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Synergistic Effect of Multi-Tone EMI on the Conducted Immunity of Integrated Oscillators

Qazi Mashaal Khan, *Graduate Student Member, IEEE*, Lokesh Devaraj, *Student Member, IEEE*, Mohsen Koohestani, *Senior Member, IEEE*, Alastair R. Ruddle, *Senior Member, IEEE*, Mohamed Ramdani, *Senior Member, IEEE*, and Richard Perdriau, *Senior Member, IEEE*

Abstract—The performance of two oscillator circuits, namely a current-starved voltage controlled oscillator and a ring oscillator, is compared with respect to multi-tone direct power injection (DPI). The objective is to investigate the impact of causal dependence between multi-tones on the immunity levels of integrated blocks with different architectures but similar functionality. The multi-tone immunity analysis performed using the probabilistic noisy-OR model reveals an increase in the probability of failure due to electromagnetic interference relatively to single-tone EM disturbance. The proportions of inhibition and positive causality, as well as the mean degree of synergy (*DoS*) caused by multi-tone EM disturbances, are extensively compared for both oscillator circuits.

Index Terms— VCO, DPI, multi-tone EM disturbance, causal dependence, inhibition, synergy.

I. INTRODUCTION

IN recent years, integrated circuit (IC) technology has increasingly challenged manufacturers with electromagnetic compatibility (EMC) issues. These include maintaining the desired performance of an IC in the presence of conducted and radiated electromagnetic interference (EMI) [1]. Based on the guidelines provided in IEC 62132-4 [2], ICs are currently verified using direct power injection (DPI) of conducted single-tone radio frequency (RF) disturbances into the IC pins [3]. At each frequency, forward power is incrementally raised until reaching the lower of the immunity requirement or the level at which the circuit fails due to loss of its functionality and/or degradation of performance to intolerable levels [4].

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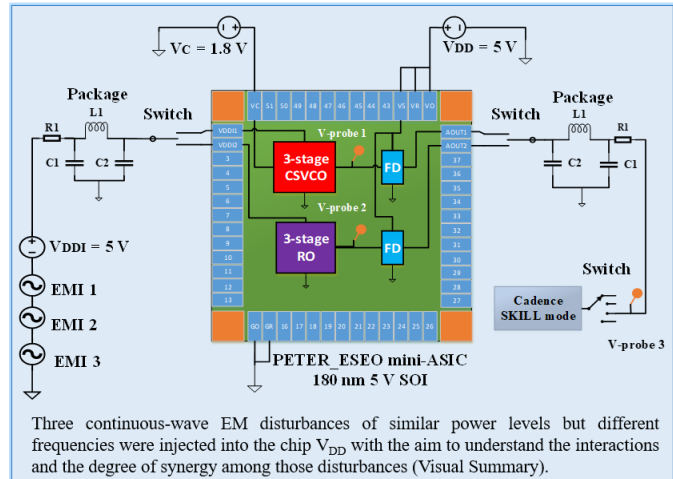
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However, as single-tone disturbances occur simultaneously, additional inter-modulation effects of the resulting multi-tone EM disturbance should perhaps be considered in immunity evaluations. Multi-tone test methods are already described in IEC 61000-4-3 [5], although mainly from the point of view of reducing test time [6]. However, to the best of the authors' knowledge, the combined effect of multi-tone interactions in integrated circuits has not previously been reported.

Simulation techniques, which are routinely used in industry in early stages of IC design, can help investigate and anticipate its susceptibility to multi-tone EM disturbances [7]. More importantly, the main challenge of multi-tone immunity analysis is the potentially infinite number of single-tone combinations that can be considered. For multi-tone measurements, however, the number of simultaneous tones that can be used is limited

Take-Home Messages:

- The simulated multi-tone EM disturbance impact for two different IC designs with similar functionality has revealed an increase probability of failure due to the causal synergy between simultaneous single-tone disturbances.
- The increase in the number of simultaneous tones from two to three tones shows a relative decrease in the probability of EMI failures.
- The frequency divider, output pad (i.e. pad capacitance and ESD structures) and package have an impact on the multi-tone EM immunity evaluation.

due to amplifier saturation, and also the calibration required for compensating the cable loss / attenuation factor, can lead to additional measurement uncertainties. Consequently, simulation offers a more practicable approach to investigate relatively large sets of tone combinations, as well as higher orders of multi-tones.

