

Measuring Power and Energy of CMOS Circuits: A Comparative Analysis

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Abstract--- This paper presents and compares a set of experimental results on the measurement of power and energy consumed using an ammeter and a non-conventional capacitor-based method. A standard cell CMOS multiplier is utilized as a circuit under test. The paper shows, as main result, that the capacitor-based method allows the designer to obtain information unreachable with conventional ammeter measurements.

I. INTRODUCTION

Power and energy consumption are critical issues in the design of CMOS digital circuits and systems and a great amount of effort has been devoted to estimate these parameters in the early design phases [1][2]. Nowadays, a set of useful tools is being marketed to know in advance the amount of the power consumption of the fabricated circuits.

However, actual measurements of power are still mandatory. First, during the manufacture and testing stages, it is necessary to know the real power consumption to check if the circuit fits the specifications. On the other hand, at system level or in circuits where the power consumption depends to a large extent on the data processed, it is easier and convenient to perform measurements to know the power/energy consumed by such circuits.

The standard procedure to measure power/energy is to connect an ammeter in series with the power supply pins, as is reported in [12][13][7][8][9]. This is a simple technique, but the amount of information that can be extracted from this measurement is limited. Thus, other methods have been proposed. In [10], are presented a summary of several of such techniques. Jenkins et al. in [5] uses a small resistor (2Ω) in series with the supply pin, and measure with an electron-beam probe the drop voltage in the resistor. The same approach is used by Callaway et al. in [11], but using a 100Ω resistor. In [3], the author also uses a resistor and give several advises on both the

technique and instrumentation. In [15], the drop voltage in a resistor is utilized to determine if the transient current is abnormal or not. Thus, possible defects in the circuit can be detected.

Other approach is inspired by the Keating-Meyer technique for I_{DDQ} testing [18] and by the MTCMOS solution to leakage power control [6]. This technique (hereafter referred as C-based measurement) uses a switch and a capacitor in parallel with the supply pins to measure the energy consumed in a given period of time [17]. In [4][16] the authors present a variation of such technique that uses four switches and two identical capacitors to perform the measurement in synchronous digital ICs in a cycle-by-cycle basis. The information published, however, does not deal with the problems related to the switch charge injection and capacitor matching, and only relative energy measurements are presented.

The goal of this paper is to check and compare by experiment the capabilities of two measurement techniques: ammeter and C-based methods. Several experiments have been made by using a cell-based CMOS integrated circuit with different logic depth as a benchmark circuit. The rest of the paper is organized as follows: the next section summarizes the measurement methods. Section III describes the results obtained from measurements made on a board containing a full custom multiplier. Finally, in section IV the conclusions of the work are presented.

II. METHODS TO MEASURE THE CONSUMPTION OF CMOS CIRCUITS

A. General

By measuring the instantaneous current supplied to the IC, $i_{DD}(t)$, it is possible to calculate the charge, energy and power consumed by an IC. The main problem lays on the proper measurement of $i_{DD}(t)$, which is difficult in most cases because of the $i_{DD}(t)$ waveform characteristics. That

is the reason why in those cases when is not necessary to obtain an extremely detailed acquisition of the current waveform, other measurement techniques have been proposed. They are easier to implement but some trade-offs must be carefully analyzed. These techniques try to measure the current, either indirectly or by measuring an alternative magnitude.

B. Measurements with an ammeter

In most cases, it is not necessary to know the instantaneous value of $i_{DD}(t)$, the averaged (I_{DD}) value of it is enough. That average value is calculated applying the general equation

$$I_{DD} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T i_{DD}(t) dt \quad (1)$$

Average power and energy are easily calculated from I_{DD} . In this case, the best approach to measure I_{DD} is to connect an ammeter in series with the supplying pins. The input pattern is applied in infinite loops to the IC. Thus, the resulting current waveform is periodic. The ammeter averages the power supply current over a window of time and, if the period of the current waveform is much smaller than this window, a stable reading is obtained, showing the average current I_{DD} [12][3].

