The Effect of Differential Driver Asymmetries on Common-Mode Frequency Spectrum

Vlastimil NAVRÁTIL, Marco LEONE

Corporate Technology, Siemens AG, Erlangen, Germany

navratil@feec.vutbr.cz, marco.leone@siemens.com

Abstract. *A frequency spectra determination of the common-mode signal due to the differential driver asymmetries is presented. The analytical expression for the Fourier series is developed and the evaluations for different dependencies are introduced. The effect of the skew time and amplitude imbalance is shown in a parameter study. From the general analytical solution a compact expression for small amplitude imbalances is deduced. This allows to study the influence of the driver time skew on the resulting common-mode signal, which is the source of unwanted electromagnetic radiation. It is found that for realistic driver parameters, the driver skew is the most responsible.*

Keywords

Differential signalling, Common-mode signal, Fourier series, Electromagnetic compatibility.

1. Introduction

One of the main electromagnetic interference (EMI) problem on digital high-speed printed boards (PCBs) is the common-mode (CM) radiation from currents on peripheral conductive structures. The parasitic ground plane inductance is responsible for the common-mode radiation. The common-mode currents are small in comparison to the functional differential-mode currents on the traces, but due to the large extent of the external common-mode current path, e.g. cables connected to PCB, the common-mode radiation may dominate the differential-mode contribution from the whole system. The resulting voltage drop across the ground plane represents the common-mode noise source, which excites the external structure. The differential signalling is used as a method for reducing this common-mode voltage. This means is very often used for routing high speed signals to prevent the EMI problem. There are lots of conditions for the EMI compatible trace routing. The PCB layout, especially splits in the ground plane [1], [2], the used differential drivers and also the equivalent propagation trace length of the differential trace pair play a great role in the total profit of differential signalling.

A study of the differential and single trace with arbitrary trace position [3], with splits in the ground plane and the effect of current imbalance is presented in [1]. In this paper the influence of driver asymmetries on the common-mode frequency spectrum is studied. The effect of the skew between the differential signals and the influence of amplitudes imbalance are investigated in terms of the resulting common-mode frequency spectrum. Fig. 1a shows a sketch of a differential driver with the two corresponding time domain output signals. Fig. 1b shows the two differential output signals, defined by the pulse time t_p, the rise time t_r (the same value for the fall time is expected), the skew time t_s and the differential amplitudes A_1 and A_2.

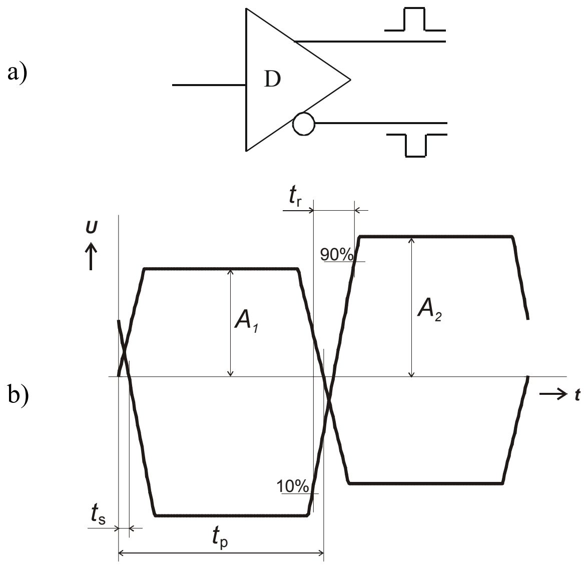

Fig. 1. Differential schematic representation (a) and the time domain output signals with all defining parameters (b).

2. The Analytical Technique for the Fourier Series Determination

From the theory of signal processing and analysis an approximating technique to determine the Fourier transform is used in the following [4] - [6]. This technique uses the theorem of the derivative of the Fourier transform

$F(\omega)$, the theorem of the time shifting (t_0) and the Fourier transform of the Dirac impulse $\delta(t)$, i.e.

$$\frac{d^n f}{dt^n} \leftrightarrow (j\omega)^n F(\omega) \; , \tag{1}$$

where ω is the angular frequency,

$$f(t-t_0) \leftrightarrow F(\omega) e^{-jt_0\omega} \; , \tag{2}$$

$$\delta(t) \leftrightarrow 1 \; . \tag{3}$$

If the function $f(t)$ is sufficiently smooth, then it can be approximated by a small number of polynomial pieces as shown in Fig. 2.

