency spectrum. The two output signals of a differential driver (Fig. 1a) are defined in the time domain by the pulse time t_p, the rise time t_r (the same value for the fall time is assumed), the skew time t_s and the differential amplitudes A_1 and A_2 (Fig. 1b).

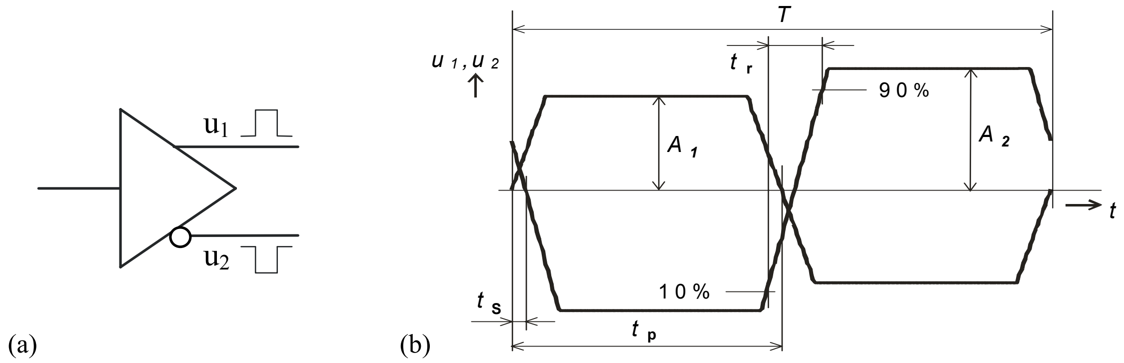

Fig. 1: *Differential driver (a) and time domain output signals u_1 and u_2 with all relevant parameters (b).*

2 FREQUENCY SPECTRUM OF COMMON- AND DIFFERENTIAL-MODE SIGNAL DUE TO DRIVER ASYMMETRIES

Because of the non-ideal driver behaviour, a certain common-mode (CM) signal appears in the output signals. Also the differential-mode (DM) signal is slightly disturbed. The amount of disturbance depends on time skew and amplitude imbalance. In the following, the frequency spectrum of the CM and DM signal is determined.

To obtain compact engineering expressions, the real exponential signal shape during the rise/fall times is linearly approximated by a trapezoidal signal with the frequency spectrum [3]:

$$C_{k\_trpz} = A\frac{t_p}{T}\left|\frac{\sin(k\pi t_p/T)}{k\pi t_p/T}\right|\left|\frac{\sin(k\pi t_r/0.8/T)}{k\pi t_r/0.8/T}\right|, \tag{1}$$

with the time period T of the periodic signal.

Assuming a half-wave symmetry, the spectrum (1) of the trapezoidal pulses has only odd harmonics. The output differential signals are denoted by $u_1(t)$ and $u_2(t) = \alpha \cdot u_1(t - t_s)$, where α is the amplitude factor A_1/A_2. Because the Fourier transform ***F*** is linear, the frequency spectrum coefficients for the CM and the DM signals C_{cm}, C_{dm} respectively, can be generally written as follows:

$$C_{cm} = \left|\boldsymbol{F}\{u_1 - u_2\}\right| = \left|\boldsymbol{F}\{u_1\} - \boldsymbol{F}\{u_2\}\right| = C_{k\_trpz}\left|\left(1 - \alpha \cdot e^{j\omega t_s}\right)\right|, \tag{2}$$

$$C_{dm} = \left|\boldsymbol{F}\{u_1 + u_2\}\right| = \left|\boldsymbol{F}\{u_1\} + \boldsymbol{F}\{u_2\}\right| = C_{k\_trpz}\left|\left(1 + \alpha \cdot e^{j\omega t_s}\right)\right|. \tag{3}$$

This general approach allows to determine the CM and DM spectra for arbitrary differential signals, replacing C_{k_trpz} by the corresponding frequency spectrum. Using (1) and (2), the common-mode frequency-spectrum coefficients for a trapezoidal differential signal (for $\alpha = 1$) are obtained as

$$C_{cm} = \frac{6.4A}{(\pi k)^2}\cdot\frac{t_p}{t_r}\cdot\left|\sin\left(k\frac{\pi}{2}\frac{t_s}{t_p}\right)\sin\left(k\pi\frac{5}{8}\frac{t_r}{t_p}\right)\right|, \tag{4}$$

where *k* is an odd integer number.

