Experimental study on the power consumption of timers embedded into microcontrollers

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***Abstract*—An experimental study on the current consumption of timers embedded into microcontrollers is presented in this work. The study is carried out in two commercial microcontrollers (MSP430FR5969 and ATtiny2313) and the experimental results are compared with the scarce data provided in their datasheets. The sensitivity (expressed in μA/MHz) reported in the datasheet seems to be only applicable if the frequency divider of the timer equals one. Otherwise, such a sensitivity is lower but there is a significant offset component, leading to a higher power consumption at the same operating frequency. The knowledge extracted from this work is expected to provide guidelines to better use embedded timers in low-power sensor applications.**

Keywords—autonomous sensor, current consumption, low-power electronics, microcontroller, digital timer.

I. INTRODUCTION

A microcontroller unit (MCU) is a low-cost programmable processor-based digital integrated circuit widely used in electronic instrumentation [1]. Actually, an MCU can be considered as the mastermind of a smart sensor system. It is the responsible of scheduling and executing different types of tasks, for instance: data acquisition, storing to internal or external memory, data processing, communication to other devices, and displaying. In order to perform these tasks, an MCU has three main blocks embedded [2]: 1) a central processing unit (CPU), which executes instructions sequentially; 2) a memory, which saves the instructions to be executed and the data to be processed; and 3) peripherals, which carry out actions in parallel with the CPU activity. Peripherals can be digital (e.g. a digital timer/counter), analog (e.g. an analog comparator), or mixed (e.g. an analog-to-digital converter, ADC).

Timers are the most popular digital peripherals integrated into MCUs and play an important role in sensor applications, as exemplified via the three following cases:

1) The semiconductor market offers many integrated sensors providing a time-modulated output signal (i.e. a signal whose period, frequency or duty cycle is modulated by the measurand) that need to be measured via a digital timer [3], as shown in Fig. 1(a). Examples of these commercial sensors are: ADXL202E, S9705, TMP03/04, MAX6576/6577, which are intended to measure acceleration, light, and temperature (the last two models), respectively.

2) Classical analog sensors (such as resistive, capacitive, and inductive sensors) are often connected to interface circuits (e.g. an oscillator) that also provide a time-modulated output signal [4]. A particular case of that is the concept of direct sensor-to-MCU interface circuit, where the MCU excites the sensor and this provides a time-modulated signal with

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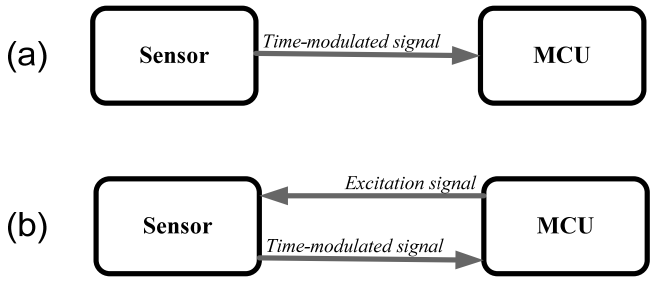

Fig. 1. Sensor providing a time-modulated output signal directly connected to an MCU without requiring an ADC.

information about the resistance [5],[6], capacitance [7],[8], or inductance [9],[10] of the sensor, as represented in Fig. 1(b).

3) In autonomous sensors, the node generally wakes up for sensing and transmitting data once in a while, and the rest of the time is inactive to save energy [11],[12]. In such cases, a timer (operating in a low-power mode, LPM) is in charge to generate an interruption signal to the CPU so as to activate the system and carry out the measurement, with a certain periodicity.

In the previous cases #1 and #2, the accuracy and resolution of the measurement mainly depend on the features of the timer that carries out the time-to-digital conversion [13]. In addition, an ADC is not required for the digitization of the information.

Nowadays, MCU-based measurement systems are expected to be of low power to extend the lifetime of the batteries [1]. Therefore, taking into account that timers are completely involved in the measurement as indicated before, information about the power/current consumption of the timer is of significant importance. Unfortunately, MCU datasheets do not provide many details on that, and often the information is null, as happens, for instance, in the PIC24F family from Microchip. In other commercial microcontrollers, such as the MSP430 family from Texas Instruments, the current consumption of the embedded timer is specified just with a single value, for example: 3 μA/MHz. However, the user of this timer would appreciate more information on that subject, for instance: a) is there only a dynamic component on this current consumption?, b) is this sensitivity (expressed in μA/MHz) applicable throughout the operating frequency range of the timer?, and c) in case of using the internal divider of the timer, is there any difference in the current consumption? These issues and doubts will be clarified next.