This method presents many advantages, as direct display reading, accuracy, and small disturbance. However, the drawback of this method is that is not possible to determine the energy consumed in a single transition between two input patterns, or in shorts periods of time. On the other hand, in spite of its simplicity, it is necessary to be careful when using an ammeter to measure the average current supplied to an IC [10].

C. Non conventional measurement methods

In those cases where is necessary to measure the average current consumed by a circuit in a short period of time (i.e. during the execution of a sequence of microprocessor instructions, or the IC response for a set of input patterns), the use of an ammeter is not feasible because its large integration time [14]. In addition, in these cases the repetition of such sequence could not be possible or desirable.

In order to solve the problem described above, measurement of the drop voltage on a resistor in series with supply lines and the C-based measurement method are suitable for this purpose. Both methods have been analyzed elsewhere [10]. This paper focus only in experimental results obtained from the C-based method.

D. Capacitor-based measurement

This method consists in temporarily disconnect the power supply by means of a switch, keeping the circuit supply pins connected to a capacitor. Then, one or more changes in the inputs are applied and the energy required is

supplied by the capacitor, thus decreasing its voltage. By measuring the drop voltage a measure of the energy consumed by the circuit can be obtained.

The experimental setup has the following structure (see Figure 1): a supply voltage V_{DD} is connected to the CMOS circuit through an electronically controlled switch S. There is a capacitance C_{DD} connected between the supply pin and the ground pin of the circuit. Finally, there is a measurement circuit connected to the supply pin. The actual C_{DD} value is the combination of the external capacitance C_{DDext} (for example, the decoupling capacitors) and the parasitic internal IC capacitance C_{DDint} between the VDD and ground nodes.

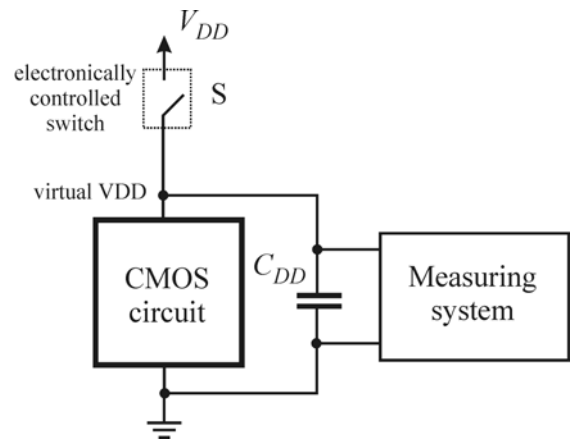


Figure 1. Experimental setup.

The system operates as follows: the switch S is closed and the capacitance C_{DD} holds the supply voltage at V_{DD} . Then, the switch is opened and a change on the inputs is applied to the circuit. As a consequence of the energy consumed by the circuit, the voltage at the supply node decreases ΔV volts. The measuring circuit captures this voltage drop. Finally, the switch is closed. Assuming that the capacitance C_{DD} has a constant value, the energy consumed by the circuit is related to ΔV by means of the following expression:

$$E = \frac{1}{2} C_{DD} V_{DD}^2 - \frac{1}{2} C_{DD} (V_{DD} - \Delta V)^2 = E_0 \left[2 \frac{\Delta V}{V_{DD}} - \left(\frac{\Delta V}{V_{DD}} \right)^2 \right] \quad (2)$$

where $E_0 = C_{DD} V_{DD}^2 / 2$. Thus, by measuring ΔV it is possible to find E if C_{DD} and V_{DD} are known. From equation (2) it is easy to derive expressions for the average power and current in the measuring period of time. Also, equation (2) can be normalized, thus obtaining a figure independent of the C_{DD} tolerance, parasitic capacitances and so on. By making such calculation for each input change, it is possible to calculate the energy consumed by a given sequence of input changes, by adding the energy consumed by each input change in the sequence.

Several side effects have to be taken into account to minimize errors [10]. However, this method of measurement presents an important advantage: The

feasibility to measure the energy consumed by a circuit in a single input change. As a main drawbacks, there are the problems derived from the EMI sensibility, and the accurate calibration of the capacitor C_{DD} , if absolute measurements are required.