Oscillator circuits that are integrated into electronic sub-systems such as function generators, phase-lock loops etc. [8], are likely to experience a multi-tone EM environment. Their performance with respect to EM disturbances is not readily predictable due to their non-linear behavior. Hence, the evaluation of IC designs with respect to multi-tone immunity is desirable to gain confidence in the achievement of their intended performance characteristics.

The analysis of the immunity levels of a current-starved voltage controlled oscillator (CSVCO) and a ring oscillator (RO), previously investigated using single-tone disturbances in [9], is extended here to consider multi-tone threats using the probabilistic *noisy-OR* model [10]. The use of such probabilistic models to predict the impact of multi-tone EM disturbances and to overcome the limitations of multi-tone analysis are discussed in [11].

The paper is arranged as follows. In Section II, the description of the setup to test the oscillator circuits, the failure criteria and the EMI simulations used to estimate the probability of failure are given. The procedure for multi-tone immunity analysis using the noisy-OR probabilistic models to identify the causal interactions between simultaneously occurring single-tone disturbances are discussed in Section III. The results obtained from steady-state simulations for single and multi-tone EM disturbances are extensively analyzed in Section IV. The concluding contributions of this study are presented in Section V.

II. MATERIALS AND METHODS

This section presents the simulated immunity testing for the CSVCO and RO circuits. Both oscillators were included in the PETER_ESEO research chip [9] in silicon-on-insulator (SOI) 180 nm 5 V technology, provided by the XFAB foundry. They were designed to have matching aspect ratios and fixed output frequency values. Both circuits were designed using Cadence Virtuoso and the EMI simulations were implemented in Spectre. A hierarchical parasitic extraction was carried out to approximate their time-domain responses.

A. Simulation Setup Description

The simulation model consists of three single-tone EMI sources connected to the isolated power supply (V_{DDI}) of the simulated block (as shown in the Visual Summary). The remaining model setup includes the IC package model, the switches, the PETER_ESEO die, the Cadence SKILL mode to monitor the output, the global power supply (V_{DD}) and the biasing control supply (V_C).

The die consists of 52 pads, with electrostatic discharge (ESD) protection structures to both V_{DD} and ground. Each oscillator has a V_{DDI} pad and a single separate ground, benefitting from SOI technology [12]. The output of the

respective oscillator is connected to an analog I/O pad, which will clamp generated signals that are not between the range of 0 V to 5.5 V. The ceramic quad flat package of the research chip was modeled using the IC-EMC software [15] which enables the creation of an approximated package model using passive lumped elements.

The IC includes, among other circuits, the 3-stage CSVCO and RO circuits. The former is connected to the V_C supply to tune the output frequency, whereas the latter has a buffer at the output stage to stabilize the oscillating signal. Both oscillators consist of an odd number of multi-stage inverters to generate a sinusoidal output signal. For the RO, the output frequency is controlled only by the delay cell stages and the voltage supply. For the CSVCO, the rise and fall times of the cell are regulated by externally biased MOSFETs. Hence, by controlling the sizes of the MOSFETs, one can control the current provided to the delay stage, resulting in reduced output power and a broader tuning frequency range [13].

Single or multi-tone EM disturbances are injected to the V_{DDI} pad of each circuit to emulate the possibility of simultaneous occurrence of these EM waveforms in the real-world system EM environment. In the simulations, the multi-tone EM disturbances are generated by superposition of single-tones. A digital frequency divider (FD) circuit is included in the output stage of both oscillators to reduce the fundamental frequency of the generated signal [14]. This helps to ease the practical difficulties of monitoring the frequency at the analog output pin without filtering effects due to package parasitics. The FD circuit is powered by the main V_{DD} and is entirely isolated from the EMI injection. The switches ensure that the RF signals injected into the V_{DDI} pad of each oscillator do not interfere with any other inputs. Additionally, voltage probes are added to monitor the voltage fluctuations before the FD and at the output node. This helps us to observe the behavior of each oscillator without any filtering effects.

B. Failure Criteria

The operating frequency of an oscillator is generally used to evaluate the performance of the circuit with respect to injected EMI [16]. To determine the performance of each circuit, the output frequency under EM disturbances is monitored at the connecting node before the frequency divider (BFD), as well as at the analog output pin after the frequency divider, output pad and package (AFD). The failure criteria are relative frequency deviations of $\pm 5\%$ from the nominal output frequencies of the CSVCO and RO, both before (BFD) and after (AFD) the FD circuit (Table I).

