High Power EMI on Digital Circuits Within Automotive Structures

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Abstract—This paper considers the impact of high power electromagnetic interference on performance of digital electronics, more specifically timer, used for controlling spark plug sequence in an automobile. We carry out measurements on a commercially available timer to observe soft and hard upsets and identify important circuit and interfering signal parameters pertaining to the upsets. We observed that as bias voltage decreases, the device becomes less immune to interference. This implies that EMI effects will become more dominant on next generation integrated circuits since bias voltage drops in proportional to the technology size. Subsequently, we proceed to address a more practical case where a timer inside an automobile is subject to a train of high power Gaussian pulses. For the latter case, not only do we investigate characteristics of the interfering signal such as pulse width and magnitude, but also we study impacts of scan angle (incident angle) since scattering from the automobile highly contributes to EMI interference to the timer. Our analysis suggest that pulse duration and scan angle are critical to assessing EMI effects on the timer operation. Experiments are complemented with an analysis that employs our recently developed hybrid S-parameters approach to integrate numerical EM tools (Method of Moments and HFSS) with circuit tools such as Advanced Design System (ADS). Such approach enables us to address EMI analysis of complex structures housing mixed signal circuits with a high simplicity and flexibility. Implications of our findings are discussed and future work that will lead to a more practical and realistic assessment of EMI on performance of electronic systems is addressed as well.

I. INTRODUCTION

Recent security threats on electronic and computer systems accentuate the importance of intentional EMI/EMC analysis of electronic systems. Experimental studies reported in [1], [2] have already shown that serious damage can be done to electronic systems with High Power Microwave (HPM) sources. Severity of such a threat was emphasized with an experiment that hand-held HPM units, which can be located in a suitcase, can lead to serious damage on electronic systems from a 50 meters distance [2].

In addition to increased efforts on understanding of intentional EMI, recent advances in communication systems, specifically in wireless communication, leads to unintentional EMI on electronic systems that stipulates understanding of different classes of EMI. As the number of antennas on automobiles rises with increased use of satellite and land-communication systems, unintentional coupling among electronic systems becomes inevitable. Moreover, increased use of wireless communication at homes, electromagnetic compatibility and interference among electronic gadgets necessitate understanding and analysis of unintentional EMI for better performance. Examples can be also further extended to both intentional and unintentional EMI concern in commercial airplanes as well.

The prevalent approach to EMI evaluations is based on experimental studies. The measurements are typically carried out on a prototype of the test structure before mass production. However, experimental studies lead to inevitable increase in cost and time requirements on performance evaluation. Hence, theoretical prediction of the EMI/EMC evaluations has taken a more important focus.

Theoretical efforts for numerical EMI evaluations are centered around developing highly-efficient and computationally cost-effective numerical tools such as Finite Element Method (FEM), Method of Moments (MoM), Finite Difference Time Domain (FDTD) etc. for the enclosures, Multiconductor Transmission Line Theory for cable bundles and Modified Nodal Analysis (MNA) and Harmonic Balance Method (HBM) etc. for circuit analysis. Due to the complexity of realistic EMI/EMC problems, theoretical analysis primarily stipulates integration of these tools. While numerous techniques ([3], [4], [5]) integrating aforementioned tools are developed to address limited number of EMI problems, susceptibility (intentional and unintentional EMI) analysis is generally given little attention.

We recently proposed hybrid S-parameter method with the goal of extending existing port analysis to accommodate intentional and unintentional EMI impacts on electronic modules ([6], [7], [8]). In other words, we considered external plane wave excitations as well as port (internal) sources, and proposed hybrid S-parameters for characterization of transmission line networks and mixed signal circuit systems. We introduced constant voltage sources at the ports to treat forced waves and considered induced propagating modal waves as additional entries in S-parameter matrix (hybrid S-parameters). The resulting hybrid S-matrix and voltage sources were subsequently exported to any circuit analysis tools such as HSPICE and ADS with the the corresponding linear and non-linear circuit
terminations at the ports. With this approach, the structures are solely treated in EM domain. Whereas, the electronic components attached to the ports are handled in circuit domain with the hybrid S-parameters providing an interface between domains. This approach also allows for optimization of circuit components without a need to re-evaluation of the matrix associated with the large structures enclosing the PCBs and circuits.