Similarly, using (1) and (3), the frequency spectrum of the differential signal results in:

$$C_{dm} = \frac{6.4A}{(\pi k)^2}\cdot\frac{t_p}{t_r}\cdot\left|\cos\left(k\frac{\pi}{2}\frac{t_s}{t_p}\right)\sin\left(k\pi\frac{5}{8}\frac{t_r}{t_p}\right)\right|. \tag{5}$$

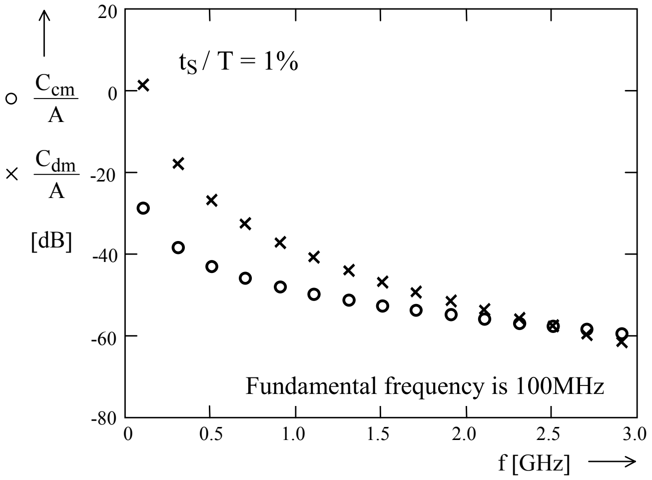

Fig. 2: *Frequency spectrum of the common- and differential-mode signal.*

The results (4) and (5) reveal that the parameters which determine the CM and DM frequency spectrum are the ratios t_r / t_p and t_s / t_p. As an example, the frequency spectrums for the CM (4) and the DM (5) signal normalised to the amplitude A and with following parameters t_p = 5ns, t_r = 2ns, t_s = 0.1ns is shown in Fig.2. Large differences are visible between the CM and DM frequency spectrums for the first harmonics, while for the higher harmonics the amplitudes are comparable.

3 ODD- AND EVEN-MODE CURRENTS ON THE DIFFERENTIAL TRACES DEPENDING ON TERMINATION IMPEDANCE

For determining the currents on the traces the termination network has to be included. As sketched in Fig. 3a, the oppositely directed trace currents I_1 and I_2 can be generally decomposed into an ideally balanced odd-mode (I_{odd}) and a small equally directed even-mode portion I_{even}. The amount of imbalance may then be quantified by a current imbalance factor $\kappa = I_{even} / I_{odd}$.

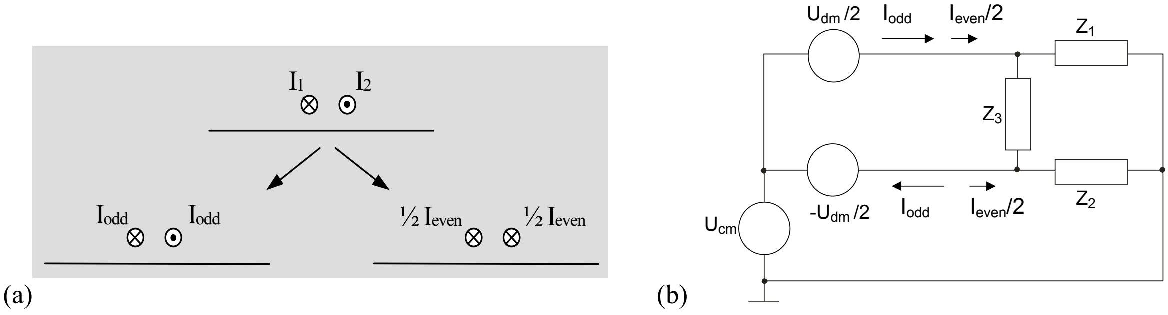

Fig. 3: *Decomposition of a differential signal into an odd- and even-mode current (a) and equivalent circuit of the differential signalling (b).*