C. EMI Simulations

All the EMI simulations were recorded for a time-period of 1 μ s. The EM disturbance was injected after a delay of 300 ns to allow the oscillator to stabilize and reach its nominal operating frequency. The Cadence SKILL mode function was applied to measure the output frequency of the oscillators at discrete time-steps (1.4 to 1.5 ns) over the steady-state period (700 ns).

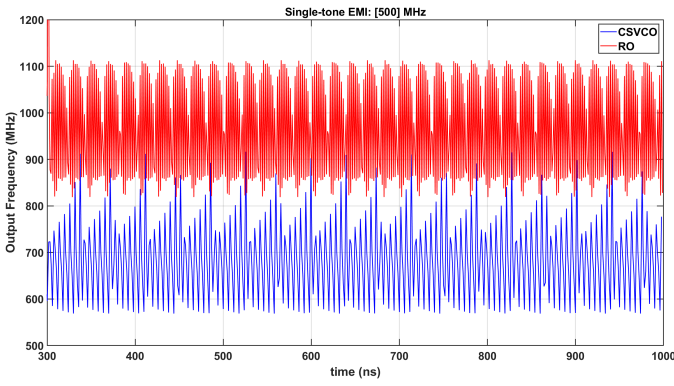


Fig. 1. Output frequency of CSVCO and RO, BFD due to single-tone EM disturbance at 500 MHz.

An example of the impact of single-tone EM disturbance at 500 MHz on the output BFD frequencies is illustrated in Fig. 1, for both CSVCO and RO circuits. This result shows that the output frequency response of both oscillators is different for the same EM disturbance. As mentioned in [9], both oscillators are susceptible to single-tone EM disturbances at frequencies from 50 MHz to 1 GHz. Within this range, a total of 15 arbitrarily single-tone EM disturbance frequencies were chosen.

The number of frequencies selected for multi-tone analysis was restricted in order to limit computational requirements. For instance, the total number of conditional probability distribution entries required for n frequencies is 2^n . Furthermore, the total number of non-repeating combinations $N(n, r)$ for multi-tones up to order r is given by:

$$N(n, r) = \frac{n!}{r!(n-r)!} \quad (1)$$

A total of 105 two-tone and 455 three-tone cases were obtained from combinations of the 15 arbitrarily selected frequencies shown in Table II [11].

The failure criteria were applied for each time-step in the steady state period, allowing the probability of EMI failure to be calculated by dividing the number of time steps with failure by the total number of time steps. For example, the failures due to single-tone EM disturbance at 500 MHz are shown in Fig. 2 for the CSVCO BFD, where the dotted lines represent the $\pm 5\%$ tolerance. In this case, the output frequency under EMI is found to be beyond the tolerance at several instances (shown by red circles in Fig. 2) and the probability of EMI failure is calculated as 0.679 in this case.

TABLE I
NOMINAL FREQUENCIES OF CSVCO AND RO

Type of Oscillator	Operating frequency (BFD)	Frequency divider (FD)	Output frequency (AFD)
CSVCO	703 MHz	8 (3 stages)	87.9 MHz
RO	955 MHz	8 (3 stages)	79.5 MHz

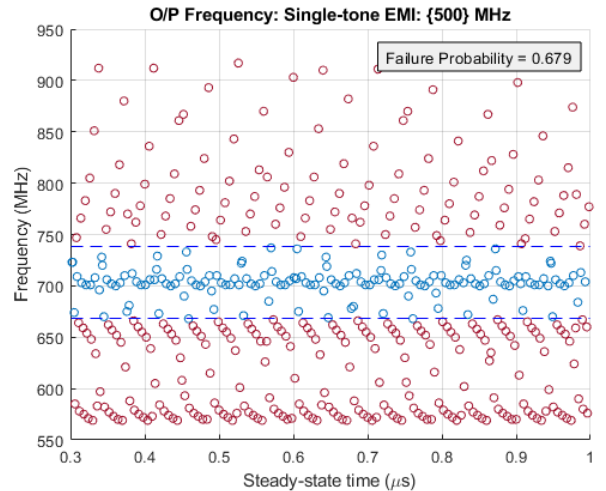


Fig. 2. Steady-state output frequency of CSVCO BFD for single-tone EM disturbance at 500 MHz.

