Shaping Electromagnetic Emissions of Event-Driven Circuits Thanks to Genetic Algorithms

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***Abstract*—This paper presents a method to shape by design the electromagnetic spectrum of any event-driven circuits. Contrarily to synchronous circuits, which are driven by a clock, event-driven or asynchronous circuits can be tuned to adjust their computation instants by setting appropriated delays in their local synchronization mechanisms. Thanks to this prominent feature, shaping their electromagnetic spectrum is feasible. For that purpose, a mask in the frequency domain is defined to constrain their electromagnetic spectrum. Thanks to a genetic algorithm, well-suited delays are computed to be compliant with the mask. This approach has been evaluated on an event-driven micropipeline circuit. We observe that the resulting spectrum fits within the mask and does not present harmonics as its synchronous counterparts. Moreover, the highest peak of the event-driven circuit is 3.2 times smaller than the highest peak in the spectrum of the synchronous design.**

Keywords-Event-Driven Circuit; Micropipeline; Electromagnetic Spectrum.

I. INTRODUCTION

Electromagnetic compatibility (EMC) specifications are established in order to ensure the correct operation of different equipment in a common electromagnetic environment. Indeed, the unwanted generation, propagation and reception of electromagnetic energy in integrated circuits may cause unwanted effects, such as electromagnetic interference (EMI) or, even worst, physical damage. A device that emits, whether deliberate or unwanted, electronic emissions in its environment is referred to the aggressor. On the contrary, the circuit that is made malfunctioning or destroyed by the emission is referred to the victim. These kinds of issues are well-known by the circuit designers when they implement on the same die a RF transceiver and a baseband digital controller [1]. Indeed, the digital baseband controller tends to generate huge electromagnetic emissions disturbing the operations of the analog RF part of the circuit [2]. The clock signal of the digital circuit especially generates strong periodic current pulses on the power supply, producing a wide spectrum able to make inoperative a sensitive analog block [3].

Techniques for shielding the sensitive parts of electronic circuits are developed, for a long time, by designers in order to develop immunity against electromagnetic aggressions [4]. Techniques for hardening the circuitry have also been developed in order to make the circuit more robust [5][6]. Several techniques exist for synchronous designs to reduce their electromagnetic emissions [7][8]. Nevertheless, the clocked activity still produces periodic current pulses that pollute the electromagnetic spectrum. Contrarily, the asynchronous designs, also known as clockless circuits, show a spread electromagnetic spectrum. Philips Research and Philips Semiconductors developed an asynchronous version of the 80C51 microcontroller for a contactless smartcard application [9]. In comparison with the 80C51 synchronous version, the asynchronous one consumes about four times less energy and its spectrum does not have clock harmonics [10]. In this example, the advantage of asynchronous design for EMC has been presented but no strategy has been developed to control the electromagnetic spectrum by design.

The first attempt to control the electromagnetic emissions by design is made in [11] using asynchronous circuit and the Force Directed Scheduling (FDS). Their method has been applied to a finite impulsion response filter. This study shows a 9dB reduction of the highest peak component of the electromagnetic spectrum.

Nevertheless, to the best of our knowledge, there does not exist efficient strategy for shaping and controlling the electromagnetic spectrum by design.

In this paper, we present a genetic algorithm approach, for asynchronous circuits, not only to minimize the electromagnetic spectrum peaks but also the way to respect a spectral mask, like for example the Federal Communications Commission (FCC) spectral mask.

Section II of this paper describes the micropipeline event-driven circuitry used to apply the method. The current modelling is introduced in Section III. Section IV describes the genetic algorithm for shaping and controlling the electromagnetic spectrum. The simulation results are presented in Section V and a conclusion is given in Section VI.

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II. MICROPIPELINE

In order to shape the electromagnetic emission, using event-driven circuits is required. In our method, the Micropipeline class [12] is used, but other classes, such as Quasi-Delay Insensitive, Speed-Independent or Burst-mode circuits [13] for instance could be easily used.

Sutherland introduces first the Micropipeline in 1989 [12]. In the micropipeline architecture, the data path is kept from synchronous circuits and the global clock signal is removed. The synchronization between the registers, in the control path, is made by local controllers using a handshake protocol [12]. The controller sends a request signal when valid data are at the inputs of its registers and an acknowledgement signal to notify to the previous stage that its registers are ready to receive new data. To be valid, data have to be captured after their processing by the combinational logic. In order to ensure that the timing assumption, given in (1), the request signal has to be delayed of a value at least equal to the critical path of the corresponding combinational logic (see Figure 1).

$$D_{Capture} > D_{Launch} \quad (1)$$

Our method keeps the architecture of the micropipeline circuit and uses the set of delays to shape and control the emitted electromagnetic spectrum. This approach can be considered as a generic method.

