Stochastic modeling of microcontroller emission

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***Abstract*—The conducted emissions from a microcontroller are known to be dependent on the program being run in the core. It is important to know which and how many programs are to be tested to fully evaluate the conducted emission behavior of a microcontroller chip. This paper presents a stochastic estimation-based methodology, for estimating electromagnetic emission levels and emission intervals from a microcontroller, based on the functional blocks activated programmatically. The predicted and actual measurement results show a good match with a confidence level of 76%. Secondly, it is found that for present sample, 8 programs are sufficient to compute an emission interval with 95% confidence level.**

***Index Terms*—Electromagnetic compatibility; conducted emission; microcontroller units (MCU); stochastic model**

I. Introduction

The conducted emission (CE) from the microcontroller is dependent on how much current the chip consumes while each of its functional blocks is active [1], [2]. Hence, there is a dependency on programs running on the microcontroller, that decide how much the chip will emit. Several methods in the present literature are dependent on the more deterministic model of measuring the transient currents between the power supply and ground pin [1]–[3]. Some methods also focus on using power spectrum analysis or assumption on the internal activity of the model and inverse compute the emission [4]. In the current literature, most of the models are dependent on IC-level tests (1ohm/150ohm [1]). However, for Tier-1 suppliers or OEMs, such measurements are hard to execute - they have access to CISPR25 (CE) tests for the complete board as well as reports of functional tests of the microcontroller. Secondly, with the over-the-air software releases in the automotive, it is hard to predict whether the IC will fail the EMC for the new programs, beforehand during pre-production testing. Hence, we propose a methodology that utilizes CISPR25 Voltage CE [7] results for the analysis. From a certain number of tests run with a number of programs, a stochastic method is built to answer the following questions:

1) From a known set of measurements for conducted emission, predict the emission from a new program - which is known to use certain functional blocks
2) For a given microcontroller - predict the emission bands within which maximum emission peaks will lie, irrespective of the program being run, with a certain level of confidence.

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For the current study, we have explored the effect on only one functional block, i.e. RAM of the microcontroller on the emission spectrum

II. About Micro-controller

For this experiment, STMicroelectronic's STM32F072 Discovery Board is used [8]. The functional block diagram for STM32 is shown in Figure 1. It is a 32-bit microcontroller with an ARM Cortex-M0 CPU. It provides 16K bytes of RAM and 128KB of flash memory. It can provide High-Speed Internal (HSI) Clock from 8MHz up to 48MHz. For the present

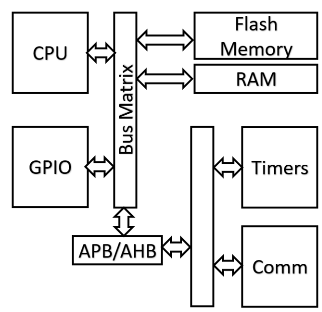

Fig. 1: Functional Block representation of micro-controller [8].

work, we have chosen to study the effect of RAM on the overall emission levels. The RAM utilization is known to have the highest impact on emission levels [2] while the switching of fast GPIOs and the communication channels contribute to emissions at the higher frequency spectrum.

III. Measurement Setup

The measurement setup for conducted emission is built as per CISPR25. The voltage is measured between power and ground pins since they are known to contribute the most in the emission spectrum [3]. The power cables connecting power pins viz., 5V Supply (P2 header-pin1), GND (P2 header-pin2) are of length 200mm. The DUT is placed on styrofoam with a 50mm height on the metal surface. Two LISN units are connected between the power supply and DUT. The emissions are measured from LISN by a Spectrum Analyzer, which serves the purpose of an EMI receiver. For every measurement, the frequency is swept from 100kHz to 500MHz. To keep the noise floor to a minimum level and measure the small peaks, the RBW (Resolution bandwidth) is kept at 1kHz. The attenuation is set at 0dB.

