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# Vectorial voltage measurement for ICs on multi-IC PWB

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**Abstract** - When a multi-IC PWB fails compliance with the EMC emission requirements it is necessary to locate the IC(s) that can be the cause for this shortcoming. With many applications, too high-induced voltage levels in the ground layer of the PWB are the main cause the RF emission.

Many measurement tools do exist to measure the near-field magnetic field component underneath a PWB. These tools are sensitive enough to locate RF emission areas when measured in the frequency domain but are not fine enough to allocate a certain quadrant of an IC. Most certainly not when the emission is dependent on time i.e. instruction codes being processed. For this purpose, a measurement methodology in the time domain, containing amplitude and phase information has been developed. Up till recent this has not been feasible by lacking suitable measurement equipment.

In this paper a measurement technique is defined in the time domain with sufficient sensitivity and with the capability to be synchronised with the clock frequency or other trigger events generated by the system to be measured.

## 1. INTRODUCTION

All electric and electronic products have to comply with EMC requirements for RF emission as well as immunity. Many products are build up from a group of ICs, forming the system, which then determines the total RF emission from that product.

However when such products i.e. systems are created, the individual contribution of each IC to the RF emission needs to be determined to obtain the best options to improve the overall performance by EMC measures on silicon. Even further, the contribution to the RF emission from each module on silicon needs to be determined to show the main causes to this RF emission.

This kind of measurements is only feasible in the time domain, different from the frequency domain measurements where all signal contributions are collected into one measurement bandwidth at the selected frequency of the EMI receiver. In the time domain, the measurement

taken can be synchronised with an activity on silicon resulting in information about the individual contribution of each module to the RF emission.

By taking balanced vectorial measurements, four points against a common reference are measured in time. The voltage gradient in a ground or supply layer of the PWB can be analysed underneath each IC, with minimum cross-talk of other ICs on the board.

The measurement method is only suitable when continuous ground and supply layers exist without slits, at least not in the area where these points and their reference for measurement are taken. Furthermore, it is assumed that the ground or supply layer structure is rotation symmetric to allow analysis of the on-chip activities versus the obtained voltage gradients. Measurements on irregular structures remain valid to determine the RF emission from that IC on that PWB application, but no or less relation can be derived with the on-chip activities as the gradient voltages will be disturbed.

This vector voltage measurement and analysis method is also suitable (non-intrusive) for high density PGA and BGA packaged ICs where little flexibility is left over for measurements on individual ground and supply pins like with PLCC and QFP, where pins could be lifted and bend upwards for measurement purposes.

## 2. MEASUREMENT PRINCIPLE

With PGA and BGA package applications on a PWB it is assumed that a grid structure will result in the PWB layer underneath the IC package due to large number of vias. These vias are necessary to make contacts to the balls or pins to the various PWB layers. Even with the supply and ground pads / vias on the PWB it is assumed that heat spreaders are applied in the PWB grid to ease the soldering process. Due to this grid structure in the PWB layers, common impedance in the ground plane and the supply layer(s) can be derived for this area through which currents will flow. Under the assumption that the supply pins and ground pins are equally spread over the rings of pins, it may also be assumed that the external decoupling capacitances with the supply are equally spread too. Under

these assumptions, which will not be valid for every application, and under the assumption that the noise currents from the IC are equally distributed to all supply and ground pins, the overall voltage induced in the PWB ground layer can be close to zero. This situation is illustrated in Figure 1.

When the PWB structure of the ground and supply layer with the PWB are electrically and mechanically rotation symmetric the voltage gradient in the PWB can be measured. Due to the symmetric structure, a relation can also be drawn about the on-chip gradient voltages as these are equally represented as voltage gradients in the PWB layers, as depicted in Figure 1.

