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WIRELESS SENSOR NODE WITH LOW-POWER SENSING

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Abstract. *Wireless sensor network consists of a large number of simple sensor nodes that collect information from external environment with sensors, then process the information, and communicate with other neighboring nodes in the network. Usually, sensor nodes operate with exhaustible batteries unattended. Since manual replacement or recharging of the batteries is not an easy, desirable or always possible task, the power consumption becomes a very important issue in the development of these networks. The total power consumption of a node is a result of all steps of the operation: sensing, data processing and radio transmission. In most published papers in literature it is assumed that the sensing subsystem consumes significantly less energy than a radio block. However, this assumption does not apply in numerous applications, especially in the case when power consumption of the sensing activity is comparably bigger than that of a radio. In that context, in this work we focus on the impact of the sensing hardware on the total power consumption of a sensor node. Firstly, we describe the structure of the sensor node architecture, identify its key energy consumption sources, and introduce an energy model for the sensing subsystem as a building block of a node. Secondly, with the aim to reduce energy consumption we investigate joint effectiveness of two common power-saving techniques in a specific sensor node: duty-cycling and power-gating. Duty-cycling is effective at the system level. It is used for switching a node between active and sleep mode (with the duty-cycle factor of 1%, the reduction of in dynamic energy consumption is achieved). Power-gating is used at the circuit level with the goal to decrease the power loss due to the leakage current (in our design, the reduction of dynamic and static energy consumption of off-chip sensor elements as constituents of sensing hardware within a node of is achieved). Compared to a sensor node architecture in which both energy saving techniques are omitted, the conducted MATLAB simulation results suggest that in total, thanks to involving duty-cycling and power-gating techniques, a three order of magnitude reduction for sensing activities in energy consumption can be achieved*.

Key words: *wireless sensor networks, sensor elements, power cosumption, duty-cycling, power-gating*

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1. INTRODUCTION

Wireless sensor networks, WSNs, consist of a large number of sensor nodes, SNs, deployed randomly (or in some specific places) within a restricted area. Applications for WSNs range from consumer electronics, military target tracking, industrial monitoring, health monitoring, home environmental control, forest fire detection, greenhouse monitoring, etc [1]. Since SNs are usually battery-powered devices and operate unattended for a relatively long period of time, maximizing energy efficiency of SN is critical [1], [2]. Typically, this constraint is imposed by the limited capacity of the SN's battery [3]. To optimize the design of SN, an accurate power consumption model, which allows a good forecast of battery lifetime, is needed. In order to extend the lifetime of SN, a wide variety of techniques for minimizing SN's energy consumption have been proposed in literature [4], [5], [6]. Some of them deal with saving energy at MAC (*Media Access Control*) level [7], [8], [9], others at routing protocols [10], [11], [12], third with dissemination data aggregations or fusion [13], [14], fourth with involving novel architectures that utilize the optimized radio and digital parts [15], [16], [17], fifth employ on-chip power gating in order to reduce the static power loss [18], [19]. To address the problem of power saving within a SN, two promising approaches based on dynamic voltage scaling [20], [21] and power gating [22], [23] are used. The first represents a useful solution for high performance SNs, while the second is effective in SNs operating with low duty-cycle where the SNs alter between *off* and *on* states to minimize the energy consumption [22], [16], [17].

SNs, as constituents of WSN, are capable of performing computation, communication and sensing of oriented tasks. Accurate prediction of the SN lifetime requires an accurate energy consumption model and estimation of sensor activities. The energy model which accurately reveals the energy consumption of SN is an extremely important part of the protocol development, sensor node micro-architecture design (radio, microcontroller and sensing subsystem), battery capacity, and performance evaluation in WSNs. There have been various attempts to model SN energy consumption. In [24] a model that includes MCU processing and radio transmission and receiving is considered. In [25] and [26] sensing activities including sensor sensing, sensor logging and actuation are omitted. In [23] a comprehensive energy model for WSN that takes into account all key energy consumption sources within a SN is described. By studying component energy consumption in different SN states the authors in [27] present the energy models of the SN core components. In [28] a combination of two complementary approaches intended to reduce the energy consumed by a sensor node, duty cycling (waking up a sensing board only for the time needed to acquire a new set of samples and powering it off immediately afterwards) and adaptive sensing strategy (a huge computation approach which is able to dynamically adapt the sensor activity to the real dynamics of the process) is proposed.