This work aims to experimentally evaluate the current consumption of digital timers embedded into commercial MCUs (MSP430FR5969 and ATtiny2313). The knowledge extracted from this study is expected to provide guidelines to better use timers in low-power sensor applications and, hence, to extend the battery lifetime in autonomous sensors [14],[15].

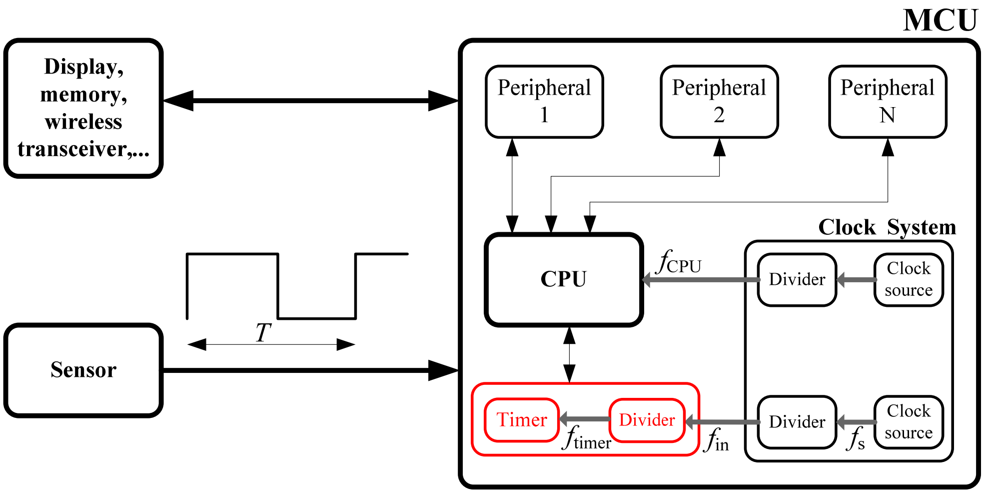

Fig. 2. Block diagram of an MCU-based measurement system for a sensor that provides a time-modulated output signal.

II. System Overview

Fig. 2 shows a block diagram of an MCU-based measurement system for a sensor providing an output signal whose period, frequency, timer interval, or duty cycle is modulated by the measurand. The MCU, by means of the embedded digital timer, measures the sensor output signal and then sends the corresponding digital data to a display, an external memory, and/or a transceiver.

The MCU has different embedded peripherals (e.g. UART, ADC, timer, among others) that carry out actions in parallel with the CPU activity. The peripheral of interest herein is the digital timer, with the following operating principle. Between two events (e.g. two rising edges of the sensor output signal with a period T), the timer counts the number of pulses coming from its reference clock signal, whose frequency is f_{timer}. It is advisable to have $(1/f_{timer}) << T$ so as to improve the measurement resolution. However, the higher the value of f_{timer}, the higher the current consumption of the timer. Therefore, there is a trade-off between resolution and consumption.

The reference clock signals required for the different blocks embedded into the MCU are provided by a clock system. This has several clock sources that can be, on the one hand, either internal or external, and, on the other hand, either of low or high frequency. In the last generation of MCUs, this clock system usually offers a high flexibility to assign to each embedded block its own clock signal coming from a specific clock source. In addition, the frequency provided by these clock sources can be decreased (generally, by a factor that is a power of 2) by a divider (also known as a prescaler). For instance, in Fig. 2, one of the clock sources is connected to a first divider providing a signal at a frequency f_{in}, which is then divided internally into the timer to have a signal at f_{timer} that becomes the reference for the timer.

Low-power MCUs have different LPMs (also called sleep modes) to adapt its current consumption to the needs. The following four operating modes are usually available:

1) *Active mode*: The CPU, memory, and (required) peripherals are active, thus causing the highest current consumption. This is the mode to be used when the CPU executes instructions to, for instance, process the data.

2) *Low-power mode at high frequency* (LPM-HF): The CPU and memory are disabled, but the required peripherals (e.g. a timer) can be active operating at high frequencies (say, units or tens of MHz).

3) *Low-power mode at low frequency* (LPM-LF): Idem 2) but the peripherals operate at low frequency (say, less than 100 kHz).

4) *Ultra low-power mode*: The core supply is disabled, thus stopping the CPU and the peripherals (although in some MCUs a real-time clock can be active) and losing the contents of the volatile memory. This mode provides the lowest current consumption but it has the highest wake-up time and charge.