III. TYPES OF MULTI-TONE INTERACTIONS

The noisy-OR model [10] has been used to identify the causal dependence between simultaneously occurring single-tone EM disturbances [11]. If n single-tone disturbances, denoted as T_i for $i \in \{1, 2, \dots, n\}$, are causally independent when they occur simultaneously, then the probability of failure due to the resulting multi-tone disturbance $P_N(F|T_1, \dots, T_n)$ can be estimated using the noisy-OR model [10] as:

$$P_N(F|T_1, \dots, T_n) = 1 - \left\{ (1 - \lambda_0) \prod_{i=1}^n (1 - P(F|T_i)) \right\} \quad (2)$$

where the terms $P(F|T_i)$ are the failure probabilities for single-tone EMI and λ_0 represents the probability of failure in the absence of EMI (assumed to be zero).

The probability of multi-tone failures can also be obtained using Cadence simulations. Any difference between the probability values derived from multi-tone simulations and the noisy-OR estimates indicates a violation of the causal independence assumption. Any dependence resulting from interactions between simultaneously applied single-tones can have either positive or negative impact on the probability of the IC failure.

If the probability of failure for multi-tone EM disturbance is less than any of the probabilities for any of the single-tone contributors, then the simultaneous single-tones interact to produce a cancelling effect, which is classified as an *inhibition* type interaction [11], [18]. By contrast, if the probability for multi-tone EM disturbance is greater than any of the probabilities for any of the single-tone contributors, then the simultaneous single-tones interact to produce a reinforcing effect, classified as *positive causality*. Positive causality is further subdivided into *synergy* and *asynergy*. The former is true when the probability of multi-tone EM disturbance is greater than that estimated using the noisy-OR model (2), whereas the latter is true otherwise.

TABLE II
PROBABILITY OF EMI FAILURE OF CSVCO AND RO DUE TO SINGLE-TONE DISTURBANCES BFD AND AFD

Single-tone (MHz)	50	100	200	300	350	450	500	550	600	650	700	750	800	900	950
CSVCO (BFD)	0.849	0.902	0.9	0.854	0.790	0.653	0.679	0.805	0.904	1.0	0.010	0.309	0.540	0.593	0.614
CSVCO (AFD)	0.941	0.923	0.66	1.0	0.5	0.4	0.667	0.9	0.981	1.0	1.0	0.538	0.566	0.254	0.22
RO (BFD)	0.782	0.818	0.821	0.792	0.833	0.953	0.931	1.0	1.0	1.0	1.0	0.572	0.173	0.062	0.0
RO (AFD)	0.827	0.717	0.667	0.333	1.0	1.0	0.976	1.0	1.0	0.627	1.0	1.0	0.884	0.468	0.0

IV. RESULTS AND DISCUSSION

For single-tone EM disturbance injection at frequencies close to the nominal output frequencies (i.e., 703 MHz for CSVCO, BFD and 950 MHz for RO, BFD) there were very few or no failures. For calculation purposes [11], the absence of failure is considered 0.0001 (shown in Table II as 0.0), whereas the certainty of failure is considered 0.999 (shown in Table II as 1.0). Further, to identify the sub-type of interactions that were classified as positive causality, i.e., as synergy/asynergy, the two-tone and three-tone probability of failure obtained from the single-tone failure probabilities using (2) were compared with the simulated values.

From an IC designer's perspective, inhibition interactions are less of a concern due to their canceling effect. Conversely, interactions with positive causality, either synergy or asynergy, are significant as they increase the probability of failure.

To illustrate the possible multi-tone combinations, the associated probability of failures, *degree of synergy* (*DoS*) as defined in [11] and the interaction proportions (i.e. inhibition (I), asynergy (A) and synergy (S)) of RO BFD are included in Tables III & IV for two and three-tone EM disturbances, respectively.

A. Two-Tone Immunity Analysis

The proportion of interaction types associated to two-tone EMI for CSVCO and RO (BFD and AFD) are illustrated in Fig. 3 (a). When comparing BFD, the inhibition interactions

are higher by 18.1% for the RO than the CSVCO. Furthermore, by observing the positive causality, the RO has 18.1% lower asynergy interaction points than the CSVCO, but their synergistic proportions are the same. This observation shows that the probability of failure due to two-tone disturbances for the RO is lower than the CSVCO.