III. MEASUREMENTS USING THE DESCRIBED METHODS

Some experiments have been performed using a 8×8 bits cell-based multiplier to check the usefulness of each approach, as well as to know the practical limits of each technique. The IC implements five instances of an 8×8 bits Guild array multiplier [20]. It was designed to measure the relation between logic depth and consumption as is described in [23]. Each circuit block has its own separate clock tree and pipeline registers [21]. Each instance has the same inputs but a different maximum number of cells between successive pipeline register (this number is defined as the *multiplier granularity* β). That is, in the instance with granularity 1, the logic depth between two pipeline registers is one cell, if it is 2, there are two cells between two successive pipeline registers, and so on [22][23].

The measuring board (see Figure 2) has four jumpers J1-J4 that allows selecting each one of the different methods to measure the IC consumption. For instance, by connecting J1 to an ammeter, it is possible to measure the average current. Connecting J2, the drop voltage in the resistor R can be measured. To use the C-based method, jumpers J3 and J4 must be connected. The PMOS transistor and the transmission gate TG work as a single electronically controlled switch that minimizes the undesirable charge injection produced each time the PMOS is opened and the node V_{VDD} remains floating. The measuring board includes a microcontroller, which manages the proper open/close timing of the "composite" switch. External signals also allow synchronizing the opening and closing operations from an external equipment. Also, the capacitor C_{DDext} (decoupling capacitor) must be connected.

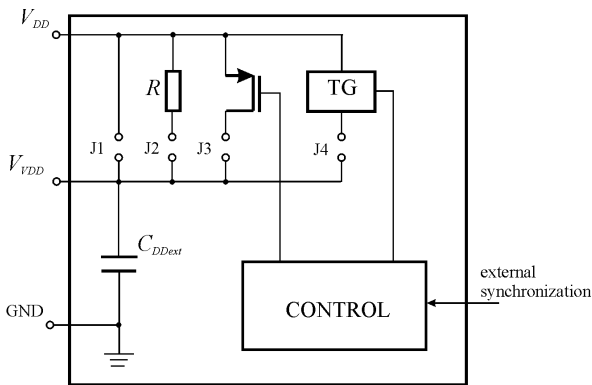


Figure 2. Measuring board.

A. Experiments with the multiplier IC

The block diagram of the board where the multiplier is mounted is shown in Figure 3. The multiplier IC has one pin connected to core- V_{DD} and one separated pin connected to pads- V_{DD} , allowing an independent measurement of the core or pad consumption. The input patterns were applied from a 16 bit Linear Feedback Shift-Register (LFSR) controlled by an independent clock source and the multiplier output pins were connected to a Logic Analyzer to test the correctness of the multiplication.

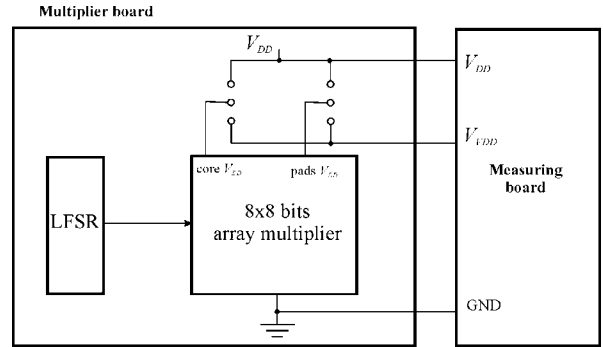


Figure 3. Block diagram and connection of the multiplier board.

B. Results using an ammeter

The measurements were made by applying an infinite loop of $2^{16} - 1$ pseudo-random input patterns for five clock frequencies and for the five granularities. The results for power consumed from core- V_{DD} by the clock signal and datapath are shown in Figure 4 and Figure 5, respectively, as a function of granularity (β) and clock frequency. Results from pads- V_{DD} are shown in Figure 6. In this case, power consumption is independent of granularity, as expected.