Most EMI mitigation and protection techniques primarily rely on shielding the circuit boards and cable bundles. Not only does this approach lead to high cost, but it is also insufficient since it fails to perform as expected due to inadequate understanding of the coupling phenomenon. Therefore, it becomes important (1) to have a better understanding of electronics to combat with EMI at circuit level and (2) to possess well-established theoretical tools to study characteristics of interfering signal and also understand the impacts of enclosures and shielding on EMI/EMC performance. In this paper, we address the former by carrying out an experimental analysis on a commercially available timer (primarily used for controlling the spark plug sequence in an automobile) manufactured by Philips. We aim to observe soft and hard upsets under various EMI signals and to identify important circuit parameters for minimizing EMI effects. For the latter, we employ hybrid S-parameter analysis to address a more practical case where the timer located inside an automobile is subject to a train of high power Gaussian pulses. Not only do we investigate the characteristics of the interfering signal such as pulse width and magnitude, but also we study issues such as scan angle (incident angle) since scattering from the automobile highly contributes to EMI interference. For the theoretical study, we integrate numerical EM tools (Method of Moments and HFSS) with circuit tools such as Advanced Design System (ADS) via hybrid S-parameter analysis. In the final section, we discuss implications of our findings and address future work toward a more practical and realistic assessment of EMI on the performance of electronic systems.

II. ELECTROMAGNETIC INTERFERENCE ON THE JOHNSON DECADE COUNTER (TIMER) IN ISOLATION

In this section, we report high power EMI effects on a Philips 74HC4017 Johnson decade counter (timer) mounted on a RT/Duroid 5880 Printed circuit board (PCB). Our primary goal is to investigate upsets in the timer due to EMI and identify the most important electronic design parameters and EMI characteristics related to the upsets. It is known that those upsets are categorized as “soft errors”, implying a reversible disruption to the device operation, and on the other hand, “hard errors” resulting in a physical failure (irreversible) of the device [9].

A. Measurement Setup

Referring to the measurement setup in Fig. 1(a), the EMI is injected via a hybrid power combiner connected to the clock signal as well. The timer has 11 decoded outputs ($O_0 \sim O_9$ and $O_{5 \sim 9}$), active clock inputs ($CP_1, CP_0$), and a master reset input (MR). It is designed to advance with positive or negative edge trigger depending on the pin connections of the clock and master reset inputs. For our experiments, MR and $CP_0$ were set to logic low and high respectively to provide negative edge clock trigger at the $CP_1$ clock input. An HP8116A 50MHz pulse function generator was used to generate the clock pulse signal. EMI signal was obtained via an HP 8753C 300kHz - 6GHz network analyzer set.

To investigate interference effects on the timer, the clock pulse and EMI signal were connected to the $CP_1$ clock input port through the power combiner and the decoded outputs were then measured using Tektronics 450 digital oscilloscope. In other words, the measurement was setup in a way to investigate the impact of disrupted clock signals on the timer performance. The oscilloscope was connected to a computer controlled by Labview program to obtain experimental data. The counter was biased with 2V or 3.3V DC and the power and frequency of the interference signal ranged from 0 to 23dBm, and 1 to 3GHz, respectively.

B. Measurement Results

The decoded output ($O_7$) without EMI is given in Fig. 1(b) for a 2V DC bias and 3.4MHz clock pulse having 50% duty cycle applied to the VCC and $CP_1$ port respectively. As displayed, the output had 320ns width and 2.936µs period...
indicating that the counter is at normal operation with 26ns propagation delay. To observe the interference effects, 23dBm signal at 1GHz was combined to 3.4MHz clock pulse using the combiner and applied to the \( CP_1 \) port.

Fig. 2(a) displays voltage saturation level at the VCC implying that the device can not turn off the output (\( O_7 \)) (viz. critical device error). The voltage level also changes with respect to time as well. This demonstrates that the interference power severely degrades the device performance by invalidating the negative edge trigger of the clock signal at the port. From the device data sheet, it is noted that the port front is a CMOS inverter. Therefore, the device upset can be attributed to the changes of input/output voltages and the increase of propagation delays in CMOS inverters [10]. After EMI was terminated, the device returned to normal operation implying no permanent failure. Thus, this indicates that the upsets were soft errors.

When the interference was at 3GHz, the timer displayed a gradual degradation at the output pulse level as the power was increased. This is seen in Fig. 2(b) that the device becomes less immune to the interference at 3GHz and most likely due to less EMI power is reflected at 3GHz than at 1GHz as observed with S-parameters measurement. At 20dBm, the output pulse level drops to 1.14V sufficient to cause malfunction (see Fig. 2(b)).

The relationship between interference and bias voltage was also investigated. Specifically, the bias voltage was increased to 3.3V while other inputs remained the same as before. We observed that the output pulse showed no changes with respect to the power and frequency of interference signal. Therefore, we conclude that the device becomes more vulnerable to interference as the bias voltage decreases. This is likely due to increase in delays in CMOS device as bias voltage decreases [11].

