Comparing Simulated Impact of Single Frequency and Multitone EMI for an Integrated Circuit

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Abstract—**The electromagnetic immunity characteristics for integrated circuits are currently verified using tests involving single-frequency continuous wave disturbances. In real operational environments, however, systems may be exposed to simultaneous interference sources at multiple frequencies. Simulation results obtained for the electromagnetic susceptibility of a simple voltage-controlled oscillator to randomly generated multitone interferences are compared with corresponding data obtained for single frequencies. The results obtained are used to assess the validity of the current approach of testing circuit designs for immunity using single frequency noise source. Notable differences in the output response of the circuit to single and multitone interference, which could possibly lead to system malfunctions, are illustrated.**

Keywords—Electromagnetic interference, multitone immunity, single frequency, electromagnetic immunity, integrated circuits.

I. INTRODUCTION

Integrated circuits (ICs) are present within the electronic components of most complex systems (e.g., road vehicles, medical and military equipment etc.), often providing safety, mission and/or security critical functions. Increases in the proportion of electrical and electronic components within such systems may lead to higher levels of intra-system emissions, while increasing use of radiocommunications also creates increasingly complex external environments. These internal and external electromagnetic disturbances may lead to system malfunctions due to electromagnetic interference (EMI). Currently, immunity verification testing of IC designs is carried out with reference to BS EN 62132 [1]. The guidelines provided in this standard include testing the ICs with amplitude modulated single frequency continuous wave (CW) disturbances. However, several studies in the literature ([2]–[7]) also discuss the need to demonstrate immunity to multiple frequency (multitone) CW disturbances. The main reason for this is the non-linear behaviour of the electronic systems and the resulting intermodulation products for multitone noise sources, as discussed in [3], [7], [8].

In practice, a comprehensive analysis of immunity to multiple sources is impracticable due to the cost and time required to evaluate the potentially infinite range of possible combinations of frequencies, amplitudes, polarizations and waveform modulations. Nonetheless, more limited multitone testing is possible [9] and has already been identified as an acceptable approach in at least one immunity test standard [10].

More typically, system components at different hierarchical levels are tested with single frequency noise sources with an amplitude equivalent to, or higher than, the net amplitude of multiple noise sources that are reasonably foreseeable in the expected system EM environment [6]. As an example, if the system environment consists of two co-existing noise sources, with frequencies $f1$ and $f2$ and corresponding amplitudes $a1$ and $a2$, then the immunity test verification of the component under test is carried out using CW at frequencies $f1$ and $f2$ individually, each with an amplitude $\geq a1 + a2$ (due to the uncertainty regarding the operational environment). However, for complex systems with many internal and external noise sources this approach becomes impracticable and could potentially lead to over-engineering whilst providing no knowledge as to its true impact.

Prior to fabrication and immunity testing, simulation tools like Cadence Spectre can be used to predict the susceptibility of IC designs [11]. Simulation has therefore been used to compare the effectiveness of single frequency and multitone interference for a representative IC design. In this study the multitone EMI noise sources are also randomly distributed in frequency, in order to limit the computational burden. In addition, knowledge of the operational electromagnetic (EM) environment could be also be used to further minimise the computational costs of a simulation-based investigation.

Section II provides a functional description of the sample IC, a current starved voltage-controlled oscillator (VCO), as well as the processes to generate the single and random multitone noise samples for the EMI simulations. In section III, the EMI impact metrics for this test case are defined and the probability of EMI impact causing deviations from the expected operation of the VCO are discussed, for both single and multitone noise samples. The results are summarised in tables to indicate the safety margin that could be achieved by the current immunity testing approach. The conclusions of this analysis, as well as plans for future work, are then outlined in the final section of the paper.

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II. CASE-STUDY

A. Circuit Function

The choice of the particular IC design for this study was somewhat arbitrary, based solely on the availability of corresponding design and simulation data to the authors. The VCO circuit (see Fig. 1) is assumed to be provided with a DC supply voltage of 5 V (Vdd) and a bias voltage (Vin) of 1.6 V (to tune the output frequency) in order to produce an output voltage with amplitude $A_0 = 2.5$ V at a target frequency $F_0 = 277$ MHz. For the purposes of this investigation, EMI is assumed to affect only the main power supply provided through the Vdd rails. Furthermore, input supply voltages exceeding 5.5 V are assumed to be eliminated due to surge protection circuits.