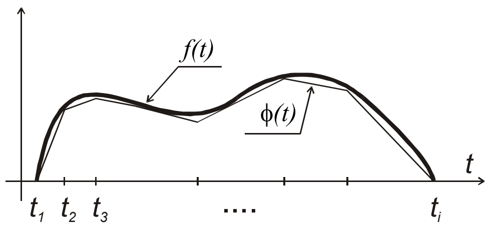

Fig. 2. Linear approximation of a function $f(t)$ by $\phi(t)$.

In the following, the approximating polynomial is denoted as $\phi(t)$. Differentiating $\phi(t)$ twice, we obtain a sequence of Dirac impulses

$$\phi''(t) = \sum_i c_i \delta(t - t_i) \; . \tag{4}$$

The Fourier transform $\Phi(\omega)$ of the approximating polynomial $\phi(t)$ is set up using (1), (2) and (3), as

$$(j\omega)^2 \Phi(\omega) = \sum_i c_i e^{-j\omega t_i} \; , \tag{5}$$

and consequently

$$\Phi(\omega) = -\frac{1}{\omega^2} \sum_i c_i e^{-j\omega t_i} \tag{6}$$

For a periodical signal $\phi(t)$, as considered here, the Fourier transform must be converted into the corresponding Fourier series with the spectral coefficients C_k to be determined.

Knowing the Fourier transform $\Phi(\omega)$ the spectral coefficients C_k of a Fourier series of a finite function $\phi(t)$ with time period T are equal to the values of the Fourier transform $\Phi(\omega)$ of this function for the discrete angular frequencies $\omega = k\,(2\pi/T)$, divided by period T, i.e. [4]

$$C_k = \frac{1}{T} \Phi\left(k \frac{2\pi}{T}\right) \; . \tag{7}$$

Eqn. (7) together with (6) will be used to set up an analytical solution for the spectral coefficient of the CM frequency spectrum of imperfect differential drivers.

3. Determination of the CM Frequency Spectrum

The non-zero skew time t_s between the two differentetial outputs and the slight amplitude differences (see Fig. 1) are responsible for a small unwanted common mode signal on the differential traces in addition to the intentional differential signal.

As shown in Fig. 3, the real exponential signal shape during the rise/fall times is approximated by a linear function. In this case, the common-mode signal function is piecewise linear, so that the approximation polynomial $\phi(t)$ and the function $f(t)$ are identical.

The approximating technique presented in the preceding section is applied to the common-mode signal $V_{cm}(t)$, as sketched in Fig. 3. Using Eq. (6) and subsequently (7) the coefficients of the Fourier series are obtained as

$$\begin{aligned} C_{k,\substack{A_1<A_2 \\ A_1\geq A_2}} = -\frac{1}{2\pi k \omega} \Big[& -(\phi_1' \mp \phi_2') \cdot e^{-j\omega t_1} + \phi_2' \cdot e^{-j\omega t_2} \\ & - \phi_3' \cdot e^{-j\omega t_3} + (\phi_3' \pm \phi_4') \cdot e^{-j\omega t_4} + (\phi_4' \mp \phi_5') \cdot e^{-j\omega t_5} \\ & - \phi_5' \cdot e^{-j\omega t_6} + \phi_6' \cdot e^{-j\omega t_7} - (\phi_6' \pm \phi_1') \cdot e^{-j\omega t_8} \Big] \; , \end{aligned} \tag{8}$$

where k is the number of harmonics. In the case studied here, only odd harmonics appear.

The times t_i (for i = 1, 2, ... 8) are defined as follows:

$t_1 = t_r / 1.6$, $t_2 = t_r / 1.6 + t_s$,

$t_3 = t_p - t_r / 1.6$, $t_4 = t_p - t_r / 1.6 + t_s$,

$t_5 = t_p + t_r / 1.6$, $t_6 = t_p + t_r / 1.6 + t_s$,

$t_7 = 2t_p - t_r / 1.6$, $t_8 = 2t_p - t_r / 1.6 + t_s$.