While the timer is measuring the sensor output signal, there is no need to have the MCU in active mode. In order to reduce the current consumption, it is preferable to operate in either LPM-HF or LPM-LF depending on the required f_{timer}. Assuming that the timer is the only peripheral running, the overall current consumption of the MCU equals

$$I_T = I_{mode} + I_{timer} \quad (1)$$

where I_{mode} is the current consumption corresponding to the LPM selected, and I_{timer} is the current consumption of the timer itself. It is worthy to mention that generally $I_{mode} >> I_{timer}$. The latter contribution (I_{timer}) can be expressed in a first approximation as:

$$I_{timer} = I_{offset} + I_{dyn} \quad (2)$$

where I_{offset} and I_{dyn} are the offset and dynamic components, respectively. The former is expected to be independent of f_{timer}, but it depends on the operating conditions of the divider associated to the timer, as demonstrated next. The latter, however, is expected to increase proportionally with f_{timer}. Accordingly, (2) can be expressed as:

$$I_{timer} = I_{offset} + k \cdot f_{timer} \quad (3)$$

where k is a proportionality constant that relates the current consumption of the timer with its operating frequency. As indicated in the introduction section, the datasheets of MCUs specify either nothing (this is the case for the ATtiny2313) or just the k value. For the MSP430FR5969, k seems to be specified as 3 μA/MHz.

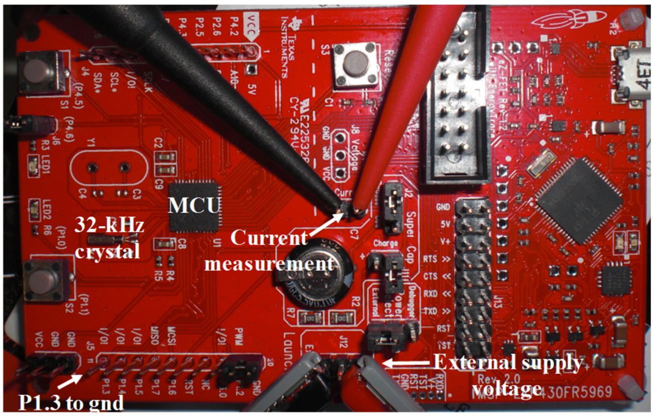

Fig. 3. Measurement setup to characterize the current consumption of the timer embedded into the MSP430FR5969.

III. Materials and Method

The experimental study on the current consumption of embedded digital timers has been performed in two commercial MCUs: MSP430FR5969 from Texas Instruments, and ATtiny2313 from Microchip. The study on the former was more extensive since this is a low-power MCU that offers more flexibility in the selection of the clock and LPM.

The following instrumentation was employed during the experimental tests. An external power supply (Keysight E3631A) provided the supply voltage to the MCU, to be precise: V_{DD} = 3.0 V. A digital multimeter (Agilent 34410A), with an integration time of 100 NPLC, measured the average current consumption of the MCU. A waveform generator (Keysight 33510B) provided a unipolar square signal (at a frequency of 1 kHz) emulating the sensor output signal. All measurements were carried out at room temperature.

The MSP430 was tested using its evaluation board (MSP-EXP430FR5969), as shown in Fig. 3. The timer under test was the 16-bit TA1 (Timer_A type), with a maximum operating frequency of 8 MHz. The following three-step methodology was applied to carry out the experiments:

1) First, the square signal was connected to the P1.3 digital input to assess that the timer was correctly set to measure the signal period. The MCU was by default in an LPM, except when the CPU was attending the interruption generated by the rising edges of the square input signal.

2) After checking that the timer was measuring properly, P1.3 was connected to ground and the interruptions were disabled. In addition, the timer (and the rest of peripherals) were stopped. In such conditions, the MCU was always in an LPM, and the current measurement provided the value of I_{mode}.

3) Idem step #2 but with the timer running continuously, thus measuring the overall current I_T. Then, applying (1), the value of I_{timer} was computed as $I_{timer} = I_T - I_{mode}$.

In step #3, the current consumption was measured at different operating frequencies of the timer, ranging from 4 kHz to 8 MHz. To be precise, three different scenarios were tested, as summarized in Table I. In scenarios #1 and #2, the timer operated at a high frequency and, therefore, the MCU was in LPM-HF (identified as LPM1 in the MSP430 family). On the other hand, in scenario #3, the timer ran at a low frequency and, hence, the MCU was in LPM-LF (identified as LPM3 in the MSP430 family).