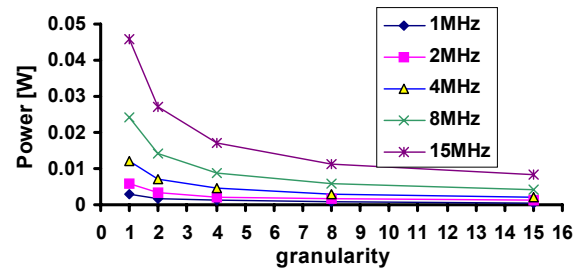


Figure 4. Clock consumption.

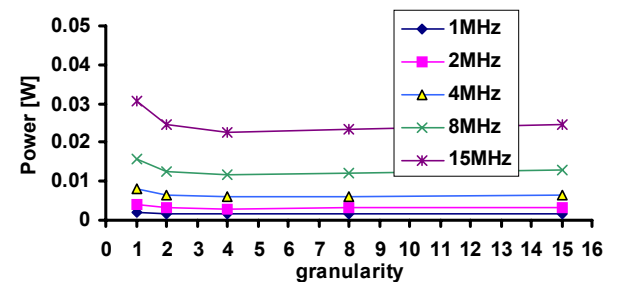


Figure 5. Datapath consumption.

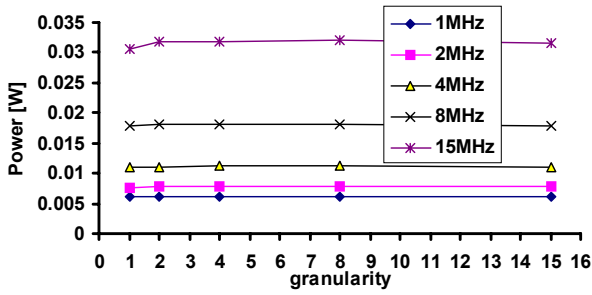


Figure 6. Pads consumption.

C. Results with C-based measurements

The external capacitance was $C_{D_{Dext}} = 10$ nF and a set of results were obtained.

For instance, by disabling the LFSR the multiplier clock consumption can be measured. Figure 7 shows a superposition of drop voltages that represents this consumption for $\beta = 1, 2, 4, 8$ and 15 . In this experiment, the switch is alternatively closed and open. The period of time when the switch is open is $51.4 \mu s$ and at the end of this period the drop voltage ΔV can be measured and the energy and power easily calculated. As the multiplier clock is a free running signal, power calculated using this method is easily comparable with ammeter measurements.

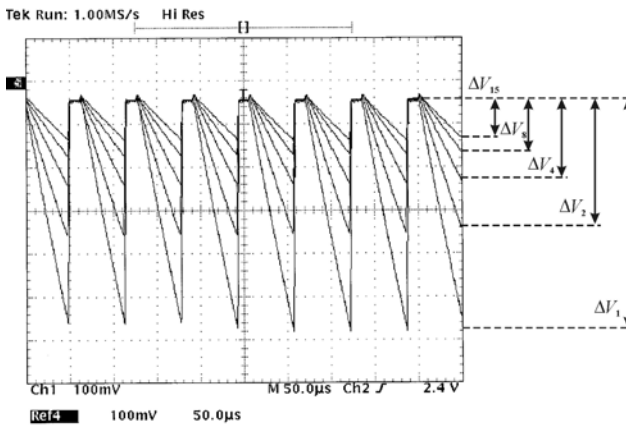


Figure 7. Waveforms for granularities = 1, 2, 4, 8 and 15. Clock frequency = 200 KHz and $C_{D_{Dext}} = 10$ nF.

As shown, it is clearly visible the consumption due to the different switching capacitance of the clock tree associated to each granularity.

Other experiments are devoted to measure the power of sets of multiplications. For instance, Figure 8 shows the drop voltages produced for 4 non-consecutive sets of 50 multiplications. Notice the changes in the slope and shape of the decaying voltages which are due to the different consumption associated to each set and also to each individual multiplication.