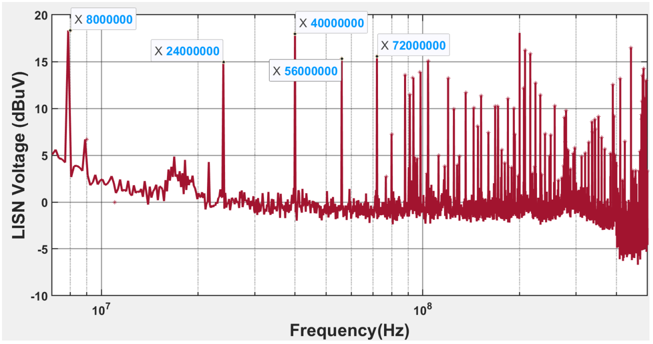

Fig. 2: Emission spectrum for 3x3 matrix multiplication program.

To quantify the effect of the RAM of the microcontroller, several programs are flashed on the microcontroller one by one, and corresponding emissions are captured as voltages at LISN. In each program, matrix multiplication of 2 matrices is performed and stored in the third matrix. To vary the RAM utilization, the sizes of the matrices are varied from 3×3 to 35×35. These programs and corresponding RAM and Flash memory utilization is shown in Table I.

In Figure 2, the emission spectrum obtained from 3x3 matrix multiplication is shown. Here, the clock source is of 8MHz. The emission envelope shows the fundamental and harmonic components of this source.

TABLE I: Design of Experiment for CE measurements

Matrix size for multiplication	RAM(KB)/ out of 16KB	RAM (K) (%)	Flash(KB)/ out of 128KB	Flash (%)
3x3	1.66	10.375	5.38	4.20
9x9	2.51	15.687	5.38	4.20
18x18	5.36	33.5	5.38	4.20
25x25	8.88	55.5	5.4	4.21
30x30	12.11	75.687	5.39	4.21
32x32	13.56	84.75	5.35	4.17
35x35	15.91	99.437	5.39	4.21

IV. Methodology

A. Prediction of emissions for a new program

The aim of this analysis is to estimate the emission from one program when the emissions from several other programs are known. The envelope of emission peaks is characterized as a random signal. The individual peaks for every program, for all frequencies, define the vector space $\mathbf{X}$ with $\mathbf{X}$ = [emission-program1, emission-program2,...], $\mathbf{X} \in \mathbb{R}^{\mathrm{M}\times\mathrm{N}}$ with M number of programs, and N number of frequency points. The mean of a program over all frequencies is

$$u_i = \frac{1}{N} \Sigma_{j=1}^{N} \mathbf{X}_{ij}, \tag{1}$$

$U_i = [u_1, u_2, ...u_M]$ is a column vector of means of each program emissions. Then the $M \times M$ covariance matrix is

$$\hat{\mathbf{R}}_{xx} = cov(\mathbf{X}) = (1/N)[(\mathbf{X} - U) \cdot (\mathbf{X} - U)^T] \tag{2}$$

It is a symmetric matrix and can be diagonalized. Applying Singular Value Decomposition (SVD) [6] to diagonalize the matrix $\hat{\mathbf{R}}_{xx}$.

$$\hat{\mathbf{R}}_{xx} = \mathbf{U} \cdot \mathbf{S} \cdot \mathbf{U} \in \mathbb{R}^{\mathrm{M}\times\mathrm{M}} \tag{3}$$

where, $\mathbf{U} \in \mathbb{R}^{\mathrm{M}}$ is a matrix of eigenvectors and $\mathbf{S}$ is a diagonal matrix with eigenvalues s_i arranged in the order of decreasing values. To reconstruct the entire emission sample space we consider r most significant eigenvectors such that $s_i \geq 1$ (Kaiser's criterion). Let

$$\mathbf{U}_r = [\mathbf{U} : s_i \geq 1] \in \mathbb{R}^{\mathrm{M}\times\mathrm{r}}, \quad 1 \leq \mathrm{i} \leq \mathrm{r} \leq \mathrm{M} \tag{4}$$

The eigenvectors represent the principal axes of the data. The projection of the data on the principal axes (also called as principal component) is denoted by

$$\mathbf{Q} = \mathbf{X}^T \cdot \mathbf{U}_r \in \mathbb{R}^{\mathrm{N}\times\mathrm{r}} \tag{5}$$