The values of the first derivatives $\phi'(t)$ are listed in Tab. 1.

ϕ'_1	$\frac{\lvert A_1 - A_2 \rvert}{t_r/1.6}$	ϕ'_4	$\frac{\lvert A_1 - A_2 \rvert \cdot \left(2 - \frac{t_s}{t_r/1.6}\right)}{t_r/0.8 - t_s}$
ϕ'_2	$\frac{\lvert A_2 \rvert}{t_r/1.6}$	ϕ'_5	$\frac{\lvert A_2 \rvert}{t_r/1.6}$
ϕ'_3	$\frac{\lvert A_1 \rvert}{t_r/1.6}$	ϕ'_6	$\frac{\lvert A_1 \rvert}{t_r/1.6}$

Tab. 1. The first derivatives of the common-mode signal for the determination of the Fourier-series coefficients.

The ± signs in Eq. (8) are used in the two cases $A_1 \geq A_2$ or $A_1 < A_2$.

In case that the differential amplitudes are equal ($A_1 = A_2 = A$) the following compact formula can be derived from (8):

$$C_k = -\frac{6.4A}{(\pi k)^2}\cdot\frac{t_p}{t_r}\cdot\left[\sin\left(k\frac{\pi}{2}\frac{t_s}{t_p}\right)\cos\left(k\pi\left(\frac{5}{8}\frac{t_r}{t_p}-\frac{1}{2}\right)\right)\right] \quad (9)$$

where k is an odd integer number.

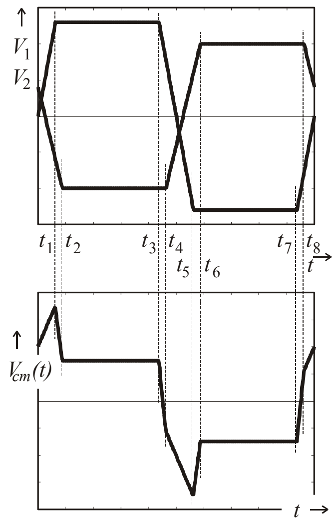

Fig. 3. Sketch of the differential signals V_1, V_2 and of the examined common mode signal V_{cm}. The time values t_i are used in the following formulas.

This formula is more suitable for engineering purposes because of the short closed form as compared to (8). Furthermore, it reveals that the parameters which determine the common-mode frequency spectrum are the ratios t_r / t_p and t_s / t_p.

To validate the analytical solution, the Fast-Fourier Transform implemented in MATLAB was used. The linear approximation corresponds well with more precise exponential approximation [7]. As an example, a signal with the following parameters was used: $t_p = 0.9911$ ns, $t_r = 180$ ps and $t_s = 50$ ps. The first harmonic amplitude is 0.4V for the exponential approximation. The linear approximation yields a value of 0.407 V.

The application of the approximating solutions (8), (9) for the frequency spectrum determination may serve as a tool to study the differential signalling behaviour. An investigation of the signal integrity and an estimation of the maximum electromagnetic radiation from the printed circuit board can be commonly applied for this technique.

4. Parameter Study

With the developed formulas (8) and (9), the common-mode frequency spectrum can be studied for different conditions. As an example the differential signal with equal amplitudes ($A_1 = A_2 = 1$V) and with time parameters $t_p = 5$ ns ($f = 100$MHz), $t_r = 1$ns and $t_s = 0.25$ ns was used. The resulting CM frequency spectrum is shown in Fig. 4. It is visible that for this example the first harmonics are in the range of –20 dBV.

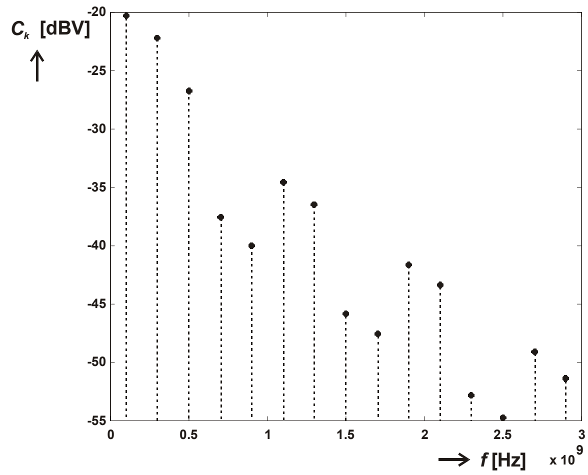

Fig. 4. Frequency spectrum (first 30 harmonics) of the common-mode signal, ($A_1 = A_2 = 1$ V, $t_p = 5$ ns, $t_r = 1$ ns, $t_s = 0.25$ ns).