The ATtiny2313 was tested using the same instrumentation and methodology indicated before. Its clock source was the 8-MHz internal oscillator. The timer under test was the 16-bit timer 1. While this was running, the MCU was in a LPM called *idle mode*. Three different values of f_{timer} (125 kHz, 1 MHz, and 8 MHz) were tested in two scenarios: a) employing the divider of the clock system and applying $f_{timer} = f_{in}$, and b) employing the divider of the timer and using $f_s = f_{in}$ = 8 MHz.

TABLE I. Scenarios under Test to Evaluate the Current Consumption of the Timer Embedded into the MSP430

Scenario	f_{in}	Divider [a]	f_{timer}
1	8 MHz [b]	1	8 MHz
		2	4 MHz
		4	2 MHz
		8	1 MHz
2	1 MHz [b] [c]	1	1 MHz
		2	500 kHz
		4	250 kHz
		8	125 kHz
3	32 kHz [d]	1	32 kHz
		2	16 kHz
		4	8 kHz
		8	4 kHz

a. It corresponds to the divider associated to the timer.

b. The clock source was the integrated high-frequency digitally-controlled oscillator (DCO).

c. The DCO, with respect to scenario #1, was initially divided by 8 using its specific divider.

d. The clock source was the (on-board) external low-frequency 32-kHz crystal.

TABLE II. Experimental Results Obtained in the Different Scenarios under Test for the MSP430

Scenario	I_{mode}	I_{offset}	k (μA/MHz)
1	109.75 μA	8.22 μA	2.04
2	33.40 μA	1.02 μA	2.04
3	676.9 nA	34.9 nA	2.09
Divider = 1	--	30 pA	3.06

IV. Experimental Results

Table II reports the experimental results of I_{mode} for the MSP430 and the three scenarios under test. As can be seen, I_{mode} clearly increases with increasing f_{in}. These values agree with those specified as typical in the MCU datasheet, to be precise: 115 μA, 35 μA, and 0.6 μA for scenarios #1, #2, and #3, respectively.

Figs. 4, 5, and 6 represent I_T for scenarios #1, #2, and #3, respectively. For the three cases, I_T increases proportionally with f_{timer}, as expected. Then, using the values of I_{mode} reported in Table II, I_{timer} was computed and represented in Figs. 7, 8, and 9 for scenarios #1, #2, and #3, respectively. A straight line was fitted (via the least-squares method) to the experimental data in Figs. 7-9 to find the values of I_{offset} and k expressed in (3), and these are also summarized in Table II. Accordingly, k is around 2 μA/MHz for the three scenarios, and I_{offset} depends on f_{in} with a sensitivity of around 1 μA/MHz.

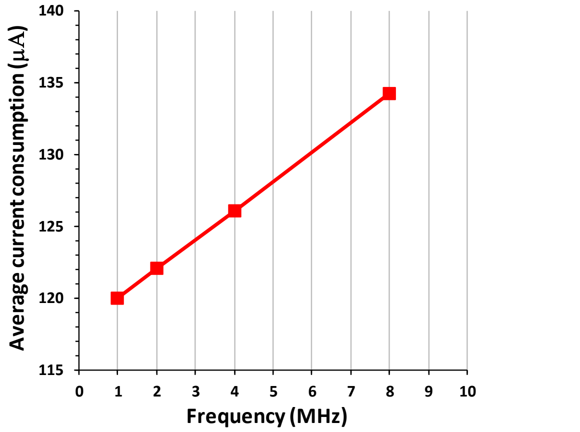

Fig. 4. Overall current consumption (I_T) versus f_{timer} in scenario #1 for the MSP430.

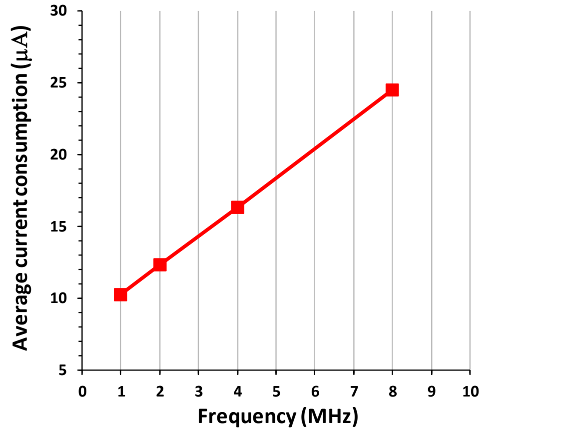

Fig. 7. Timer current consumption (I_{timer}) versus f_{timer} in scenario #1 for the MSP430.