A similar comparison for AFD shows that the proportion of inhibition was reduced by 3.81% for the CSVCO and increased by 2.85% for the RO. The synergy interactions are increased by 21.9% and 0.95% for the CSVCO and RO, respectively, which means that the immunity levels of the CSVCO to two-tone disturbances were reduced with the addition of the frequency divider. Nevertheless, for the RO, the immunity levels are observed to have slightly improved. In common, for both oscillators the proportion of asynergy reduces with the addition of a frequency divider.

The differences in the proportion of interaction types between circuits demonstrate that the EMI performance of ICs can vary depending on their design and architecture.

B. Three-Tone Immunity Analysis

While maintaining the same operating conditions, the steady-state response of both oscillators was also monitored for three-tone EM disturbances. As shown in Fig. 3 (b), increasing the number of tones from two to three resulted in enhanced inhibition proportions for both oscillators. This change can be due to the inter-modulation effects rising with more tones and eliminating the impact of each other. Thus, the

TABLE III
PROBABILITY OF EMI FAILURE DUE TO TWO-TONE DISTURBANCES (RO BFD)

Two-tone (MHz)	100, 300	100, 500	100, 750	100, 800	100, 900	300, 500	300, 750	300, 800	300, 900	500, 750	500, 800	500, 900	750, 800	750, 900	800, 900
$P(F T_1, T_2)$	0.73	0.81	0.91	0.91	0.9	0.86	0.89	0.87	0.91	0.73	0.91	0.95	0.6	0.53	0.33
$P_N(F T_1, T_2)$	0.96	0.99	0.92	0.85	0.83	0.99	0.91	0.83	0.8	0.97	0.94	0.94	0.65	0.6	0.22
<i>DoS</i> (%)	-24.1	-18.2	-1.7	6.6	8.1	-12.3	-1.8	4.5	13.2	-24.9	-3.8	1.9	-6.7	-11.8	47.6
Causality	I	I	A	S	S	I	A	S	S	I	I	S	A	I	S

TABLE IV
PROBABILITY OF EMI FAILURE DUE TO THREE-TONE DISTURBANCES (RO BFD)

Three-tone (MHz)	100, 300, 750	100, 300, 800	100, 300, 900	100, 500, 800	100, 500, 900	100, 750, 900	100, 800, 900	300, 500, 750	300, 500, 800	300, 500, 900	300, 750, 800	300, 750, 900	500, 750, 800	500, 750, 900	500, 800, 900	750, 800, 900
$P(F T_1, T_2, T_3)$	0.84	1.0	0.77	1.0	0.72	0.74	0.82	0.95	0.91	1.0	0.93	0.71	0.95	1.0	0.47	
$P_N(F T_1, T_2, T_3)$	0.98	0.97	0.96	0.99	0.99	0.93	0.86	0.99	0.93	0.92	0.84	0.98	0.97	0.95	0.67	
<i>DoS</i> (%)	-14.2	3.2	-19.9	1.0	-26.9	-20.4	-4.6	-4.2	-1.3	9.1	11.5	-27.3	-1.8	5.7	-29.0	
Causality	A	S	I	S	I	I	A	A	A	S	S	I	A	S	I	

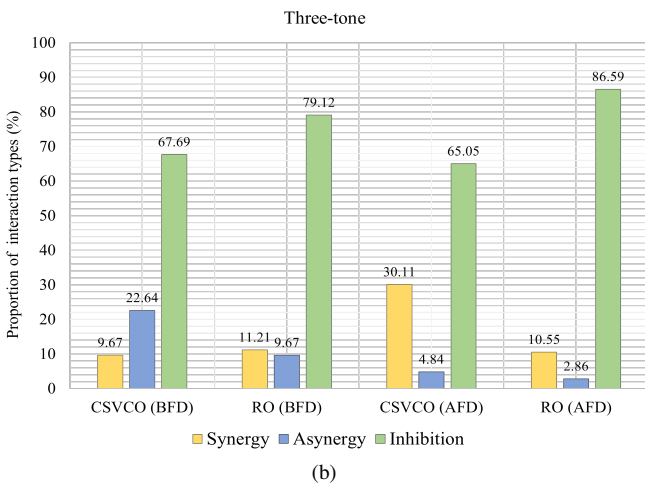
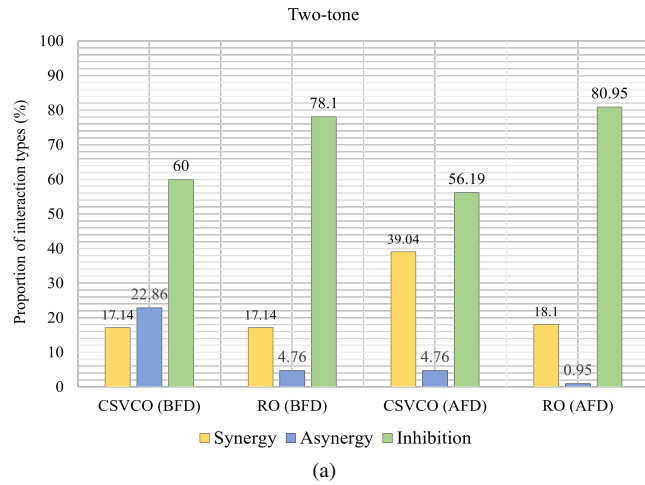