### III. Susceptibility of a Timer inside an Automobile Subject to High Power EMI

We next consider a more complex setup in which a timer mounted on a RT/Duroid 5880 board enclosed with a metallic box is located behind engine compartment of an automobile (see Fig. 3(a)). The automobile is illuminated with a train of high power Gaussian pulses from driver’s side while the timer was active. The incident wave is polarized such that \( H_z \neq 0 \) and \( E_z = 0 \) (ie. \( TE_z \) mode)

As Fig. 3(b) displays, the timer is mounted on an RT/Duroid 5880 board with single clock input (QCLK) and 4 output (\( QT1 \ldots QT4 \)) microstrip lines inside a box with ventilator apertures. The timer has actually three inputs (VCC, Enable and Clock). However, to keep our analysis simple...
without compromising accuracy, we did not include VCC and Enable in the course of this study since we did not expect that they would play critical role.

Our objective in this study is to investigate characteristics of high power Gaussian pulses to fail the operation of the timer. In particular, we vary scan angle and pulse width ($\phi$ and $\sigma$ respectively in Fig. 3(a)).

For this study, we used our own positive edge triggered timer designed with AMI 0.5$\mu$m MOSIS (Timer was in production process during the preparation of this article). Having used our own timer, we had the advantage of using an accurate SPICE model to integrate it with our numerical EM and Circuit solvers as explained in the subsequent section.

A. Numerical EM and Circuit Tools

We used numerical EM and circuit tools to model each component of the problem (see Fig. 4(a)). Specifically, we employed our own Multilevel Fast Multipole Method- Method of Moments (MLFMM-MoM) code EMCAR (validated with measurements, see [12]) to model the automobile subject to high power train of Gaussian pulses. Timer board and enclosing box were analyzed with HFSS (Ansoft) to extract S-parameters for the board and generate hybrid S-parameters to integrate with ADS. In the final step, the entire composite model (automobile+ timer box+timer board) was combined with ADS platform through hybrid S-parameters to perform time-domain analysis with the SPICE model of Timer. Among the numerical tools used, EMCAR and HFSS are full wave frequency domain EM solvers. Whereas, ADS is both time and frequency domain circuit analysis tool.

B. Analysis

Due to the high complexity associated with the problem, we decomposed our analysis into three major components (see Fig. 4(a)). We note that coupling from timer box to automobile is very small compared to coupling from automobile to timer so that we neglect scattering back from the timer box to the automobile. This is a valid assumption because size of the timer box is very small as compared to overall size of the automobile. Therefore, total field solution is mainly due to scattering from the automobile body.

Referring to Fig. 4(a), we represent train of Gaussian pulses (carrying 99% energy of an ideal Gaussian pulse) in frequency domain through its Fourier transform. At each frequency point, EMCAR simulations were performed with the automobile and field values in the presence of the automobile were excitation to the timer board inside the metallic box (see Fig. 3(a)).

To integrate timer PCB board and the enclosing box with SPICE model of the timer in ADS, we carried out port analysis of Timer board with enclosing box via S-parameter modeling in HFSS. We defined 10 ports at the terminals of each signal line (2 port at the terminals of clock bus, 8 port at the terminals of output lines). To account for incident wave excitation, we performed hybrid S-parameter analysis and modified existing S-parameter matrix ($10 \times 10$) with additional entries and export the resulting matrix $11 \times 11$ to ADS for time-domain analysis with SPICE model of the timer (see Fig. 4(b)).

C. Results

Electric Field Shielding (EFS) of the automobile and the timer box play critical role in determining EMI power level to disrupt the timer operation. Therefore, we carried out EFS analysis of automobile and timer box for varying scan angles (see Fig. 5(a)). In both analyses, incident magnetic field was polarized in the $\hat{x}$ direction (see Fig. 3(a)-(b)) and accordingly the electric field vector was on $x-y$ plane. We also note that for a large span of frequencies, only $\hat{y}$-component of the electric field will penetrate the timer box. Therefore, EFS of timer box was computed with E-field being on $\hat{y}$-direction and perpendicularly impinging on the timer box in $\hat{x}$-direction (refer to Fig. 3(b)).

Fig. 5(a) clearly shows that the highest coupling in the automobile occurs around $100MHz$ for each scan angle. To evaluate performance of the timer for the case where majority of the power is coupled to the timer box, $T = 10ns$ period for the Gaussian pulse train was chosen to obtain frequency distribution in integer orders of $100MHz$. We also note that with $T = 10ns$, majority of the power propagates at $100MHz$. Therefore, throughout our analysis, we kept pulse repetition frequency constant at $100MHz$.