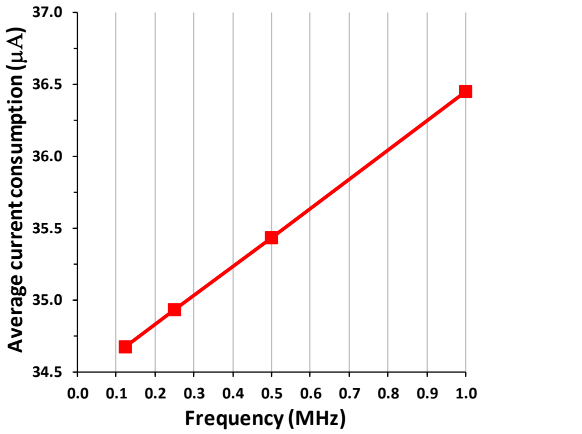

Fig. 5. Overall current consumption (I_T) versus f_{timer} in scenario #2 for the MSP430.

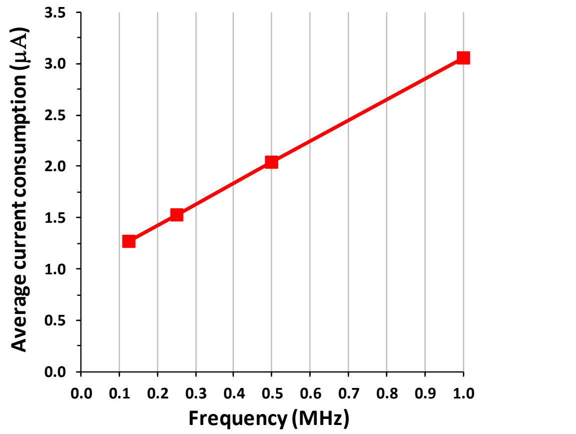

Fig. 8. Timer current consumption (I_{timer}) versus f_{timer} in scenario #2 for the MSP430.

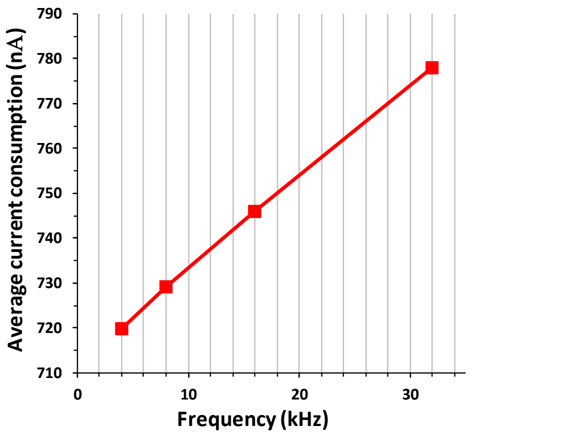

Fig. 6. Overall current consumption (I_T) versus f_{timer} in scenario #3 for the MSP430.

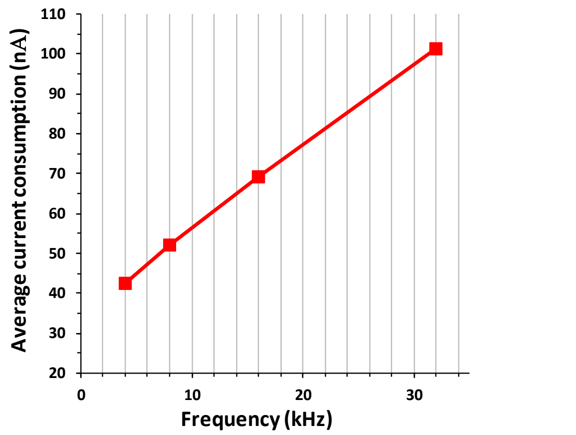

Fig. 9. Timer current consumption (I_{timer}) versus f_{timer} in scenario #3 for the MSP430.

The values of I_{timer} shown in Figs. 7-9 corresponding only to the cases where the divider (of the timer) equals 1 (rightmost values) were also represented together versus frequency. The result is shown in Fig. 10 and the fitting values are also reported in Table II. In such conditions, the sensitivity (3.06 μA/MHz) is almost equal to that specified in the datasheet, whereas the offset component (30 pA) is negligible. Therefore, the data in the datasheet seem to correspond to the case where the divider of the timer equals 1.

