An EMI radiation grouping approach based on spectral cluster in near filed scanning for assessment

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Abstract. With the ever-increasing operating frequency in integrated circuit, it is very essential to assess the radiation used to help the IC designer. Based on the similarity of electromagnetic patterns obtained from the radiation of ICs and their nonlinear edge, we develop a post-processing technique to group the electromagnetic patterns. A near field scanning is performed to obtain and extract the electromagnetic pattern that is used to validate the technique. Experiment results show that it can accurately group the electromagnetic patterns by which radiation assessment can be performed.

Keywords: EMI; grouping; radiation; near field scanning

1. Introduction

Near field scanning is an established technique that is usually used to detect the electromagnetic (EM) field distribution on a plane above the device under test (DUT), such as an integrated circuit (IC) or printed circuit board (PCB). The electromagnetic field distribution on the plane can be visualized, which is called electromagnetic pattern. The pattern’s mechanism is currently needed to study further based on the strength of the emitted frequency, the form of the package, etc., it has been evidenced that electromagnetic patterns are constructive for assessing radiation quantity, localizing emission source[1] and designing for electromagnetic compatibility (EMC) of sub-system, module or sub-module [2], such as PCBs [3] and ICs [4]. In recent years, near field scanning was widely employed to measure the characterization of IC electromagnetic radiation [5], evaluate patch antenna radiation pattern [6] and observe magnetic domain in magnetic material with a high-resolution probe [7]. Near field scanning plays an important role in electromagnetic interference diagnosis. In [8], a near-field-to-near-field transformation method for the EMI radiation is proposed to obtain magnetic field on multiple planes by the expansion of the probe output based on the theory of plane wave spectrum.

Nonintrusive electromagnetic interference (EMI) detection is a powerful method for EMI diagnosis in high-speed links and multiple signal PCB designs. A noncontact time-domain voltage measurement method is used to detect the EMI signals of two adjacent on a PCB by a near field electric probe, and a reconstruction algorithm is developed to recover the voltage without contact [9]. From statistical view, a high order statistics (HOS) method is used to detect the number of electromagnetic interference...
sources [10], which is performed in frequency domain considering the characteristics of EMC problem. The EMIs, which are detected from a normal and a faulty circuits, are compared to recognize the switch fault in DC-DC converters [11].

The electromagnetic pattern is extracted after near field scanning and the EMI source is located at the position with higher radiation strength, which is applied to a chip [12], and the flash memory is found to be the major EM emission of the chip. The probe’s position is correctly localized by a 2D optical tracking system in near field measurement [13], and an emission source microscopy (ESM) algorithm inspired from synthetic aperture radar (SAR) technique is applied to localize radiating sources.

Machine learning has been applied to many fields such as face recognition, data mining, object detection and recommendation systems. With the ever-increasing operating frequency of IC, electromagnetic interference is becoming more complex, which is not coped with by conventional analysis. In [14], the EMI radiation is predicted by combining the deep neural network (DNN) and Bayesian optimization algorithm (BOA). Besides, using the power supply and temperature variation, the RF integrated interference limitation is also estimated by elaborately designing a DNN, which is helpful to improve the working-effectiveness between the IC designer and the EMC designer [15] and promote the exchange of the designers’ issues and solutions. To our understanding, the shape of electromagnetic pattern can reveal much information about the emission source and is usually irregular due to the structure of the device under test (DUT) and the scanning distance between probe and its surface [16]. The scanning step has an important impact on the gradient of the shape, which plays an essential role in localization accuracy.

In this paper, using the electromagnetic patterns, an EMI source diagnosis algorithm based on spectral cluster is investigated, which is used to group electromagnetic patterns based on similarity and diagnose their corresponding radiation. This paper is organized as follows. The EMI source diagnosis and grouping algorithm are developed in section II. Section III introduces the near field scanning experiment. Experiment results and discussion are arranged in section IV. And Section V draws the conclusion.

2. EMI Source Grouping and Assessment Technique on Electromagnetic Pattern

Near field scanning is performed by a mover which is controlled by a computer. An electromagnetic probe that is connected to a spectrum analyzer is controlled to sense the electromagnetic field emitted by the DUT along its surface in a specific scanning area. A spectrum matrix with same size as the scanning area would be obtained for a single frequency after scanning. As shown in Figure 1, for an \( m \times n \) scanning area with \( m \times n \) sense points, if the number of scanning frequency points of the spectrum analyzer is \( N \), which is denoted as \( f_1, f_2, \ldots, f_N \), the spectrum matrix for each \( f_i, i = 1, 2, \ldots, N \) is expressed as,

\[
S = \begin{bmatrix}
    s_{11} & s_{12} & \cdots & s_{1n} \\
    s_{21} & s_{22} & \cdots & s_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    s_{m1} & s_{m2} & \cdots & s_{mn}
\end{bmatrix}
\]

\( (1) \)

Where each \( s_{ij} \) is sensed by the probe at each scanning point in the scanning area.