Immunity of IC-level designs are usually verified by direct power injection (DPI) using conducted EMI at sensitive input pins of the circuit [12]. The incident power level of the single frequency EMI samples used for DPI tests are generally varied according to ranges provided by EMC standards for ICs [1].

B. Single and Multitone Noise Generation

For the susceptibility analysis of the VCO circuit, several single and multiple EMI sources were simulated. To reduce the computational time, the frequency of all EMI cases (single and multitone) were chosen from within the range 1–300 MHz. Nevertheless, a much broader spectrum could be considered for further analysis.

To categorize the EMI, samples the frequency range under investigation was split into three arbitrary sub-domains, denoted *D1* (1–10 MHz), *D2* (10–100 MHz) and *D3* (100–300 MHz). The frequencies of all of the single frequency noise samples were chosen to be within any of the frequency sub-domains. Depending on the selected sub-domain, the single frequency samples are simply categorized as belonging to the categories {100}, {010} or {001}, which indicate whether the single frequency noise is from the *D1*, *D2* or *D3* sub-domains, respectively. The single frequency noise sources were sinusoidal noise waveforms, each with a fixed amplitude of 0.5 V and a zero initial phase. The frequency of each noise sample was uniformly distributed with a fixed increment. For the case-study, 20 noise samples were taken for each sub-domain.

The multitone noise samples were generated by superposition of multiple sinusoidal waveforms (at most three for the case-study), each with a frequency randomly selected uniformly within each sub-domain, assuming that not more than one source can occur in any of the three sub-domains considered. This leads to three possible categories for two-tone sources, denoted by the categories {011}, {110} and {101}, as well as one combination for three, denoted by {111}.

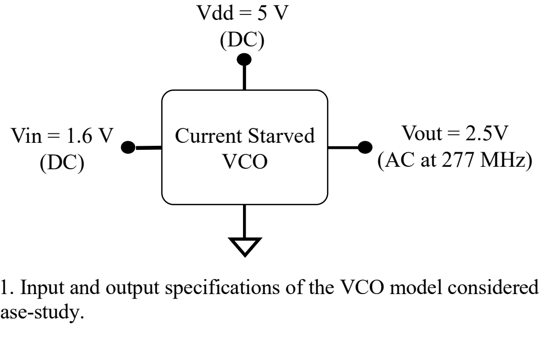

Fig. 1. Input and output specifications of the VCO model considered for the case-study.

The time-varying EMI signals for each interference case *i*, representing single and multitone interference corresponding to categories denoted by $\{a_i\, b_i\, c_i\}$ where $a_i, b_i, c_i \in \{0,1\}$, are assumed to be of the form:

$$EMI_i(t) = \frac{0.5}{[a_i + b_i + c_i]} \sum_{k=1}^{a_i+b_i+c_i} sin(2\pi f_{ik} t) \qquad (1)$$

where $a_i + b_i + c_i \in \{1,2,3\}$ and the frequencies f_{ik} (for $k \in \{1,2,3\}$) represent the frequency components that are included in the interference.

Using (1) and ensures that the net amplitude (for any number of noise sources considered) is limited to 0.5 V. It should be noted that, the random multitone noise samples generated could be further randomized by taking random amplitude values for each noise source, such that the total amplitude is always 0.5 V, irrespective of the number of frequency components that are included.

III. SIMULATION RESULTS

A. EMI Impact Metrics

The output parameters of the VCO circuit that were used to determine the susceptibility due to single and multitone EMI impact are:

- the deviation from the expected output frequency (i.e., $F_0 = 277$ MHz); and
- the deviation from the desired output amplitude (i.e., $A_0 = 2.5$ V) at F_0.

For each EMI simulation of the VCO circuit design using the Spectre simulation platform in Cadence, the VCO output voltage was recorded for a time-period of 1 μs. To determine the deviations in frequency ΔF_i, the *SKILL mode* function of the Cadence software was used.

Based on the VCO output voltage this function determines the frequency over every 4 ns of the simulated 1 μs time-interval as a time-series (see Fig. 2). The output voltage time-series was also converted to frequency-domain by Fourier transform in order to obtain the amplitude corresponding to each frequency component within the data (see Fig. 3).