The experimental results for the timer embedded into the ATtiny2313 are shown in Fig. 11. Here, I_{timer} is directly represented versus f_{timer} for the two scenarios indicated in Section III: a) when using the divider of the clock system (in red continuous line), and b) when using the divider of the timer (in blue dashed line). In the former case, the response is quite similar to that represented before in Fig. 10, but with a higher sensitivity (7.3 μA/MHz). In the latter case, the sensitivity is lower (4.9 μA/MHz), but there is a significant offset component (20 μA), as also occurs in Fig. 7.

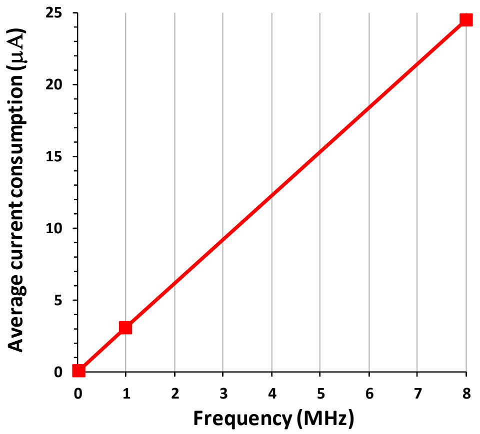

Fig. 10. Timer current consumption (I_{timer}) versus f_{timer} when the divider of the timer equals 1 for the MSP430.

V. Discussion

According to the experimental results reported in Section IV, the expression of I_{timer} in (3) needs to be reformulated:

$$I_{timer} = \begin{cases} k_1 \cdot f_{timer}, \text{ if } f_{timer} = f_{in} \\ k_2 \cdot f_{in} + k_3 \cdot f_{timer}, \text{ if } f_{timer} < f_{in} \end{cases} \quad (4)$$

where k_1, k_2, and k_3 are proportionality constants. For the MSP430, we have $k_1 \approx 3$ µA/MHz, $k_2 \approx 1$ µA/MHz, and $k_3 \approx 2$ µA/MHz; in the MCU datasheet only the first parameter is specified. For the ATtiny2313, we have $k_1 \approx 7.3$ µA/MHz, $k_2 \approx 2.5$ µA/MHz, and $k_3 \approx 4.9$ µA/MHz, which are about 2.5 times higher than those found in the MSP430.

The fact of having the divider of the timer operating at $f_{in} > f_{timer}$ generates: 1) a lower value of the sensitivity to f_{timer} (i.e. $k_3 < k_1$), but 2) an extra current consumption depending on f_{in} that appears as an offset component. Taking into account the values of k_1, k_2, and k_3 reported before, the first scenario in (4) is more favorable in terms of power consumption. Therefore, the clock system should directly provide to the timer a reference clock signal with the required value of f_{timer}, without needing the intervention of the associated divider. For example, if the timer needs to operate at 1 MHz, it is preferable to select $f_{in} = 1$ MHz and a divider of 1 rather than $f_{in} = 8$ MHz and a divider of 8. In this particular case, I_{timer} becomes more than three times smaller for both MCUs under test. Moreover, in such conditions, I_{mode} is significantly lower.

VI. Conclusions

In order to improve the performance of MCUs in terms of power and, therefore, to extend the battery lifetime in autonomous sensors, an experimental study on the current consumption of embedded timers has been carried out. According to the experimental tests reported herein, the value of sensitivity of the current consumption with respect to frequency (expressed in µA/MHz) provided in some datasheets is only applicable when the divider of the timer equals 1. Otherwise, such a sensitivity is lower, but there is a significant offset component that depends on the frequency applied to the timer before its own divider. Therefore, it is clearly preferable if the clock system directly provides to the timer the reference clock signal with the required value, without needing the intervention of the associated divider.

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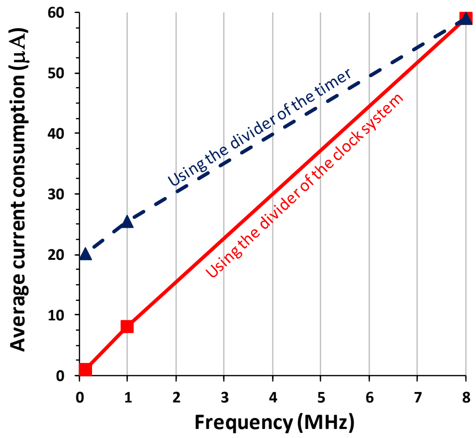

Fig. 11. Timer current consumption (I_{timer}) versus f_{timer} for the ATtiny2313.

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