As is reported in [4], [29], [30], on time radio operation dominates the system power budget for order of magnitude in respect to the other two operations (data processing and sensing) combined, even when the radio module operates at a low duty cycle (approximately from 1 to 2 %). Since data processing and sensing activities account for a small fraction of power budget, the authors suggest that SN's lifetime improvement requires a significant reduction in communication activities. However, our current research shows that by using a more realistic power consumption model of the sensing subsystem which clearly separates the power consumption of each sensor element, it is possible to derive clearer results which provide insight into which sensing elements are limiting the WSN performance. In other words, in this work we extract the impact of sensing hardware on the total power consumption and point to the fact that the contribution of the sensing subsystem to the total power consumption of the SN cannot be neglected (ignored) especially in the case when WSNs with medium- (high-) energy consuming sensor elements are used. In other words, the main novelty presented in this paper deals with involving a joint combination of two common power saving techniques (duty cycling and power gating) during the operation of a sensor node. Due to space constraints this paper concentrates only on sensing subsystem power consumption. For discussions on wireless communications and data processing activities, readers can refer to the following papers [6], [27], [30], [31].

The rest of the paper is organized as follows. In Section 2, sensor node architecture is involved and operating functionalities of all constituents are identified. In addition, details which deal with specifics of connectivity at sensor elements and the power supply are given. Section 3 concentrates on sensor node energy profile. Justification of involving two power saving techniques, duty-cycling, at system level, and off-chip power-gating, at sensing subsystem level is discussed, too. Section 4 deals with power estimation. Also, the energy profile during initialization and sensing activities is calculated. Section 5 concludes the paper.

2. Sensor Node Architecture

An overall hardware structure of a *SN* is presented in Fig. 1

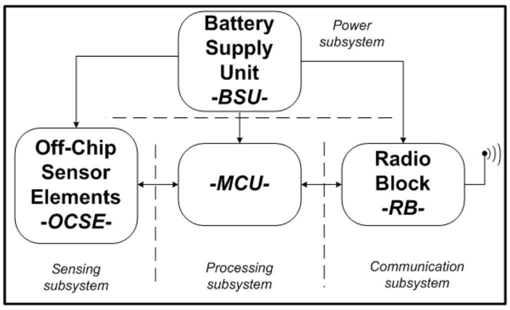

Fig. 1 Overall block scheme of a sensor node.

The SN consists of several building blocks:

a) *MCU*- referred as a processing subsystem, controls the operation of all constituents within the *SN* and performs data processing. The *MCU* includes microcontroller and memory for local data processing. Most existing processing subsystems employ microcontrollers, notably Texas Instruments' MSP430, Intel's Strong ARM, or Atmel's AVR. These microcontrollers enable some of their internal components to be turned-off completely when they are idle or sleep. CMOS compatible memories including static random-access memory, SRAM, and embedded dynamic random-access memory, DRAM, permit SNs to perform more complex digital signal processing algorithms (collection, aggregation, and compression) and log more sensor data.

b) Off-Chip Sensor Elements (*OCSE*) – called a sensing subsystem, implemented as a set of passive and active sensors (digital or analog) convert input information from the external environment into electrical signals. In most applications, wireless SNs are used for monitoring light, pressure, vibration, flow rates in pipelines, temperature, ventilation, electricity, etc. Commonly, sensor elements generate voltage or current signals at their outputs. These signals are first amplified (conditioned) and then digitized with an analog-to-digital converter, ADC, before data are digitally processed, stored and transmitted.