We reconstruct the vector space of emissions, by linear combinations of principal components and eigenvectors in the form of coefficients,

$$\hat{\mathbf{X}} = \mathbf{U}_r \cdot \mathbf{Q}^T \in \mathbb{R}^{\mathrm{M}\times\mathrm{N}} \tag{6}$$

In order to construct emission spectrum for new program $\hat{\mathbf{y}}$:

$$\hat{\mathbf{y}} = \mathbf{v} \cdot \mathbf{Q}^T \in \mathbb{R}^{\mathrm{N}} \tag{7}$$

where $\mathbf{v} \in \mathbb{R}^{\mathrm{r}}$ is column vector containing coefficients for new program. These coefficients are computed by interpolating the coefficients from consecutive programs using their RAM utilization $K_{y\times y}$, for example, for estimating the emission profile for a 32x32 matrix, the coefficients are found by interpolating coefficients $K_{30\times30}$ and $K_{35\times35}$ using RAM utilization percentage from Table I.

$$\mathbf{v}_{32\times32} = \mathbf{v}_{30\times30} + \beta \cdot (\mathbf{v}_{35\times35} - \mathbf{v}_{30\times30}) \tag{8}$$

$$\beta = \frac{K_{32\times32} - K_{30\times30}}{K_{35\times35} - K_{30\times30}} \tag{9}$$

To test this algorithm, we divide the X matrix as a test and train matrix. Let $\mathbf{y} \in \mathbf{X}$ be the program emission we need to estimate. Then train matrix, $\mathbf{X}_{train}$ is obtained by set subtraction of $\mathbf{y}$ from $\mathbf{X}$ as $\mathbf{X}_{train} = \mathbf{X} - \mathbf{y}$. An emission spectrum for new program, $\hat{\mathbf{y}}$, is computed using above method.
The 2-norm error is calculated as ($\hat{\mathbf{E}}$): $||\mathbf{y} - \hat{\mathbf{y}}||$. The procedure is repeated to find the emission of all intermediate RAM utilization values while omitting them from the train matrix to evaluate the overall 2-norm error from the estimation.

B. Estimation of emission interval

The aim of this part of the analysis is to estimate the emission interval (the upper bound and lower bound) with 95% confidence.

Consider matrix $\mathbf{X}$, for each frequency (each column), the mean and standard deviation is computed for $\mathbf{X}$,

$$\mu = E[\mathbf{X}]_{j=1}^{N}, \quad \sigma = std[\mathbf{X}]_{j=1}^{N}$$

Here, we assume the sample data to be distributed according to Student's t-Distribution [5]. A $100 \cdot (1 - \alpha)$ prediction interval for any observation x_0 is obtained by intervals:

$$\mu - t_{\alpha/2} \cdot \sqrt{1 + 1/n} \cdot \sigma < x_0 < \mu + t_{\alpha/2} \cdot \sqrt{1 + 1/n} \cdot \sigma \tag{10}$$

where, $t_{\alpha/2}$ is the t-value with 'n-1' degree of freedom. Hence, we have upper and lower limits L_u, L_l as

$$L_u = \mu + t_{\alpha/2} \cdot \sqrt{1 + 1/n} \cdot \sigma, \quad L_l = \mu - t_{\alpha/2} \cdot \sqrt{1 + 1/n} \cdot \sigma$$

From Eq. (10), the limits of the interval depend on the inverse of the number of programs. We need to find the minimum number of programs needed to reasonably compute the estimation interval. To obtain this number, the same experiment is repeated while considering n = 4 till n=18 number of programs. In every iteration, one of the programs is omitted to later validate whether it fits in the interval.

V. Results and Discussion

Figure 3 shows the comparison between measured and predicted emission spectrum for program using 32x32 matrix. We observe a very good match of the predicted spectrum in the first 100MHz, later the peak values are missed slightly or underestimated for some frequency points.