III. CURRENT MODELLING

As far field EM measurements are targeted in this study, the EM spectrum directly depends on the circuit current consumption [1].

In synchronous CMOS circuits, the modelling of the current consumption is based on the following considerations:

- Gate switching produces the current consumption.
- The clock tree and the clock switching activity of the flip-flops produce an important part of the current consumption.
- Most of the gate switching activity is localized in time just after the clock edges.

Figure 2 shows a CMOS circuit current consumption with peaks on the clock edges. Therefore, current pulses may simply model the consumption of a digital CMOS circuit.

In synchronous circuits, because of the clock signal, all the registers capture data at the same time producing a uniform distribution in time of the current peaks and strongly impacting the electromagnetic spectrum by generating

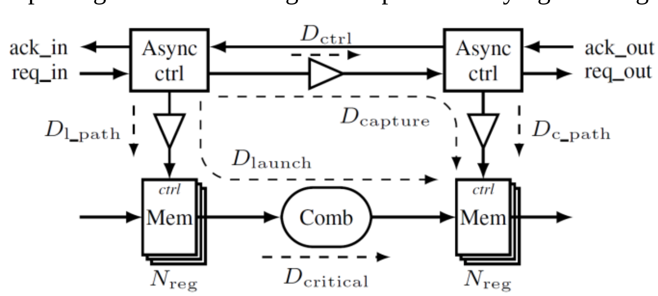

Figure 1. Architecture of a micropipeline circuit.

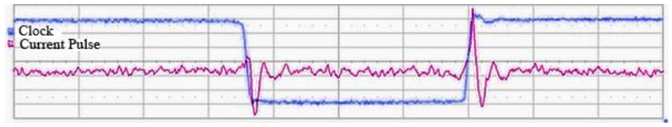

Figure 2. CMOS current consumption with peaks on the clock edges.

harmonics. In asynchronous designs, as the global clock is removed, the peaks distribution is no more uniform. This helps to reduce the harmonics. Therefore, the memorization instant of the registers can be seen as an event that introduces a peak in the current signal. These events could be distributed in time in order to shape the electromagnetic spectrum. To simply evaluate the current consumption a current pulse is placed on the current waveform when registers capture data.

Figure 3 illustrates the architecture on an *n*-stage linear micropipeline. The request signal of each stage *n* of the micropipeline is delayed of d_n. The total current consumption of this design is modeled as in Figure 4. The current consumption is seen as a sum of current peaks, which are distributed in time in function of the circuit delays.

Once the current curve is obtained, a Fast Fourier Transform (FFT) is performed in order to evaluate the electromagnetic spectrum.

IV. GENETIC ALGORITHM

A mask in the frequency domain is used to specify the targeted electromagnetic spectrum and to evaluate the circuit spectrum. A genetic algorithm (GA) is used to find the delays of micropipeline circuits to fit within the spectral mask.

The GA is a technique dedicated to optimization problems. Introduced by Professor Holland from the University of Michigan [14], this algorithm is inspired from the biology and natural phenomenon as the reproduction and the mutation. GA manipulates populations of individuals where, originally in biology, individuals are considered as chromosomes that evolve and mutate. This evolution can be interpreted as solutions to an optimization problem. Each chromosome is composed of genes that are the binary encoding of the parameters. The algorithm process (see Figure 5) begins with an initial population composed of *N* chromosomes that are candidate solutions to the problem. For each given chromosome *x*, a cost is evaluated with a fitness function *f(x)*. Then, they are classified from the stronger to the weaker, so that the rank increases from the best to the worst chromosome. Afterwards the parents of the next generation are selected among the current population. To select the parents, a line is created where each chromosome is a section of the line. The algorithm moves along that line in steps of equal size and allocates parents. The first parent is selected with a random number smaller than the step value. This method is called a stochastic uniform selection. During the selection, a chromosome can be selected more than once as a parent. In this case, its genes will contribute for more than one child. In the selection