Due to the small size timer box, the lowest shielding effectiveness occurs around 2.2GHz.
Therefore, for the chosen excitation frequencies (100MHz, 200MHz, 300MHz, 400MHz, 500MHz), most of the energy is reflected back (refer to Fig. 5(a)).

D. Timer Performance with No EMI

Before exposing the timer to EMI, we carried out a time-domain analysis in ADS with SPICE model of the timer to characterize timer outputs for periodic clock signal. The objective of this analysis is to generate a reference solution. Fig. 5(b) depicts the output characteristics of the timer when no EMI is applied. The clock signal is of 5V magnitude has period of 2MHz and 50% duty cycle. Timer is also enabled with 5V of VCC and Enable inputs. Fig. 5(b) shows the output of the timer and also suggests that output sequence is QT3,QT4,QT1,QT2.

E. Timer Performance for Various Scan Angles

In this section, our objective is to understand the role of incident angle direction in timer operation. To do

Fig. 5. (a) Electric Field Shielding (EFS) of Automobile and Timer Box for Varying Scan Angles - (b) Timer Output with No EMI

Fig. 6. (a) Timer Output at QT2 at Various Scan Angles(ϕ)- Pulse Period: 10ns and pulse width: 2.0ns - (b) Timer Output at QT2 at Various Gaussian Pulse Widths(σ)
so, we illuminate the automobile with a train of Gaussian pulses (periodic with 10ns and pulse width 2.0 ns) at different incidences. Our preliminary studies suggested that Gaussian pulses with a peak value of 100kV/m would generate sufficient interference to disrupt the operation. Therefore, a value of 100kV/m is used for this study.

Referring to Fig. 6(a), we show the timer response at output QT2, and observe that minimum effect occurs at $\phi = 45$ degrees. While timer is still operational at scan angle $\phi = 90$ degrees, it is completely disrupted at scan angles of $\phi = 0, 135$ and 180 degrees. The dominant effect is mainly observed when the wave is incident from the front side of the car while incident waves from side door have relatively less impact. This can be attributed to the fact that some of the energy is reflected back from the side doors. Even though Fig. 5(a) suggests that the coupling from the front side is low at 100MHz compared to coupling from side door, Fig. 6(a) implies that shielding at harmonics is also critical since energy of Gaussian pulse is distributed over the harmonics.

**F. Timer Performance at Various Gaussian Pulse Widths**

We continue our analysis by investigating impact of incident wave pulse width on the timer performance. To do so, we exposed automobile to an incident train of Gaussian pulses at angle of $\phi = 135$ degrees with 200kV/m peak value (extracted from preliminary studies). Fig. 6(b) depicts the timer response at output QT2 for various pulse widths. It is clearly seen that narrow pulses have less effect on the the timer performance than wide pulses. Similar observations were also made in [2].This implies that as power is distributed more evenly over harmonics, EMI effects become less dominant. In other words, our study suggests that EMI effects are stronger when the same energy is concentrated over a smaller bandwidth.

**IV. DISCUSSION AND CONCLUSION**

We performed experimental and theoretical studies to analyze EMI effects on the timer performance. Measurement results implied that coupling of 20dBm power at 3GHz to terminals of timer would suffice to disrupt the operation. We also identified that digital circuits become less immune to EMI as bias voltage decreases.This implies that EMI effects will become more dominant on next generation integrated circuits since bias voltage drops in proportional to the minimum technology size. We also analyzed a very practical and realistic scenario where a timer was located inside an automobile which was subject to high power train of Gaussian pulses. We integrated numerical EM tools such as MoM and FEM with a circuit tool,ADS, via recently developed hybrid S-parameters and our analysis indicated that, in addition to the power level, characteristics of interfering signal such as incident scan angle and pulse width are as important to assess EMI/EMC performance of the system. In other words, even though electronic circuits in complex platforms such as automobiles and airplanes are highly shielded with enclosing boxes, it is still possible to upset circuits with reasonably achievable EMI power levels. Similar conclusion can also be drawn from the studies in [2]. However, we also note that EMI power level required to fail electronics in automobiles is likely not as high as power levels used in the examples we presented since we did not consider wire bundles which play very critical role in evaluating impacts of the EMI on the system performance. Therefore, a fair assessment of EMI effects on RF, digital and analog circuits in complex platforms requires an extensive analysis of EM structures such as automobile body and cable bundles integrated with electronic circuits. Not only does such analysis require wisely devised hierachial approach to break the whole problem into self-manageable components, but also theoretical tools that can combine EM structure and excitations with circuit components.

In the near future, it is our objective to engage in a more realistic study in which we combine all three fundamental components, automobile body, cable bundles and electronic circuits via recently developed hybrid S-parameters.

**REFERENCES**