c) Radio Block (*RB*) – implemented as a short range transceiver which provides wireless communication with the host or SNs within a WSN. The power consumption of a transceiver can be reduced both at: i) the circuit level by developing more energy-efficient RF circuits (using weak inversion operation in the RF building blocks, RF-MEMS passive components, ultra-wideband transceivers which send narrow pulses of energy to transmit data), and ii) at a system level by using RF communication (including shortening the communication distance, minimizing the amount of data sent over the RF link or using energy-efficient communication protocols, or powering down the transceiver during idle periods, i.e., using a duty-cycling concept). For more details about this problematic see reference [30].

d) Battery Supply Unit (*BSU*) – is a part of the power subsystem acting as a controllable unit which individually switches *on/off* the power supply of each SN's building blocks. *BSU* is responsible for providing the right amount of supply voltage to each individual SN hardware component. A bulky battery is included in the *BSU* to power the SN's subsystems. The *BSU* is a very important building block of the SN intended to improve the WSN lifetime, and therefore numerous techniques based on the efficient exploitation of energy resources have been introduced with the aim to prolong the WSN lifetime. For more details see [31]. As we have already mentioned, currently, SNs are powered by batteries. However, batteries are characterized by several disadvantages, including: i) the need to either replace or recharge then periodically; and ii) being of a big size and weight compared to SN electronics. One promising solution to overcome these drawbacks is to harvest energy from the environment to either recharge a battery or even to directly power the SN. As is presented in Table 1, the energy harvesting circuits can be classified into two groups.

Table 1 Classifications of energy harvesting circuits

energy source	type of energy
human	kinetic, thermal
environment	kinetic, thermal and radiation

For more details see references [32], [33]. Among the most popular harvesting circuits used in SNs are those based on converting solar energy, as a radiation type of energy. The main advantages for using solar energy are as follows: i) it is excellent in remote or difficult access location; ii) it is a totally clean and renewable source; iii) for supplying small current loads such as SNs; and iv) in any country the use of solar energy like this is feasible throughout the entire territory.

Depending on the specific application, SNs may also include additional components like the location finding system to determine their position, a mobilizing unit to change their location, etc. More details about SN architectures and functionalities of their building blocks can be found in [34]. Different types of communication interfaces, such as parallel and serial buses interconnect the aforementioned subsystems. Among serial buses the most frequently used interconnects are SPI (Serial Peripheral Interface) and I^2C (Inter-Integrated Circuit). A SPI is a preferable design solution for high-speed, while I^2C for low-speed communication.

Today's wireless SN is a simple device, and its components that make up its subsystems are commonplace off-the-shelf components usually located on a printed circuit board.

2.1. Connecting sensor elements

Within an SN architecture, sensor elements can be implemented as:

a) on-chip constituents - typical for future generation (advanced system-on-chip, SoC design) of wireless SN designs, and
b) off-chip constituents - SN composed of discrete components typical for currently common market available (on-the-shelf) wireless SN systems.

The recent progress in ultra-low power circuit design is creating new opportunities in SN architectures with on-chip for temperature and image sensor elements [35], [36]. Important advances have been made to achieve millimeter-scale SN and standby power as low as 30 *pW* [37], or microwatt successive approximation register SAR-ADC with the figure of merit down to 4.4 *fJ* per conversion step [38], but many design challenges remain yet open.

Our design choice is based on the use of the off-the-shelf components. Such solution implies that sensor elements are of the off-chip type, i.e., externally connected components to the ADC (in our proposal ADC is a constituent of the MCU). In this paper, by involving adequate energy models, we will consider implementations of duty-cycling and power-gating techniques and investigate how to reduce the dynamic and static power when both power saving approaches are used.