The relative deviations due to EMI sample *i*, affecting the output frequency over time, $\Delta F_i(t)$, and the output voltage amplitude at F_0, $\Delta A_i(F_0)$, were calculated as follows:

$$\Delta F_i(t) = 100\left\{\frac{(F_0 - F_i(t))}{F_0}\right\} (\mathrm{MHz}) \qquad (2)$$

$$\Delta A_i(F_0) = 100\left\{\frac{(A_0 - A_i(F_0))}{A_0}\right\} (V) \qquad (3)$$

The examples shown in Figs. 2–3, correspond to the frequency and amplitude deviations (respectively) caused by two-tone EMI with frequencies of 10.8 MHz and 110.25 MHz, both with amplitudes of 0.25 V.

In general, for VCO circuits, deviations of ± 5% in the expected output frequency (i.e., 277 ± 13.85 MHz), and ± 10% in the output voltage amplitude at 277 MHz (i.e., 2.5 ± 0.25 V) are considered to be tolerable. Hence, any EMI impacts exceeding the tolerable limits for either of the two output parameters would therefore be considered to be malfunctions of the VCO circuit.

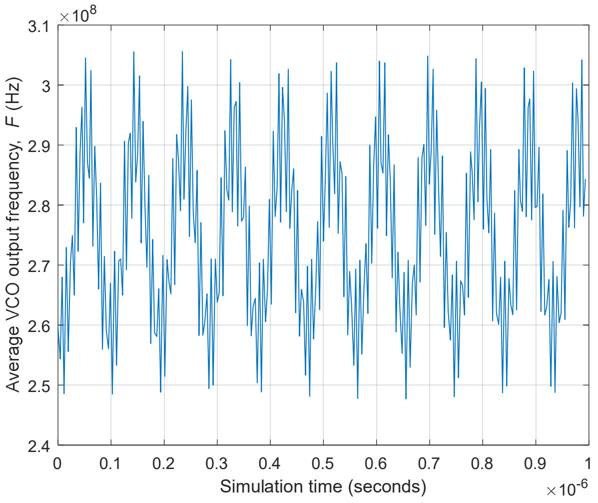

Fig. 2. EMI impact on the output frequency of the VCO circuit due to two-tone noise case from category {011}.

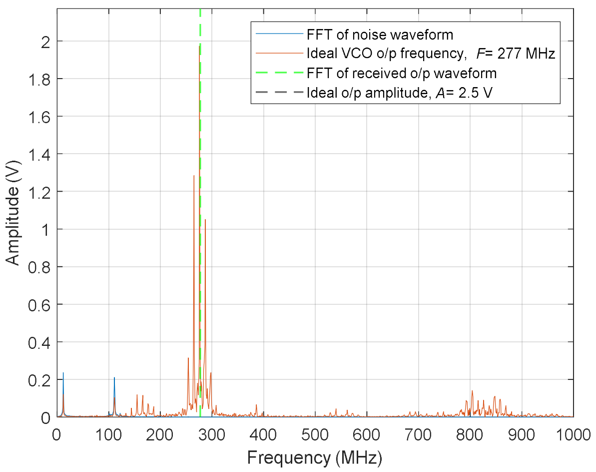

Fig. 3. EMI impact on the output voltage amplitude of the VCO circuit due to two-tone noise case from category {011}.

B. *Single Frequency EMI Impact*

Cumulative probability distributions (CPDs) for *ΔFi* and *ΔAi* due to single frequency EMI are shown in Fig. 4 and Fig. 5, respectively. The CPDs for the VCO output frequency are noticeably smoother than those for the output voltage amplitude. This is because the output frequency data comprises 275 discrete time samples for each of the 20 single frequency EMI cases spread over each of the three frequency bands (D1, D2 and D3).

The lower frequency EMI cases (from categories {100} and {010}) have relatively higher probability of malfunction due to deviation in output frequency and amplitude, when compared to the higher frequency EMI cases (in {001}), as illustrated in Tables I - II, respectively.