**Figure 1.** A scanning area with size of \( m \times n \) in near field scanning and \( s_i \) denotes the spectrum at frequency of \( f_i \).
Then, electromagnetic pattern is obtained by visualizing the spectrum matrix as a grey image or an RGB image.

2.1. Frequency Extraction Algorithm

In near field scanning, frequencies that have obvious electromagnetic pattern are seldom. In order to select these frequencies, an extraction algorithm is developed based on statistical variance or statistical standard deviation (std), which is computed as follows,

\[ \text{var}(f_j) = \sum_{i=1}^{m} \sum_{j=1}^{n} (s_{ij} - \mu)^2 \]  

Or,

\[ \text{std}(f_j) = \sqrt{\text{var}(f_j)} \]  

Where \( \mu \) is the mean of \( S \), computed as,

\[ \mu = \frac{1}{m \times n} \sum_{i=1}^{m} \sum_{j=1}^{n} s_{ij} \]  

It is known that signal variance is greater than that of noise. By setting a \( \sigma \), those frequencies that have electromagnetic pattern can be extracted by comparing their variances with \( \sigma \).

2.2. Grouping and Assessment Algorithm

For an integrated circuit, its clock usually generates many harmonics due to the nonlinear property of components such as diode, transistor and field effect tube (FET). Radiation at high frequency will be easy to be coupled by another circuit and has a significant impact on its operation stability. For a frequency and its harmonics, their electromagnetic patterns are similar in shape, which indicates they may be distributed in the same area of the IC. It is convenient to assess radiation and analyze those frequencies that have the same electromagnetic patterns after grouping. Grouping is performed based on the similarity of electromagnetic pattern. It is very natural that we can think of all spectrum matrices as a full connection network due to the harmonic relationship of the majority of frequencies. The adjacent matrix is denoted as,

\[ W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix} \]  

Its element \( w_{ij} \) is computed as,

\[ w_{ij} = w_{ji} = e^{-\frac{1}{2}(v_i^T \Sigma^{-1} v_j)} \]  

Where \( v_i \) and \( v_j \) are column vector which are obtained by flattening the spectrum matrix of \( f_i \) and \( f_j \), respectively. \( \Sigma \) is an invertible covariance matrix of the matrix formed by placing all flattened spectrum matrices as its columns.

Then the degree matrix can be obtained from adjacent matrix,

\[ D = \begin{bmatrix} d_1 & 0 & 0 & \cdots & 0 \\ 0 & d_2 & 0 & \cdots & 0 \\ 0 & 0 & d_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & d_n \end{bmatrix} \]  

Where \( d_i \) is computed as follows,

\[ d_i = \sum_{j=1}^{n} w_{ij} \]  

The Laplacian matrix is computed by subtracting \( W \) from \( D \),

\[ L = D - W \]
Where $I$ is a symmetric matrix due to the full connection of all spectrum matrices, which is grouped by spectral cluster.

To our understanding, the grouped electromagnetic patterns have the same properties. First, its shape is similar in each group, which means the EMI sources formed by these frequencies distributed in the same physical structure and area. Second, the strength of each electromagnetic pattern in a group is usually different, and the gradient between them can be used to assess the rate of attenuation of harmonic wave.

To sum up, the grouping and assessment algorithm followed after the frequency algorithm, it can be summarized as following steps:

1) Compute the variance or standard variance of each spectrum matrix for each frequency by Eq. (2).
2) Flatten each spectrum matrix to column vector.
3) Construct the adjacent matrix by Eq. (5).
4) Construct the degree matrix by Eq. (7).
5) Compute the Laplacian matrix by Eq. (8).
6) Make eigen-decomposition of Laplacian matrix, and get the eigen-vectors corresponding to the first $k$ smallest eigen-values to compose a matrix $Q = [q_1, q_2, q_3, \ldots, q_k]$.
7) Group each rows of $Q$ by k-means or other cluster algorithm.

It can be seen that there is a dimension-reduced operation on the symmetric Laplacian matrix. We can treat $I$ as a new sample matrix but it only has half information due to its symmetry. Assuming that its rows represent number of samples and columns represent features, then the dimension-reduced operation can be explained to reduce dependency or noise of the original data that is polluted when detecting and transmitting at wire.