With the restriction to electrically short traces, the currents I_{odd} and I_{even} can be calculated by circuit analysis (see Fig. 3). The voltage sources U_{cm} and U_{dm}, representing the differential driver, are replaced by the corresponding frequency spectrums C_{cm} and C_{dm}. After several steps, the following final expression for the current-imbalance factor is obtained:

$$\kappa = \frac{I_{even}}{I_{odd}} = \frac{1}{2}\frac{(Z_1 + Z_2)\cdot C_{cm} + \left|Z_1 - Z_2\right|\cdot C_{dm}}{\left|Z_1 - Z_2\right|\cdot C_{cm} + \left[\frac{1}{4}(Z_1 + Z_2) + \frac{Z_1 Z_2}{Z_3}\right]\cdot C_{dm}}. \tag{6}$$

The current imbalance factor κ given in Eq. (6) includes the time skew of the differential driver and the termination-network imbalance. The latter vanishes for $Z_1 = Z_2$, i.e. for a perfectly symmetric network.

4 ESTIMATION OF THE TOTAL EXTERNAL VOLTAGE ON A PCB

The external voltage on the ground plane of a PCB is responsible for small antenna currents flowing on cable (shield) connected to the ground of the PCB. Assuming the trace length to be short against the signal wavelength, which is a valid simplification up to several hundreds of MHz for customary trace lengths and substrate material, the external voltage on the ground plane of a PCB is given by [1]

$$U_{ext,\,diff} \approx \omega I_{odd}\left(\Delta L_{CM} + \kappa L_{CM}\right). \tag{7}$$

Besides the currents I_{odd} and the angular frequency ω, the common-mode inductances L_{CM} and ΔL_{CM} and the imbalance factor κ define the radiation level.

As sketched in Fig.4, the differential traces with mutual distance Δs are assumed to be at the height h above a ground plane with the width w. The horizontal position of the traces with respect to the centre of the ground plane is denoted by s. To compare the EMI behaviour of differential signalling with conventional single-ended trace routing, the ratio $U_{ext,diff} / U_{ext,single}$ of the corresponding external voltages is considered. The following expression which includes the cross-section geometry and the imbalance factor κ was developed in [1]:

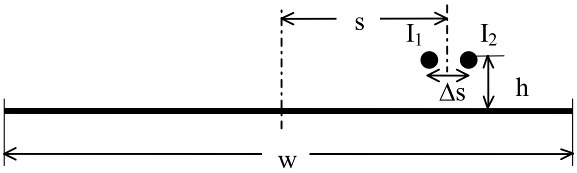

Fig. 4: *Simplified cross-section of the differential pair.*

$$\frac{U_{ext,diff}}{U_{ext,single}} \approx \frac{\Delta L'_{CM}}{L'_{CM}} + \kappa = 4\frac{h}{w}\,\frac{s/w}{1\text{-}4\,(1\text{-}2\,h/w)\,(s/w)^2}\,\frac{\Delta s}{h} + \kappa\,. \tag{8}$$

Fig. 5a shows as an evaluation of (6), the imbalance factor κ for the first 30 harmonics of a 100MHz signal with a time skew of 0.1ns and a termination asymmetry of approx. 5% (see insert in Fig. 5a). As can be seen, κ considerably increases with higher harmonics. The influence of termination imbalance alone is shown in Fig. 5b for the first harmonic, depending on the trace position S/W. Even for a relatively high fabrication tolerance of 10% the external voltage with respect to the single trace is not much affected.

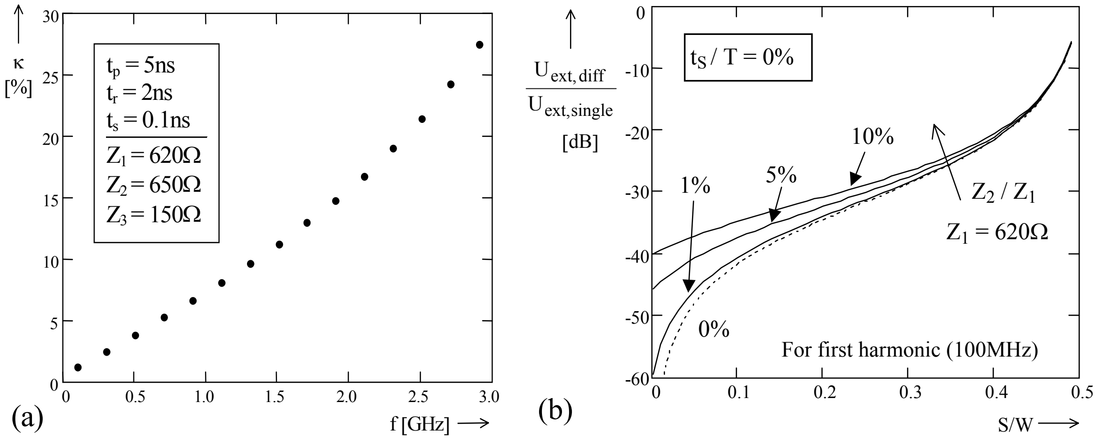

Fig. 5: *Imbalance factor for first 30 harmonics (a) and differential-to-single external voltage ratio depending on trace position (S/W) for different impedance imbalance (b).*