TABLE I. PROBABILITY OF UNACCEPTABLE FREQUENY DEVIATION DUE TO SINGLE FREQUENCY EMI

No. of Tones	**Noise Category**	$P(\Delta F_i < -5\%)$	$P(-5\% \le \Delta F_i \le 5\%)$	$P(\Delta F_i > 5\%)$
1	100	0.38	0.26	0.36
	010	0.34	0.31	0.35
	001	0.14	0.74	0.11

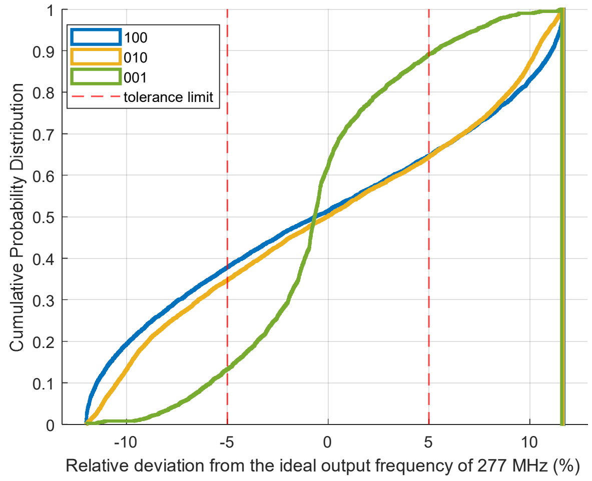

Fig. 4. CPDs for deviation from the expected VCO output frequency (i.e., 277 MHz) due to the impact of single frequency EMI.

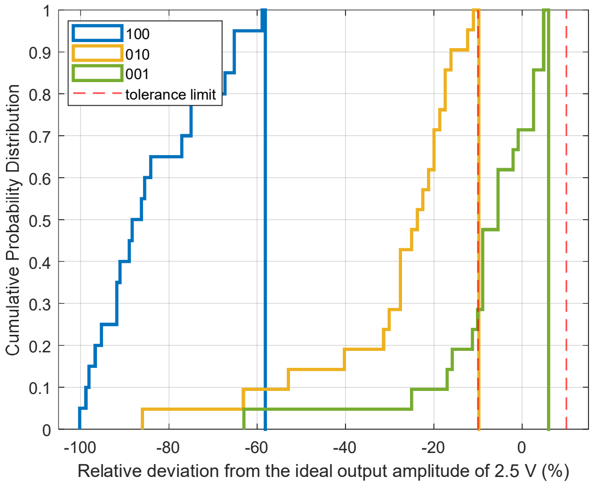

Fig. 5. CPD for the deviation from the expected VCO output voltage amplitude (i.e., 2.5 V) due to the impact of single frequency EMI.

The EMI cases from category {001}, with frequencies in band *D3* (100–300 MHz), are found to have a relatively low probability of unacceptable frequency deviation (25%). Output frequency deviations beyond the tolerable range of ±13 MHz were observed for cases taken in all the three categories for single frequency EMI, with probabilities of 74% for category {100}, 69% for category {010}, and 25% for category {001}.

Furthermore, from the analysis done to determine the probability of VCO malfunction due to deviations in output voltage amplitude it is found that the impact of single frequency noise at lower frequencies (in sub-domains *D1* and *D2*) always causes the output voltage amplitude to be unacceptable.

TABLE II. PROBABILITY OF UNACCEPTABLE AMPLITUDE DEVIATION DUE TO SINGLE FREQUENCY EMI

No. of Tones	**Noise Category**	$P(\Delta A_i < -10\%)$	$P(-10\% \le \Delta A_i \le 10\%)$	$P(\Delta A_i > 10\%)$
1	100	1.00	0.00	0.00
	010	1.00	0.00	0.00
	001	0.29	0.71	0.00

As shown in Fig. 4, for all noise cases within categories {100} and {010}, the amplitude of the output voltage amplitude at F_0 is less than 2.25 V. For the noise samples in category {001}, corresponding to frequencies above 100 MHz, the probability of $\Delta A_i < -10$ % is 29% (see Table II). It should be noted that, for all single frequency EMI cases simulated, the probability of VCO malfunction due to excessive output voltage amplitude, i.e., P($\Delta A_i > 10\%$), is zero. Thus, insufficient output voltage is always the malfunction mode for output voltage amplitude for the single frequency EMI cases.

These results indicate that the VCO circuit design is more susceptible to single frequency EMI at frequencies in the band 1–100 MHz than for the band 100–300 MHz.