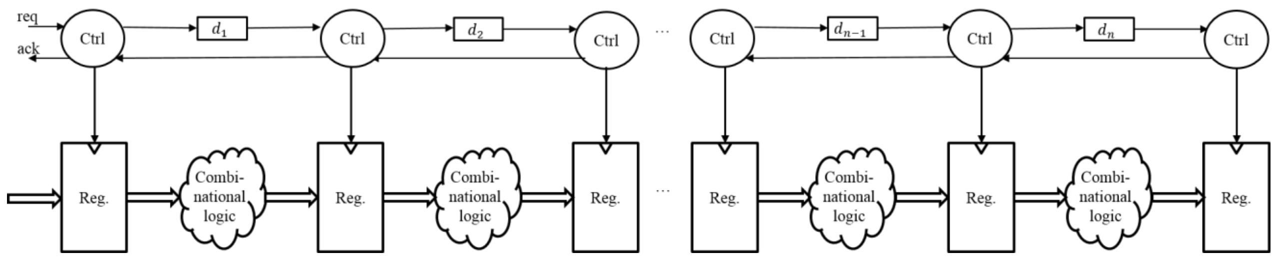

Figure 3. Architecture of an *n*-stage micropipeline

process, the chromosomes that have a better cost function are privileged. Then, the next generation is created in three steps.

Firstly, the elite children, the individuals with the best fitness value, in the current generation, are automatically selected. A proportion of the population has to be kept because there is no guarantee that the children will be better than the parents.

Secondly, the crossover children are created by the combination of two parents, this is similar to the reproduction in biology. A random binary vector is created and when its value is 1 the gene is selected from the first parent otherwise it is picked up from the second parent.

Finally, mutation children are created by applying random changes in a single individual. The mutation adds a random number chosen from a Gaussian distribution to each entry of the parent vector. The amount of mutation, which is proportional to the deviation of the distribution, decreases at each generation. This mutation step allows to explore different solutions and avoid to be locked.

To finish, the new generation is evaluated with the fitness function and the process of the algorithm is repeated. All the generations must have the same size to avoid the death of the population. The GA allows to find solutions for an optimization problem but not necessarily to find the best one (if it exists!).

In our case, we used the GA to find the delays that distribute the events in time in order to shape the electromagnetic spectrum. Therefore, the delays of the micropipeline are the genes of the individuals. The number of stages in the micropipeline defined the number of genes for the individuals. In our case, each gene has a minimal value corresponding to the critical path of the combinational logic associated to the stage. A maximal value is also determined by the designer in order to hold the expected speed performances of the circuit. The initial population is randomly chosen.

For each individual, we are able to determine the shape of the current when data are processed by the micropipeline circuit. Then, we apply a Fast Fourier Transform to have the frequency spectrum corresponding to this individual. The matching difference between this spectrum and the frequency mask is evaluated by the fitness function. When this difference is positive, the value is added to the chromosome cost. The algorithm is stopped when the best chromosome has a cost of zero. This last solution is chosen for setting the delays in the micropipeline circuit.

V. SIMULATION RESULTS

The simulations have been performed using the Matlab genetic algorithm function with the matching difference between the spectrum and the frequency mask as a fitness function.

We applied our method to an asynchronous circuit and then compared its electromagnetic spectrum to the spectrum of its synchronous counterparts. Both of them have one hundred stages. For the test case, the synchronous design has a clock period of 10 ns. The asynchronous version is designed in micropipeline [12]. We constrained the GA with delays covering a range between 5 ns to 10 ns with a resolution step of 0.1 ns. The upper bound, for the delays,

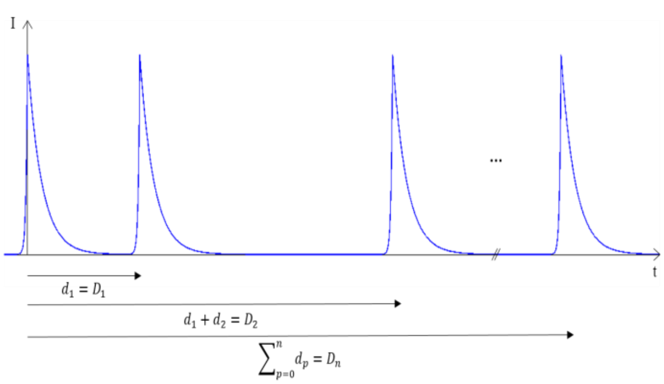

Figure 4. Shape of the total current consumption in time.

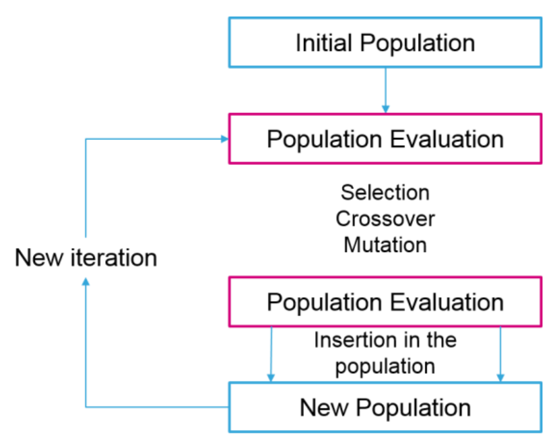

Figure 5. Genetic Algorithm Process.In our case the initial population is randomly chosen.

ensures that the total latency of the pipeline is maintained during optimization. The lower bound is the length of the critical path.