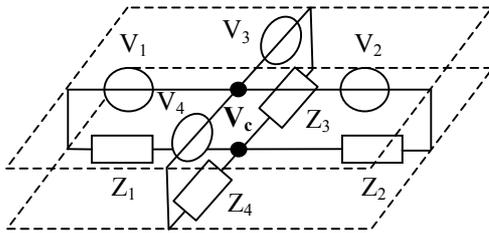


Figure 1: Vector voltages sources and common impedances in supply and ground layers

When all voltages in the IC and the impedances with the package and the PWB are equal (assuming an excitation at the centre of the IC by the supply current(s)), no voltage gradient can be found between the  $V_{1..4}$  – nodes individually (Wheatstone bridge effect). Nevertheless, vectorial voltages do occur towards a centre point  $V_C$ . By the constraint that the sum of all off-chip currents in the  $I_{ss}$ -,  $I_{dd}$ - and I/O-s, have to be equal to zero (or at least close to zero, neglecting the displacement current from the die to the surroundings), there will always be voltage gradients underneath the IC. With every application both the loading of the chip will be asymmetric as well as the on-chip “equivalent” voltage sources. These differences will result in a voltage gradient across the PWB that can be measured by using a digital sampling oscilloscope with four inputs. By measuring the four vectorial voltages (referenced to a single point) simultaneously, the phase relation information is captured too. This allows further processing of the vectorial voltages.

After obtaining the vectorial voltages, these signals can be manipulated in many ways:

- At first, the common-mode vector component needs to be subtracted from the individual measured voltages. Adding all four signals (after compensating for all delay and skew errors) and divide it by four can do this. Then a virtual centre voltage in-between the four measurement points is defined;  $V_{CM} = (\sum V_i)/4$ ,  $i = 1..4$ .

- Either from this virtual centre point, the quadrant voltage vectors;  $[V_i - V_{CM}]$  are derived or the vector voltages between the measurement points  $[V_i - V_j]$  can be derived;  $i, j = 1..4$ ,  $i \neq j$ , excluding the contribution of the common-mode voltage.
- From the obtained vectorial voltages, the mean, peak and RMS values can be taken over the obtained record length which will indicate the activity within each quadrant of the IC.
- Each vectorial voltage, taken in the time domain, can be transferred to the frequency domain by FFT. As an alternative, the normalised energy can be taken from the integral of the occurring pulse width, with their highest peak level (Parseval’s Theorem). This then can be used to approximate the RF emission spectrum envelope of that vectorial voltage.

$$\frac{1}{T} \int_0^T v^2(t).dt = \int_0^{fs} V^2(f).df$$

(Parseval’s Theorem)

In this particular case, the integral in time domain is taken over 500 ns, with sampling intervals of 100 ps. This will result in a frequency domain spectrum up till 5 GHz with spectral lines at every 2 MHz. The corner frequency will be determined by the pulse width in the time domain. The obtained manipulated vector voltages do not give a fixed relation between the measured RF emission levels in  $\text{dB}\mu\text{V/m}$ . The transfer function between the voltages and the actual RF function is dependent upon a large number of other parameters:

- size of the PWB and the position of that IC
- whether or not cables are connected to the PWB
- where these cables are connected to the PWB
- ....etc.

What the manipulated vector voltages will show is the differences in contribution between the other ICs on the multi-level board; assuming that similar measurements are taken with all ICs on that multi-level board.

### 3. CAUSES FOR MEASUREMENT ERRORS

With the measurement principle as indicated in the previous chapter, a number of errors will be introduced. These errors, when properly defined can be corrected for, which makes the measurement more useful.

With the measurement principle the following causes for errors are considered:

- timing errors with respect to the sampling moment; not all signals with each channel are sampled simultaneously. There appears to be a fixed delay in-between the sampling moment plus a stochastic timing error, which cannot be compensated for, see chapter 5.
- delay errors with respect to the delay within the oscilloscope between the signal entry up till the sampling circuit. This delay will be input sensitivity dependent i.e. whether input amplifier or attenuators are added to or take out off in the signal path; typically 7 ps/mm.
- delay caused by unequal length of the coaxial cables used; this including the cable length of the semi-rigid cables towards the measurement target. Loosely screwed connector will be electrically longer than properly fixed connectors.
- delay caused with the measurement set-up i.e. different electrical signal length between the PWB reference and the reference of the target. Either a point at the centre shall be taken a point further away.
- The choice of the reference point has great influence on the overall sensitivity of the system. See chapter 4 as the input sensitivity has to be chosen such that it can handle the vectorial voltage including the common-mode voltage with it.
- The resolution of the vertical scale. With high speed A/D only a few bits 6 to 8 are available for the entire scale. When due to the common-mode voltage a lower sensitivity is taken, only a fraction of the A/D range remains usable for the vectorial signal. Then after subtraction the error will therefor increase.

For each of the above mentioned errors a solution is given up to a certain level in the next section of this paper.

#### 4. REFERENCE POINT SELECTION

The reference point or common-mode point taken with respect to the four chosen vector positions will cause other contributions for errors. The sensitivity of the oscilloscope has to be taken such that the whole signal remains within the range of the A/D converter. Within the window presented only 8 out of 10 divisions are given for the 8-bit A/D converter. When choosing a level of e.g. 20 mV/div. the maximum range will be  $\pm 100$  mV.

The least significant level of the A/D converter becomes  $200 \text{ mVpp}/256 \approx 0.8 \text{ mV}$ . Choosing a reference point that is giving rise to high common-mode voltages with respect to the vectorial voltage to be measured causes

measurement uncertainty to the range left over for the vectorial information.

Taking the physical centre underneath the IC to be measured against will probably give the lowest common-mode contribution which therefore then results in the highest sensitivity for the vectorial voltages to be measured.

Dependent upon the signal representation and manipulation, these common-mode voltages can be accounted for. An example for such a solution is given later in this paper.

#### 5. OFFSET IN SAMPLING MOMENT

With the oscilloscope used with this experiment, errors are made during sampling, resulting in different moments where the input signal is sampled. In the output data of the scope, this error in timing is NOT considered and all samples are assumed to be taken on a 100 ps (assuming 10 Gs/s) raster WITHOUT any offset due to this relative error.

When taking a display window of e.g. 5000 points, 500 ns in time are covered with a sample rate of 10 Gs/s. When zooming in, to a time scale of 100 ps/div. it can be noted from the screen that all measurements are NOT taken simultaneously but typically with a distribution of about 50 ps between the earliest and the latest sampling moment of all four channels, see Figure 2.

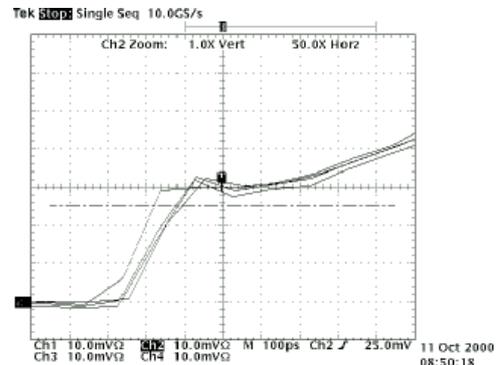


Figure 2: Waveform without “de-skew”

With the instrument, the sampling moment relative to the trigger moment can only be asked for via the IEEE-bus. For this purpose, the command “Xzero” is used to get the position in time of the first sample. Asking for this data for each of the channels allows correcting for this by the “de-skew” option with the instrument. By doing so, the error in sampling can be compensated such that all four samples are taken at identical positions in time. This can be noted in Figure 3 by an equal knee-point in the waveshape at about  $-80$  ps before the centreline.

As can be seen from Figure 3 that even all four signals are

all derived from one signal source resistively divided over 4 inputs, the sampled values are quite different due to propagation delay differences and further compensation has to be applied to allow analysis. This procedure for further compensation will be described in the next chapter.