3. Near Field Scanning on An FPGA

As described before, near field scanning experiment consists of the DUT, probe (electric or magnetic), mover, spectrum analyzer and computer, as shown in Figure 2.

![Figure 2. The near field scanning setup.](image)

It is known that the smaller the distance between the surface of the DUT and the scanning plane, the more accurate the scanning data (magnetic or electric field data). The scanning steps denoted as $s_x$ and $s_y$ shown in Figure 2 decide scanning density that is a key factor to describe details of the electromagnetic pattern. However, high scanning density is not necessary for scanning area that its electromagnetic field stays constant or not changes dramatically. Scanning with high density and wide frequency is time-consuming.

Figure 3 shows the practical experiment setup on an FPGA shielded by a circle metal clamp. The DUT is placed above a ground plane designed according to IEC61967-3 [17], and the RF magnetic field is probed in direction parallel to the scanning surface.
Figure 3. The near field scanning system with a 3-axis mover.

Figure 4. (a) Magnetic probe. (b) Its $S_{21}$ from 10MHz to 2GHz.

Figure 5. The top view (left) and bottom view (right) of the FPGA test board. The width and height of the FPGA chip are both 17 mm.

The input clock frequency of the board is configured as 50MHz injected via pin E16 and its GPIO is running at 2.5V LVTTL standard.

4. Results and Discussion
The near field scanning is running in the same step of 106 $\mu$m in x-axis and y-axis directions forming a scanning area of $160 \times 160$ points, that is $m = 160$ and $n = 160$ in Figure 1. The spectrum analyzer is configured at frequency range of 10 MHZ to 500 MHz with 1001 sweep points. The probe is placed with a distance of 1 mm above the surface of the FPGA chip, i.e. $d = 1$ mm in Figure 2.
4.1. Frequency Extraction

Figure 6 shows the variances of each frequency. It can be seen that the variances of only 15 frequencies are greater than the threshold ($r = 0.15$). They are the frequencies of 50MHz, 100MHz, 150MHz, 190MHz, 230MHz, 250MHz, 300MHz, 350MHz, 377MHz, 400MHz, 417MHz, 438MHz, 450MHz, 480MHz and 500MHz, which includes the harmonic waves of clock frequency (50 MHz).

\[\text{Figure 6. Variances of each frequency.}\]

Frequencies that are not harmonic waves of clock frequency may be generated by nonlinear properties of components such as diode and transistor. It is also caused by the third-order cross modulation.

4.2. Group the Electromagnetic Patterns of An FPGA

We apply the grouping algorithm to the spectrum matrix of the 15 frequencies extracted by their variance with $k = 4$ groups as shown in Figure 7 to Figure 10. It can be seen that electromagnetic patterns in each group are similar in shape, while dissimilar in different groups such as Group-0 and Group-2, Group-1 and Group-2. But the grouping is not perfect. It is obvious that Group-0 and Group-1 are similar, to a certain extent. The strength of EMI radiation in each group for different frequency is intuitive by observing the electromagnetic patterns.

\[\text{Figure 7. Results of Group-0}\]
As seen from Figure 7 to Figure 10, the redder the electromagnetic pattern is, the higher the radiation is. The electromagnetic patterns of harmonic wave of clock (50 MHz) are grouped in the same one as shown in Figure 9, for instance, the electromagnetic pattern of 100 MHz, 150 MHz, 350 MHz and 500 MHz. But there is exception about that, the 400 MHz and 250 harmonic waves are not grouped in the same one, so do the 450 MHz and 300 MHz. It may be explained that the signal of a trace in the FPGA
running at high frequency is coupled by its adjacent trace with low coupling efficiency, which leads to electromagnetic pattern with lower strength, such as Figure 7 and Figure 8 marked in red rectangle.

5. Conclusions
In this work, we developed a post-processing method to electromagnetic patterns of integrated circuits in near field scanning. Based on the fact that variance of signal is always greater than that of noise, frequencies that have electromagnetic patterns are extracted to be used to group. Spectral cluster is introduced to group the patterns due to their similarity in shape and nonlinear edges. The grouping technique is applied to an FPGA and has a good result. However, the number of groups has to be set artificially, which is a drawback for many cluster algorithms. Besides, interference always exists due to nonlinear properties of components such as diodes and transistors, which results in many frequencies that are not harmonics of clock frequency. These frequencies can be assessed by their electromagnetic patterns.

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