C. *Multitone EMI Impact*

For the multitone EMI cases, Fig. 6 and Fig. 7 provide the CPDs for ΔF_i and ΔA_i respectively. Similar to the previous inference for single frequency EMI impact, the presence of low frequency contributions from range *D1* is found to increase the probability of VCO malfunction, for both ΔF_i and ΔA_i, in the multitone cases. Probabilities for unacceptable frequency and amplitude deviations are summarised in Tables III–IV, respectively.

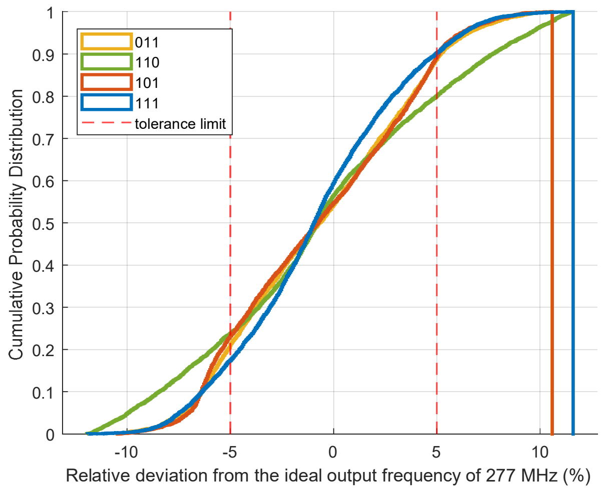

Fig. 6. CPDs for deviation from the expected VCO output frequency (i.e., 277 MHz) due to the impact of multitone EMI.

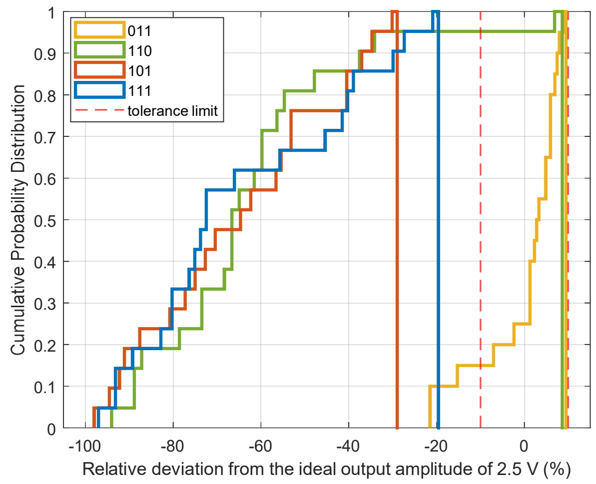

Fig. 7. CPD for the deviation from the expected VCO output voltage amplitude (i.e., 2.5 V) due to the impact of multitone EMI.

TABLE III. PROBABILITY OF UNACCEPTABLE FREQUENY DEVIATION DUE TO MULTITONE EMI

No. of Tones	Noise Category	$P(\Delta F_i < -5\%)$	$P(-5\% \leq \Delta F_i \leq 5\%)$	$P(\Delta F_i > 5\%)$
2	011	0.20	0.69	0.11
	101	0.23	0.66	0.11
	110	0.24	0.56	0.20
3	111	0.18	0.72	0.10

TABLE IV. PROBABILITY OF UNACCEPTABLE AMPLITUDE DEVIATION DUE TO MULTITONE EMI

No. of Tones	Noise Category	$P(\Delta A_i < -10\%)$	$P(-10\% \leq \Delta A_i \leq 10\%)$	$P(\Delta A_i > 10\%)$
2	011	0.15	0.85	0.00
	101	1.00	0.00	0.00
	110	0.95	0.05	0.00
3	111	1.00	0.00	0.00

From Table III, it can be seen that the highest probability of VCO malfunction due to frequency deviation corresponds to multitone noise samples from category {110}, with a total probability of 44% for frequency deviations exceeding the acceptable tolerance of ± 5%. Comparing the EMI impact due to two- and three-tone EMI cases, it can be seen that increasing the number of EMI frequencies (which also increases the number of intermodulation products) does not show any significant increase in the probability of malfunction.

D. *Comparison of Single and Multitone EMI Impacts*

Comparison of the simulation results for single and multitone EMI shows that, the probability of VCO malfunction due to single frequency EMI is much higher than for multitone EMI combinations of the types studied here.