Fig. 3. Comparison of CSVCO & RO multi-tone EM disturbance effect: (a) two-tone; (b) three-tone.

probability of failure is reduced due to three-tone disturbances. Similar to the two-tone case, after the FD, the inhibition type interactions decreased by 2.64% for the CSVCO, whereas they increased by 7.47% for the RO. It is deduced that the added effect of digital frequency dividers, analog output pad (i.e. pad capacitance and ESD structures) and package increases the synergistic proportion of interactions caused by the multi-tone disturbances for both oscillators.

C. Degree of Synergy

Each of the synergy type interactions identified during the multi-tone analysis (shown in Fig. 4) was further assessed by calculating the mean (DoS), which is defined in [11]. It can be seen in Fig. 4 that the mean DoS of the CSVCO is lower than the RO by 4.32% for two-tone disturbances (BFD). This is due to the architecture of the CSVCO, as the multi-tone RF signal initially disturbs the biasing transistors before eventually reaching the inverter stage. Thus, the CSVCO is resisting a change in frequency and causes the mean DoS to be decreased.

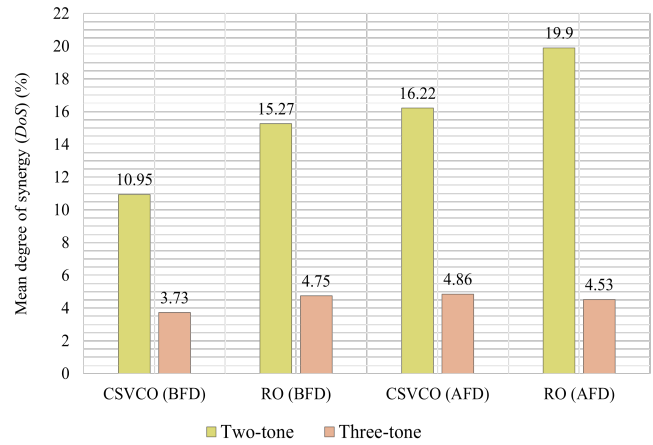


Fig. 4. Mean DoS of two-tone and three-tone disturbances: CSVCO vs. RO.

V. CONCLUSION

In this paper, various types of multi-tone interactions (synergy, asynergy, and inhibition) were investigated in a SOI integrated circuit. Steady-state simulation and probabilistic models were implemented for the first time to compare the multi-tone immunity levels of two conventional integrated oscillator designs. By using frequency deviations as the failure criteria, the causal dependence between multi-tone disturbances was observed to vary the probability of EMI failure. Alternative failure criteria such as peak-to-peak voltage and mean DC offset tolerances could also be used to characterize the immunity of both oscillators to multi-tone disturbances.

The performance of the CSVCO could be regarded better than the RO due to the relatively lower mean DoS . However, the higher proportion of synergy type interactions for the CSVCO AFD cases suggests otherwise. By comparing the BFD and AFD results, it is clear that the FD, output pad and package have an impact on the perceived EM immunity levels of the oscillator circuits in this study.

The analysis using the noisy-OR model suggested that the probability of a component failure might increase due to the positive causality of multi-tone disturbances. However, when the number of tones increased from two to three, it was evident that the probability of failure reduces (due to higher incidence of inhibition) and the single-tone immunity verification can, therefore, be regarded as a conservative approach. Since all types of interactions (synergy, asynergy and inhibition) can co-exist within multi-tone testing of a single integrated block, an integrated circuit is not always more susceptible to a multi-tone EM disturbance depending on its structure and the frequencies involved.

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