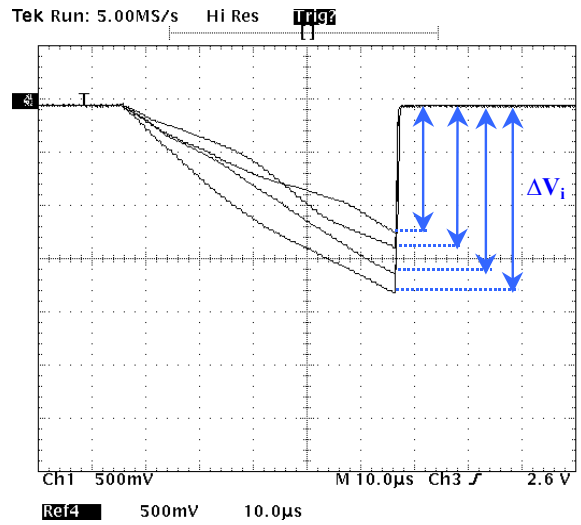


Figure 8. Drop voltages of four sets of 50 multiplications. Clock = 1MHz, $\beta=15$.

Figure 9 shows other view of the differences in the consumption of successive sets of input patterns. There, we can see the drop voltages associated to seven consecutive sets of 10 multiplications.

Even the power consumed by a single transition can be measured as is shown in Figure 10 for a single sequence of five multiplications. Notice the wealth of details that can be observed in this figure. There, the big drop voltages correspond to the rising clock edge, when the multiplication is performed. Thus, this drop voltage reflects the consumption of clock (rising edge) + logic. On the other hand, the small drop voltages correspond to the consumption associated with the falling clock edge. As the register content doesn't change in this clock edge, the drop voltages reflect only the clock consumption (falling edge).

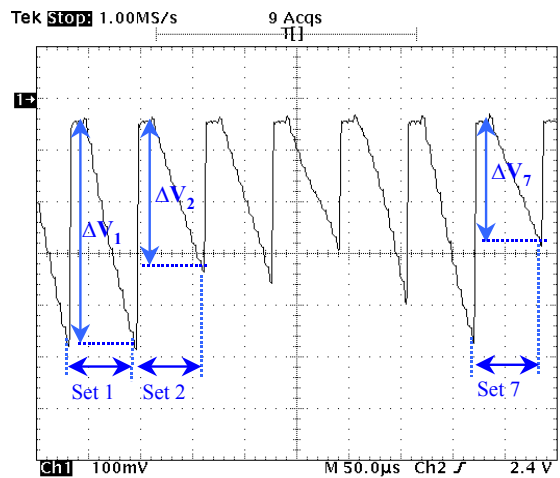


Figure 9. Seven successive sets of 10 multiplications. Clock = 200 KHz, $\beta=15$.

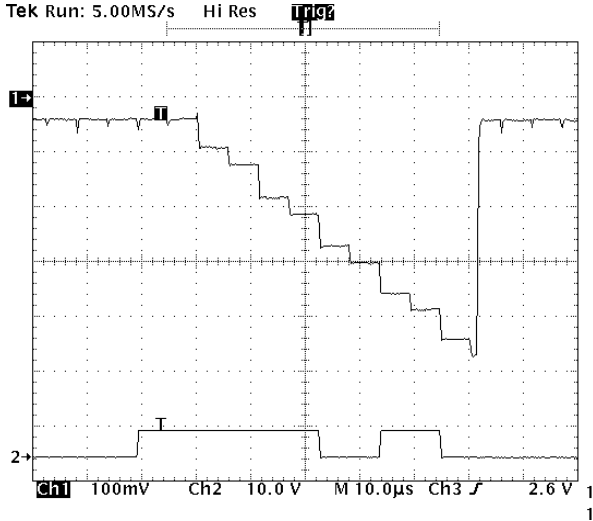


Figure 10. Five consecutive multiplications. Clock = 90 KHz, $\beta=1$. Bottom signal is the LSB of the result of each multiplication.