2.2. Power supply subsystems

In a SN, each subsystem/circuitry requires different supply voltage for its operation. For example, in most common currently used designs, the MCU and other digital circuits can run at supply voltage which ranges from 3 *V* to 1.8 *V*. Analog components such are RF transceiver and sensor elements, in order to provide correct operation and noise margins, require higher supply voltages which range from 1.2 *V* to 2.5 *V*. Batteries (Lithium 3.3 *V*−4.2 *V*) incorporated as power sources in SNs are limited in their output voltage by their chemistries, and their voltages degrade with use. Since battery voltages do not usually match the desired subsystem/circuit supply voltages, switching dc-to-dc or linear low drop-out voltage regulator power converting electronics is used. Bearing in mind that a current consumption of SN is within a range of several tens of *mA* (in active mode) down to several μA (in sleep mode) the power electronics must be specifically designed for a low-power operation. As a preferable solution, we propose linear low drop-out voltage regulator for powering the SN subsystem. In general, for powering low-level of power devices, such as SN, the linear low drop-out voltage regulator has a better performance in respect to dc-to-dc converter (dc-to-dc converters are usually designed for high output power levels and do not efficiently convert the low level of the power needed by SNs [30]).

Before we start describing the principle of operation of *BSU* (see Fig.1), it is necessary to first explain the meaning of the following two terms: power gating and duty cycle. Power gating is a technique used in integrated circuit design to reduce power consumption, by shutting *off* the current to blocks of the circuit that are not in use [39]. A duty cycle is the percentage of one period in which a signal is active. A period is the time it takes for a signal to complete an on-and-off cycle [40]. In our case, the time interval during which the SN is *on* or *off* is known as its active, T_{ON}, and inactive (sleep) time interval, T_{OFF}, respectively. According to the previous, the duty cycle (*DC*) is defined as:

$$DC = T_{ON} / (T_{ON} + T_{OFF}) \quad (1)$$

The focus of our interest in this paper is the implementation of a power distribution system, as part of *BSU* which relates to switching *on/off* both the sensor elements within *OCSE* and the transceiver (as a constituent of *RB*) in a timely defined manner. By using a combination of a duty-cycling which relates to powering the *SN* at a system level, and power-gating technique intended to power the SN at a sensor element level, a significant saving of dynamic and static power during *SN* operation can be achieved. A global scheme of *BSU* is presented in Fig. 2. It consists of:

a) Battery – acts as a main energy source for powering SN's functional unit;

b) Dual-Channel Controllable *LDO* Regulator – implemented as single-input (*in1*) two-output (*out1* and *out2*) linear low drop-out voltage regulator. By setting the control enable signals *en1* and *en2* to logic one/zero, the voltage at the outputs *out1* and *out2* can be switched on/off. At the output *out1* voltage is always present, since *en1= {1}*, while voltage at the output *out2* can be switched *on/off* by setting *en2= {1/0}*, respectively. Power-gating for OCSE is achieved by switching *on/off* the pin *out2* (output of the LDO, see Fig. 2).