However, with a tighter tolerance limit on the VCO output voltage amplitude, the probability of multitone EMI causing malfunctions would be higher than for the single frequency EMI cases. This can be observed by comparing the CPD curves of Fig. 5 and Fig. 7, where the multitone noise cases from categories {011} and {110} are associated with higher VCO output voltage amplitudes.

IV. CONCLUSION AND FUTURE WORK

With uncertainty due to limited knowledge of the target system and operational environment, ICs are currently tested with single frequency disturbances at relatively high threat levels, with the aim of ensuring that immunity to real-world multiple frequency threats can be achieved. However, a possible concern with this rule-based approach is that it could potentially lead to overengineering of the EMC design without providing awareness of residual EMI risks.

The simulation results obtained for the case study illustrated here show that the studied VCO circuit design has a higher probability of malfunction due to single frequency EMI in comparison to the impact of the multitone EMI cases. Hence its immunity to single frequency EMI disturbances indicates that it also can be expected to have adequate immunity to multitone disturbances that may in practice be encountered in its operational environment.

Nonetheless, the statistical characteristics of the single frequency and multitone results are very different, with the implication that different tolerances on the required performance metrics could potentially result in very different conclusions.

The simulations leading to this conclusion assume that the amplitude used for the single frequency EMI to be equal to the net amplitude that can be coupled into the circuit (due to surge protection measures), which may not always be the case. Furthermore, the number and range of frequencies investigated was somewhat limited.

As a part of the ongoing research for developing risk-based approaches to EMC engineering, analysis of the impact of single frequency and multitone EMI for a more complex circuit design will be undertaken, along with experimental verification of the results using standard immunity measurement techniques.

Further areas for study could include the possibility of effects associated with relationships between the injected EMI frequencies and the operating frequency of a VCO, as well as investigation of quite different types of IC design and analysis of the impact of much higher frequencies than those considered in this work.

REFERENCES

[1] BS EN 62132 (2018), “Integrated circuits —Measurement of electromagnetic immunity,” British Standards Institute.

[2] K. Armstrong and W. A. Radsky, “Extending the normal immunity tests to help prove functional safety,” in Proc. IEEE Int. Symp. EMC and IEEE APEMC, 2018, pp. 221-226.

[3] A. Duffy, A. Nisanci, H. Nisanci and K. Armstrong, "Signal integrity testing using multiple out-of-band sources in a reverberation chamber," 2008 IEEE International Symposium on EMC, 2008, pp. 1-5.

[4] M. Mardiguian, “Combined effects of several simultaneous EMI couplings,” in Proc. IEEE Int. Symp. EMC, 2000, pp. 181–184.

[5] K. Armstrong, “EMC for the functional safety of automobiles—Why EMC testing is insufficient, and what is necessary,” in Proc. IEEE Int. Symp. EMC, 2008, pp.1–6.

[6] K. Armstrong, "Testing for immunity to simultaneous disturbances and similar issues for risk managing EMC," 2012 IEEE International Symp. on EMC, 2012, pp. 121-126.

[7] W. Grommes and K. Armstrong, "Developing immunity testing to cover intermodulation," 2011 IEEE Int. Symp. on EMC, 2011, pp. 999-1004.

[8] A. Biondi, H. Rogier, D. Vande Ginste and D. De Zutter, "Multitone EMC testing strategy for RF-devices," 2012 IEEE Electrical Design of Advanced Packaging and Systems Symposium (EDAPS), 2012, pp. 89-92.

[9] G. Barth, “Benefits of multitone EMC immunity testing”, Int. J. RF & Microw. Comp.-Aided Eng., vol. 26, no. 4, May 2016.

[10] BS EN IEC 61000-4-3:2020, “Electromagnetic compatibility (EMC). Testing and measurement techniques. Radiated, radio-frequency, electromagnetic field immunity test”, Nov. 2020.

[11] Cadence (2021). Spectre Simulation Platform. https://www.cadence.com/ko_KR/home/tools/custom-ic-analog-rf-design/circuit-simulation/spectre-simulation-platform.html, accessed: Aug. 2021.

[12] I. Chahine, M. Kadi, E. Gaboriaud, A. Louis and B. Mazari, "Characterization and Modeling of the Susceptibility of Integrated Circuits to Conducted Electromagnetic Disturbances Up to 1 GHz," in IEEE Trans. on EMC, vol. 50, no. 2, pp. 285-293, May 2008.