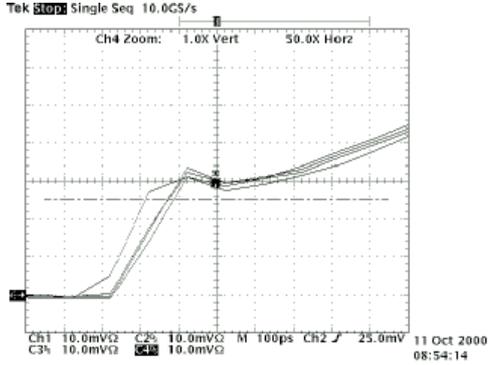


Figure 3: Waveform with “de-skew”

## 6. OTHER DELAYS

The other propagation delays within the measurement system, excluding the one that will be made by the test set-up, can be compensated for at once. In this case, the delay from the BNC entry to the internal sampling circuit as well as the delay in the coaxial cables and the delay in the semi-rigid cables up to the target, are treated as one delay. This is valid when no attenuation is expected in these circuits, but only phase delay.

The compensation for this error has to be taken in a time frame where the  $dV/dt$  is maximum, but also continuous over a few samples. With an RF sinusoidal signal, the zero crossing samples will be the best location. With the above signal a reference level of 25 mV is taken, which is indicated by the dashed line in Figure 4.

As indicated above, the delay correction shall be carried out in the sensitivity setting of the oscilloscope, as it will be used during the measurement.

To allow compensation the amplitude of the data points have to satisfy a condition such that interpolation becomes possible. A general rule can be derived:

- the signals has to have a maximum  $dV/dt$  for all channels, which is assumed to be close to equal for all four channels.
- $\text{Min}(CH_{(1-4)J+1}) > \text{reference value} > \text{Max}(CH_{(1-4)J})$

Then the slope for each channel is determined;  $dV/dt$  ( $dt = \text{sample}_{(t+1)} - \text{sample}_{(t)}$ ) and the amplitude distance between sample amplitude at  $CH_{(1-4)J}$  and the new chosen reference value.

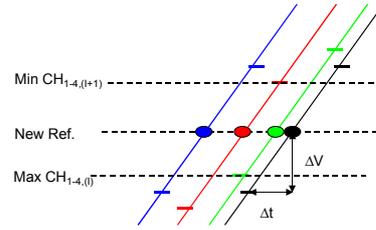


Figure 4: Compensation for signal delays.

Yet the amplitude will be interpolated over the interval as it will be unpractical to derive 4 time-axis with the 4 signals recorded. Due to this, a small error will be introduced on the corrected signals.

The new value for sample “I” of each channel become (the index “J” has been used for the sample where the correction is taken):

$$V_I^? = V_I + \Delta t_J \cdot dV/dt = V_I + (V_{REF} - V_J)/(V_{(J+1)} - V_J) * (V_{(I+1)} - V_I)/100 \text{ ps}$$

In the expression mentioned above,  $(V_{REF} - V_J)/(V_{(J+1)} - V_J)$  represents the correction factor. All the sample amplitudes of the individual channels need to be multiplied by this correction factor to obtain the corrected value. From the condition that  $V_{REF} < V_{(J+1)}$ , the coefficient  $(V_{REF} - V_J)/(V_{(J+1)} - V_J)$  will always be less than 1. With this correction method, the error can be reduced till 10 to 15 percent.

## 7. CONCLUSIONS

Although the calibration and correction coefficient calculations are somewhat tedious, the vector analysis method shows clear possibilities that could not have been taken with existing emission measurement techniques in the frequency domain.

The main difference when measurements are taken in the time domain is that phase information is maintained which is always lost when using RF frequency domain analysis. The frequency domain analysis can be worthwhile to find areas of interest. Time domain measurements can be triggered by an event that makes it possible to track the cause for RF emission when it is operation mode dependent. Having variable trigger delay (mostly build in the oscilloscope used) allows tracking of the vectorial signals at every moment of the operation cycle.

Due to the fact that the record length of the voltages recorded is short compared to the “normal” measurement time with frequency domain measurements, a large number of random measurements in the time domain need to be taken to allow comparison with the frequency domain measurements.