The influence of trace position on all thirty harmonics is displayed in Fig. 6a for the same parameters as in Fig. 5a. It is visible that when the traces are located very close to the edge, the ideal properties of differential traces are almost degraded. The effect of the driver skew time shown in Fig. 6b for a symmetric termination demonstrates the sensitivity of the EMI behaviour of differential signalling with respect to relatively small skew-time values.

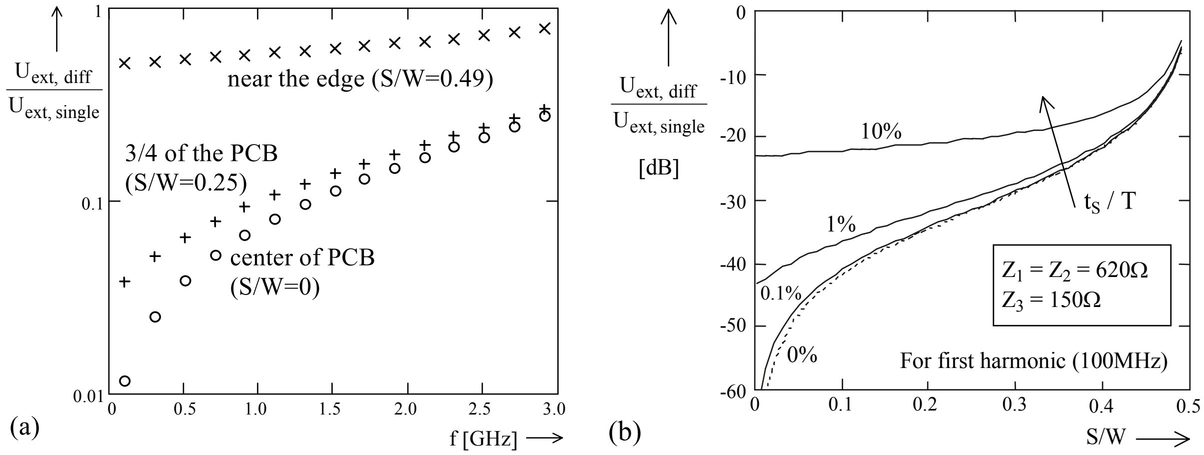

Fig. 6: *(a) External noise-voltage ratio vs. frequency for different trace positions and (b) influence of trace position for different driver skew time.*

5 CONCLUSION

The distribution of high-speed signals on printed circuit board by means of differential signalling has advantageous properties with respect to signal integrity and radiated emission. Nevertheless, radiation may become comparable to conventional single trace routing when the differential trace pair is placed near the edge of a reference plane. This is found even for perfectly balanced currents. The study was extended to include also other effects, such a small imbalances originating from non-ideal differential drivers and unbalanced impedance termination which are always present in reality. The influence of termination imbalance on the external voltage ratio is found to be relatively small for practical impedance tolerances, while the skew time has a much stronger effect. Therefore, in order to obtain the maximum benefit from differential signalling, the skew time of the driver has to be small with respect to the time period of the signal and traces should be routed far away from the edge of the PCB.

ACKNOWLEDGEMENTS

This work has been supported by the Siemens AG and by the research programme of the Brno University of Technology MSM 262200011: Research of electronic communication systems and technologies.

REFERENCES

[1] LEONE, M., NAVRÁTIL V. Analysis of the Common Mode Radiation from Differential Signalling on Printed Circuit Boards, Proceedings of the Conference EMC Zurich 2003., Zurich, 2003.

[2] NAVRÁTIL, V. LEONE, M. The Effect of Differential Driver Asymmetries on Common-Mode Frequency Spectrum, Journal Radioengineering, vol. 12, no. 1, 2003.

[3] PAUL, C. R. , Introduction to Electromagnetic Compatibility, Wiley & Sons, Inc., 1992.