Figure 6 represents the architecture of a micropipeline stage where d_{min} is equal to the delay of the critical path in order to ensure the capture of valid data. Then, d_{GA} is the delay found by the genetic algorithm in order to fit the spectrum of the circuit within the spectral mask.

A mask is chosen as an electromagnetic spectral template in order to control the magnitude of the emissions in the frequency domain. The blue curve in Figure 7 is an example of spectral mask. In our example, we want to reduce the amplitude of some low frequencies. As already mentioned, the genes are delays selected in the range of 5 to 10 ns by step of 0.1 ns. The result of the simulations is showed in Figure 7. The green curve represents the electromagnetic spectrum of the synchronous design with a period of 10 ns. As expected, the spectrum presents harmonics every 100 MHz. The blue curve represents the spectral mask used in the fitness function to evaluate the individuals. The red curve is the resulting spectrum obtained by applying our method on the micropipeline design. Its magnitude now matches the spectral mask as expected. Moreover, the spectrum of the asynchronous design does not show harmonics anymore and its highest peak is 3.2 times smaller than the highest peak in the spectrum of the synchronous design.

To enhance the spectrum quality and ease the result convergence, the architecture of the design can be modified to add delays [15]. Indeed, increasing the number of stages in the design facilitates the search of delay solutions. The range and the step of the delays are also two important parameters that can be tuned to more easily fit the spectral mask [15].

VI. Conclusion

This paper presents a design method for shaping the emitted electromagnetic spectrum by an integrated circuit. With such a strategy, fitting within a spectral mask should become a specific step in the integrated circuit design flow. In order to apply this approach, event-driven asynchronous circuits have to be targeted. We chose for this purpose micropipeline circuits because they offer an event-driven behavior and an easy implementation for most of the circuit designers. We can notice that this design strategy can be applied to any kind of asynchronous designs.

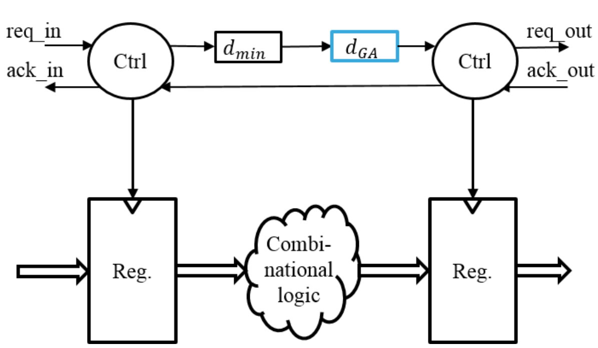

Figure 6. Micropipeline stage with the minimal delay that cover the critical path and the delay added to control the spectrum.

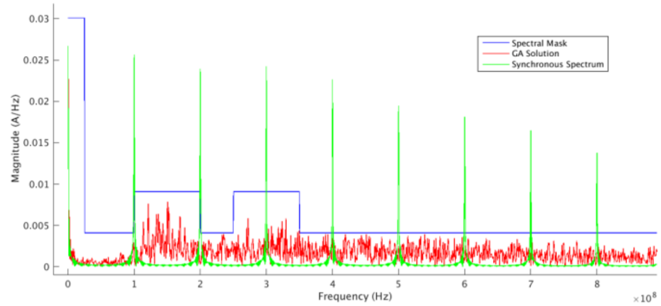

Figure 7. Simulation results, where the blue curve is the spectral mask and the red curve is the resulting spectrum of our method. The green curve is the spectrum of the synchronous version.

Once the event-driven circuit is designed, the designer has to determine the minimal and the maximal values for each delay and the spectral mask. Then, the genetic algorithm is performed. The GA determines the value of the delays so that the electromagnetic spectrum of the circuit fits within the spectral mask.

Finally, we are able to obtain with event-driven circuits an electromagnetic spectrum fitting within a spectral mask and without harmonics in comparison to the spectrum emitted by their synchronous counterparts. Moreover, we obtain a significant reduction of the electromagnetic spectral peaks with this strategy.

A test chip has been designed and fabricated. The latter is under validation with real EM measurements. Moreover, we emphasize that our EM shaping technique can be fully automated and a specific design tool should be implemented.

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