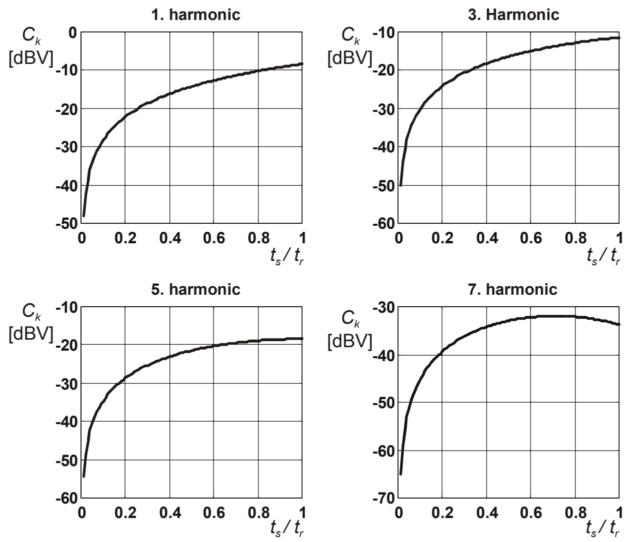

Fig. 5. The dependency of the spectral coefficient amplitudes on the ratio of the skew time/rise time ($A_1 = A_2 = 1$ V, $t_p =$ $= 5$ ns, $t_r = 1$ ns).

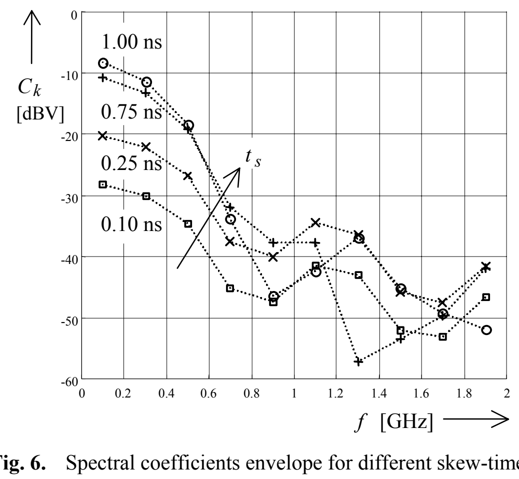

Fig. 6. Spectral coefficients envelope for different skew-time values ($A_1 = A_2 = 1$ V, $t_p = 5$ ns, $t_r = 1$ ns).

Fig. 5 shows the dependency of the spectral amplitudes on the ratio between the skew time and the rise time t_s / t_r. The same differential signal was investigated as above. The amplitude of the spectral coefficients increases with increasing skew time. It is also interesting to note that some harmonics go down again when the skew time reaches a certain value (in case of the 7th harmonics), similar to results in [8].

The frequency spectrums in Fig. 6 show the effect of the skew time on the spectrum. For the same parameters as above, a ten times higher skew time yields an increase of the first harmonic amplitude of about 20 dB.

In the preceding section the two amplitudes A_1 and A_2 of the differential signals were assumed to be equal.

The effect of amplitude imbalance is shown in Fig. 7 for an example with t_p = 500 ns, t_r = 10 ns, t_s = 5 ns and A_1 = 1 V. The amplitude imbalance is given by the factor α, referring to the relation $A_2 = A_1 (1 + \alpha)$. The results in Fig. 7 show that small amplitude imbalances of a few percent have only a minor influence on the CM frequency spectrum. This corresponds to typical imbalance values of common drivers. Therefore, eqn. (9) provides sufficient accuracy for engineering purposes.

