Effect of Differential Signal Skew on the Common-Mode Emissions in a Differential Signals

Jong-Byung Lee and Jae-Hyun Lee
Department of Radio Science and Engineering, Chungnam National University
220, Kung-Dong, Yusong-Gu, Daejon, 305-764, Korea
E-mail: jaehyun@cuvic.cnu.ac.kr

Abstract

The effect of delay skew of differential signal imbalance on trapezoidal waveform is investigated. Delay skew of a differential signal creates imbalance that results in a common-mode voltage. Closed-form expressions for the common-mode voltage are derived in both the time domain and the frequency domain. The simulation results show that a small amount of signal skew results in a series of common-mode voltage pulses. For a clock signal with a 50% duty cycle, delay skew creates a common-mode pulse train whose energy is primarily at the odd-harmonic frequencies.

1. Introduction

Differential signaling is widely employed for high-speed electronic communication. Differential data transmission schemes take advantage of the greater noise immunity and reduced radiated emissions normally associated with differential signals. Theoretically, a perfectly balanced differential data interface consisting of a differential source, a balanced conductor pair and a balanced receiver, will not generate common-mode currents, which are a significant source of radiated emissions [1]. In practice, however, imbalances in the transmitter conductor pair and/or receiver generate small amounts of common-mode currents that tend to be the dominant source of radiated emissions.

There are many possible sources of imbalance in differential signal transmission schemes. The voltages generated by the transmitter may not be exactly equal and opposite relative to conductors that are not part of the intended current path. The two differential signal conductors may not be perfectly balanced. Also, the receiver may introduce different impedances from each signal conductor to a third conductor. Any of these sources of imbalance may cause some of the signal current to flow on a conductor that is not part of the intended current path.

In this paper, we investigate delay skew which gives imbalance in differential interfaces where two wires or traces are driven with an equal and opposite voltage relative to a ground plane. It results when one half of a differential digital signal does not transition at exactly the same time as the other half.

2 Delay Skew Effects

Delay skew can result when one side of a differential digital signal source switches at a slightly different time than the other side. It may also result when one trace or wire in the differential pair is longer than the other causing the two halves of the signal to arrive at different times. As shown in Fig. 1, when the two halves of the differential signal do not switch at exactly the same time, there is a short burst of common-mode voltage.

Modeling the two sides of the differential signal as trapezoidal waveforms with amplitude A, transitions time t_r and delay skew τ_d, a simple equation for the common-mode voltage can be derived for the case $\tau_d > t_r$,

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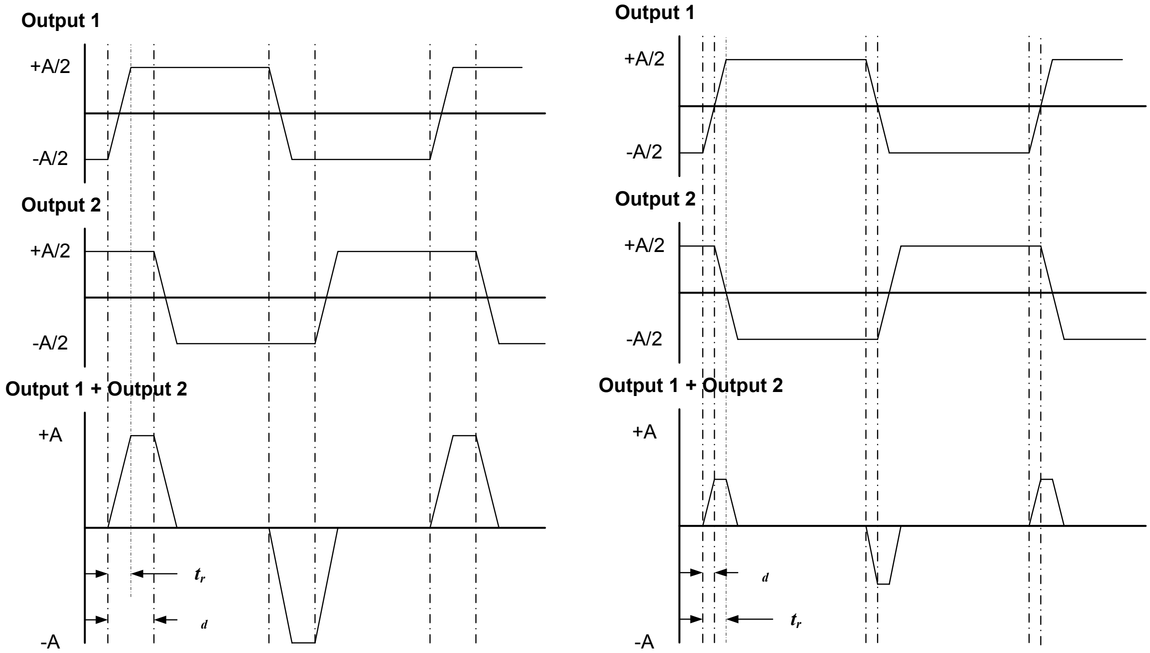
$$v(t) = \begin{cases} A(t/t_r) & 0 < t < t_r \\ A & t_r < t < \tau_d \\ A[-t + (t_r + \tau_d)]/t_r & \tau_d < t < t_r + \tau_d \end{cases} \quad (1)$$