By capturing, from an oscilloscope and the proper software, waveforms like the one shown in Figure 10, it is possible to build a histogram of the IC power consumption for many sets of input patterns (Figure 11). This information is useful, for instance, for testing [24] but also for other purposes as the validation of the maximum, average or RMS power IC specifications.

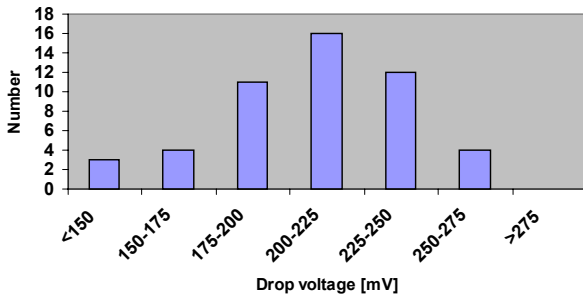


Figure 11. Histogram of 50 sets of 5 multiplications. Clock = 100 KHz, $\beta=15$.

D. Comparisons between methods

To compare C-based and ammeter measurements it is necessary to extract the average consumption of the multiplier from many C-based measurements with random sets of multiplications. This was made by averaging the consumption of 50 sets of five multiplications and of 50 sets of twenty five multiplications. For clock+datapath power, with $\beta=15$, results are shown in Figure 12.

Other experiment is to compare the C-based and ammeter measurements of the clock power. At granularities $\beta=1, 2, 4, 8$ and 15 and for frequencies from 1 MHz to 15 MHz,

the results are shown in Figure 13, where A-xMHz means ammeter measurements and C-xMHz C-based measurements.

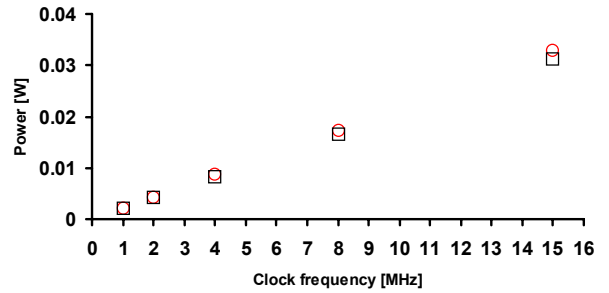


Figure 12. Datapath power. Circles: ammeter. Squares: C-based measurements. $\beta=15$.

As can be seen, results from expression (2) agree fairly well with ammeter measurements. Thus, C-based averaged results can be taken with the same confidence as ammeter measurements. However, they present the great advantage that are collected without applying repetitive input patterns. From the results, we can conclude that this method has a great flexibility to measure power in short periods of time, being reliable for power measurements in CMOS circuits.

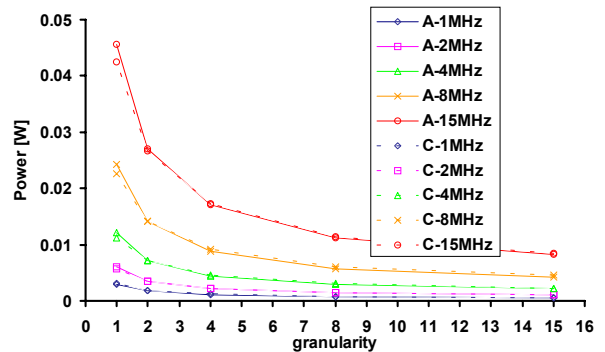


Figure 13. Comparison of clock power between ammeter and C-based measurements.

IV. CONCLUSIONS

A method that averages i_{DD} current (ammeter) is the simplest way to estimate the average consumption of an IC. However, when measuring the power in a transition between two input patterns, or between microprocessor instructions, an average measurement is no longer useful. New methodologies capable to measure the power consumed in short periods of time must be used. In this paper, results from one of them (the C-based method) have been reported. They show: (a) C-based method gives the same results as the conventional ammeter method for long measurement time, and (b) it is able to give information on the power consumption in short or very short (a single input change) period of time. An additional feature of this

method is that their results can be normalised thus obtaining a reading independent of the precise determination of the sensing element.

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