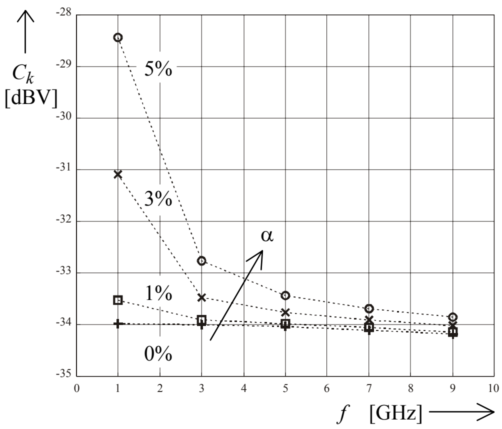

Fig. 7. Relative spectral-coefficients envelope for different amplitude imbalance (A_1 = 1 V, $A_2 = A_1(1+\alpha)$, t_p = 500 ns, t_r = 10 ns, t_s = 5 ns).

5. Conclusion

The approximating analytical solution technique for the Fourier transform was used to investigate the frequency spectrum of the common-mode signal due to differential driver imbalances. The frequency spectrum dependencies on the amplitude imbalance and the time skew were evaluated. The following results were obtained:

- the amplitudes of the common mode spectral coefficients generally increase with higher skew time. The greatest differences are observed for the first harmonics, where a ten times higher skew time may yield a 20 dB spectral amplitude increase. For special harmonics the amplitude decreases after reaching a maximum value,
- because the common-mode signal consists of the trapezoidal pulses with half-wave symmetry and with alternating polarity, it produces only odd harmonics,
- small amplitude imbalances in the typical range of a few percent have minor influence on the resulting CM frequency spectrum, allowing to use a compact closed form equation to calculate the spectral coefficients.

References

[1] LEONE, M., NAVRÁTIL V. Analysis of the common mode radiation from differential signalling on printed circuit boards. In *Proc. of the Conference EMC Zurich 2003*. Zurich, 2003 (accepted).

[2] ILAVARSAN P. Simulation/experimental analysis of single/differential signals crossing splits. In *Proc. of the 2001 IEEE International Symposium on Electromagnetic Compatibility*. Montreal, 2001.

[3] LEONE, M. Design expressions for the trace-to-edge common-mode inductance of a printed circuit board. *IEEE Trans. on Electromagnetic Compatibility*, 2001, vol. 43, no. 4.

[4] ČÍŽEK, V. *Discrete Fourier transforms and their applications*. Bristol: Adam Hilberg Ltd., 1986.

[5] BRIGHAM, E. O. *The fast Fourier transform*. New Jersey: Prentice Hall, 1986.

[6] PAPOULIS, A. *The Fourier integral and its applications*. London: Mc Graw-Hill, 1962.

[7] HOEFT, O.L., KNIGHTEN, J.L. Spectral analysis of common mode currents on fibre channel cable shields due to skew imbalance of differential signals operating at 1.0625 Gb/s. In *Proc. of the 1998 IEEE International Symposium on Electromagnetic Compatibility*. Seattle, 1998.

[8] KNIGHTEN, J. L. Common-mode current harmonics on differential pair cable shields operating in a regime as high as 2.125 Gb/s. In *Proc. of the 2001 IEEE International Symposium on Electromagnetic Compatibility*. Montreal, 2001.

About Authors...

Vlastimil NAVRÁTIL was born in Olomouc (Czech Republic) in 1976. He received the Ing. (M.Sc.) degree from the Brno University of Technology (BUT) in 1999. At present, he is Ph.D. student at the Dept. of Radio Electronics of BUT. He solves the PhD thesis in the Corporate Technology Dept. in Siemens AG (Erlangen). His research interests are the numerical modeling and the simulation of radiation mechanism on printed circuit boards.

Marco LEONE was born in Zürich (Switzerland) in 1966. He received the Dipl.-Ing. degree from the Technical University of Berlin, in 1995 and the Dr.-Ing. degree in 2000 from the Technical University Hamburg-Harburg. His research concerned the electromagnetic simulation of radiation and susceptibility on printed circuit boards (PCB). Since 2000 he has been working with Siemens AG in the Corporate Technology department in Erlangen. Currently he is working on analytical and numerical modeling of radiation mechanisms on PCB on system level. He is winner of the 2002 Best paper award of EMV 2002 International Symposium in Düsseldorf (Germany).