When τ_d is less than t_r, the expression in Equation (1) reduces to

$$v(t) = \begin{cases} A(t/t_r) & 0 < t < \tau_d \\ A(\tau_d/t_r) & \tau_d < t < t_r \\ A[-t + (t_r + \tau_d)]/t_r & t_r < t < t_r + \tau_d \end{cases} \quad (2)$$



(a) (b)

Fig. 1. Common-mode voltage due to delay skew: (a) $\tau_d > t_r$, (b) $\tau_d < t_r$.

In the time domain, this series of trapezoids can be represented by a convolution of a single trapezoid with two periodic pulse trains. One pulse train consists of a unit pulse at $t = 0$ and is period with period T. The second pulse train consists of a negative unit pulse at $t = T/2$ and is also periodic with period T.

In the frequency domain, the two pulse trains effectively sample the Fourier transform of the trapezoidal waveform at odd harmonics of the fundamental frequency. Therefore the trapezoidal waveform's transform provides an envelope of the common-mode voltage in the frequency domain.

The one-sided Fourier series coefficients corresponding to the waveforms in Equations (1) and (2) are the same and are given by:

$$|v(n)| = \begin{cases} 2A\dfrac{\tau_d}{T}\left|\dfrac{\sin(n\pi f_0 \tau_d)}{n\pi f_0 \tau_d}\right|\left|\dfrac{\sin(n\pi f_0 t_r)}{n\pi f_0 t_r}\right| & n = 1,3,5,\ldots \\ 0 & n = 2,4,6,\ldots \end{cases} \quad (3)$$

where $f_0 = 1/T$ is the fundamental frequency of the original waveform. Because τ_d and t_r are much smaller than T, the amplitude of the first several harmonics is independent of frequency and directly proportional to the amount of delay skew, τ_d.

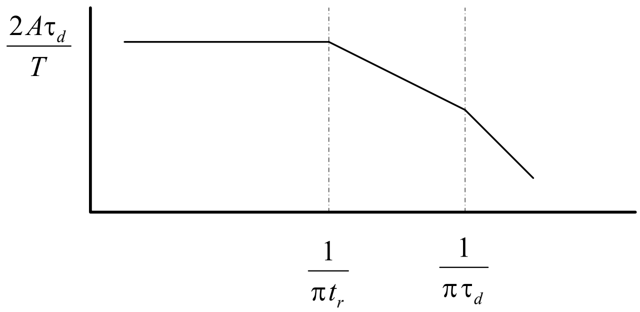


Fig. 2. The envelope of the amplitude of the harmonics in Equation (2) ($t_r >> \tau_d$).

A plot of the envelope of the amplitude of the harmonics for a waveform where $\tau_d << t_r << T$ is shown in Fig. 2. Note that the amplitude of the harmonics does not decrease with frequency below $f = 1/\pi t_r$. The common-mode voltage is a series of short pulses. This common-mode signal has more of its power in the higher harmonic frequencies than the original differential signal. The relative amplitude of the first 100 harmonics of the common-mode waveform which results from a 1% delay skew ($\tau_d = 0.01T$) in a differential signal is compared to the harmonics in a single-ended clock signal with the same amplitude (i.e. $V_{\text{pp}} = 2A$). Only the odd harmonics are shown, since the even harmonics have zero amplitude. Note that the differential waveform is almost 30 dB lower at the fundamental frequency. However, the power in the harmonics of the differential signal does not fall off with frequency as fast as the power in the harmonics of the single-ended signal. Around the 51st harmonic, the power in both signals is approximately equal [2].

A similar comparison between a single-ended signal and a differential signal with 10% delay skew shows that while the amplitudes of some harmonics are significantly reduced, many others are not affected. Of the first 15 harmonics, only the 1st, 9th and 11th are significantly attenuated.

Note that using one half of a differential clock output for our single-ended signal would have produced harmonics that were 6 dB lower than the above. This suggests that pseudo-differential clocks with delay skew can actually generate higher emissions at many frequencies than their single-ended equivalents, which have half the peak-to-peak voltage.

4 Conclusions

Delay skew produces common-mode voltages on differential signal lines. These common-mode voltages create common-mode currents that may be a significant source of radiated EMI. The common-mode voltage resulting from delay skew appears at odd harmonics of the fundamental and has an amplitude directly proportional to the amount of delay.

The amplitude of the common-mode voltage at harmonic frequencies is never more than the sum of the voltages at that frequency due to each half of the differential signal. At low harmonic frequencies, the contributions to the common-mode voltage from each half of the differential signal tend to cancel each other. However, with a little skew introduced, the contributions to the common-mode voltage from each half add at the higher harmonic frequencies. This can result in radiated emissions from a differential signal that are actually higher than the emissions due to half of the clock output operating single ended.

Acknowledgment

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