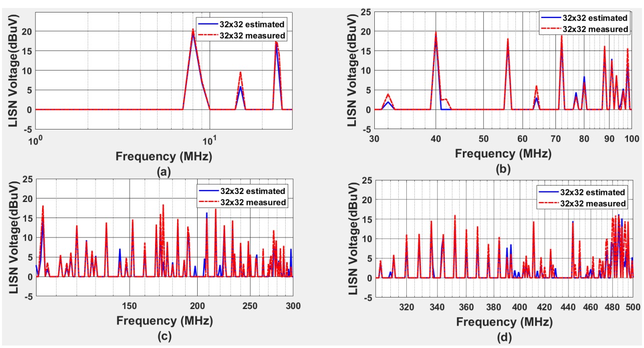

Fig. 3: Estimation of emissions for 32x32 matrix multiplication program. (a) Spectrum from 1 MHz to 30 MHz. (b) Spectrum from 30 MHz to 100 MHz. (c) Spectrum from 100 MHz to 300 MHz. (d) Spectrum from 300MHz to 500MHz

Owing to the 'Central Limit Theorem' [5], we assume, the sample size is large enough for ($\hat{\mathbf{E}}$) to follow gaussian distribution. In Figure 4, the 2-norm error from all estimations ($\hat{\mathbf{E}}$) is plotted as gaussian distribution with mean, μ_E and standard deviation, σ_E of the estimates and $\mu_E + 1\sigma_E, \mu_E - 1\sigma_E$ limits. For the prediction of the emission spectra to be reasonably accurate, this interval should be well outside of gaussian the distribution of sample program space. The program variance is computed as difference between any 2 programs i and j as ($\hat{\mathbf{P}}$): $||\mathbf{X}_i - \mathbf{X}_j||$ ($\hat{\mathbf{P}}$). ($\hat{\mathbf{P}}$) is assumed to be normally distributed with $\hat{\mathbf{P}} \sim \mathcal{N}(\mu_p, \sigma_p^2)$. The 1σ limits for the distribution around mean are : $[\mu_p + 1\sigma_p, \mu_p - 1\sigma_p]$. For the estimation to be reasonably accurate we need $\mu_E + 1\sigma_E < \mu_p - 1\sigma_p$. The interval which lies outside of this range is shaded, indicating an acceptable estimate. The probability of an estimate falling into this range comes out to be 76.20% for frequencies up to 100MHz (CE test range up to- 108MHz). Hence, the model can estimate the emission with 76.20% up to 100MHz.

Now, for the estimation of program intervals different numbers of programs are considered for computing L_u. The limits are proportional to the inverse of the square root of the number

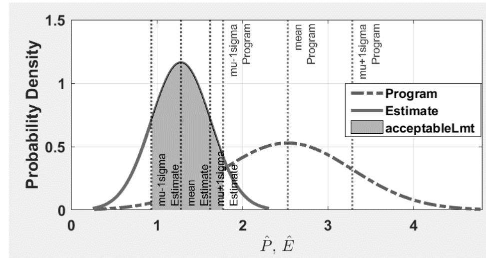

Fig. 4: Accuracy of the overall estimations.

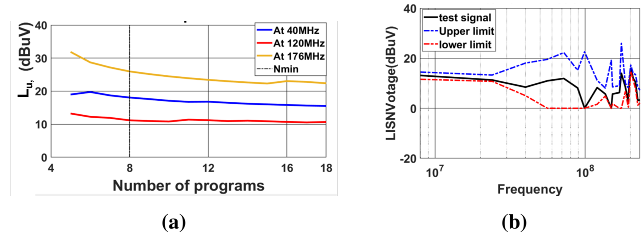

Fig. 5: (a) Minimum programs for convergence. (b) Estimation of emission interval for 8 programs.

of samples (refer equation: 10). In Fig. 5a, L_u is plotted for 3 different frequencies, 40MHz, 120MHz, and 176MHz. We observe that L_u stabilizes after 8 points. Hence, 8 programs provide useful limits. Fig. 5b depict the limits computed with 8 programs.

In future, we would like to evaluate the effect of other functional block for the microcontroller and also verify the same methodology for different microcontroller ICs.

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