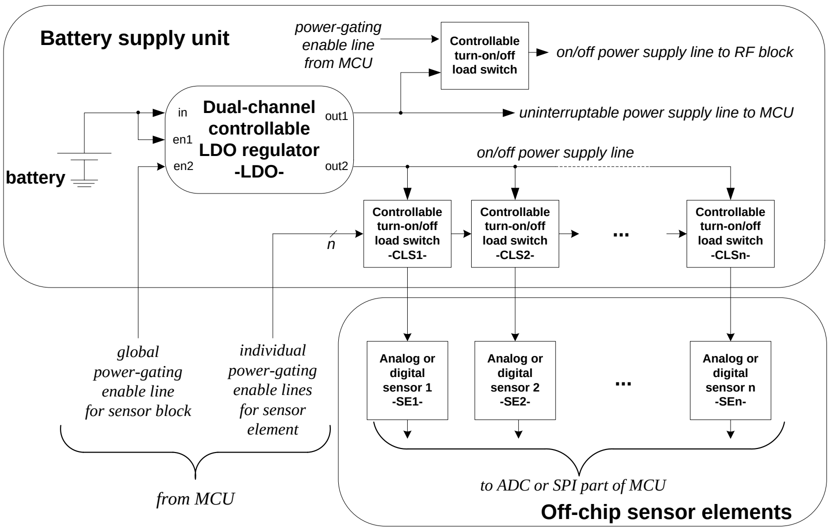

Fig. 2 Power distribution system of sensor node

c) Controllable Turn *On/Off* Load Switches (*CLSs*) – each *CLS* is implemented as a P-channel, or N-channel MOSFET transistor which can be individually switched *on/off*. In this manner power-gating at a local control level within the sensing subsystem is provided (i.e., *MCU* can separately switches *on/off* the power supply voltage for each sensor element by setting a corresponding control line to logic one/zero).

3. Energy Profile

The proposed WSN considered in this paper is composed of several SNs deployed in a restricted area. This system is primarily intended to monitor scalar values like acceleration, space orientation, and audio signals. In this type of application almost all of the mentioned sensor measurements do not need to be taken continuously which implies that the environmental conditions can be periodically sampled. For example, taking one sample per two minutes could be adequate to monitor temperature, pressure, light, humidity, etc. Power management is an efficient way to conserve energy in WSN. The crucial idea of power management is to dynamically make the SNs inactive in order to reduce their energy consumption, i.e. to decide when a SN should go to the inactive state and the amount of time to stay so. Most power management strategies proposed in literature [31], [41] assume that data acquisition (sensing `activity`) consumes significantly less energy than wireless data transmission [4]. However, in a large number of practical applications, this assumption does not hold, especially in the case when the power consumption of active (not passive) sensor element can be comparable to that of the communication subsystem. Similar problem was considered in reference [42], [43]. In order to cope with this challenge in an effective way, we propose to implement the power management concept into two levels, system and component level, respectively. At the first level, a duty cycle technique is used, by which we identify the idle and active time periods of SN's constituents. At the second level, power gating technique is used, by which unutilized sensor elements are switched off while the analyzed sensor element is switched on. In other words, our goal is that during most of the time, the inefficient (unnecessary) power consumption of sensor elements due to not-optimal configuration of hardware and software components is significantly reduced.

Let us note that a sensor node as an electrical system is time invariant, i.e. the total energy consumption depends on its individual energy consumption components. Having this in mind, in the sequel we will separately analyze the effects and benefits of implementation of duty-cycling and power-gating techniques on energy consumption only for the sensing subsystem as SN constituent.

3.1. Duty cycling

Duty cycling is a well-known technique for minimization of power consumption in wireless SNs. The main idea behind this is clear: keep hardware (sensing-, communication-, and some parts of power- and processing-subsystems – see Fig. 1.) in a low power sleep state, except during instances when the hardware is needed. Many realizations of duty-cycling technique allows even the *MCU* to be put into a low power state for long time periods, while its internal or external clock tracks the time in order to trigger a later wake-up. The wake-up time is the time from activation of the interrupt signal (by a Real Time Clock, *RTC*, circuit) to the beginning of an interrupt service routine. Let us note that, all activities which deal with the duty cycle operation (switching into different power modes the transceiver, *MCU*, and low-drop out regulator) are performed by the *MCU* under software control.

The total energy consumed by SN, E_t, depends on the dynamic (active), E_d, and static (leakage) power loss, E_s.

$$E_t = E_d + E_s = DC * T_{LF} * P_d + T_{LF} * P_s \tag{2}$$

where, $0 < DC < 1$, T_{LF} is the lifetime of a *SN*, and P_d and P_s correspond to dynamic and static power, respectively. From Eq. 2, the portion of energy lost due to the leakage is

$$\frac{E_s}{E_t} = \frac{1}{1 + DC\frac{P_d}{P_s}} \tag{3}$$

The ratio P_d / P_s is technology dependent and is proportional to the MOS transistor channel properties. Similarly as in [18][1], taking the corresponding P_d / P_s for three different CMOS technologies, we have calculated the impact of energy loss in respect to the total energy consumption in terms of a *DC* factor. The obtained results are presented in Fig. 3.

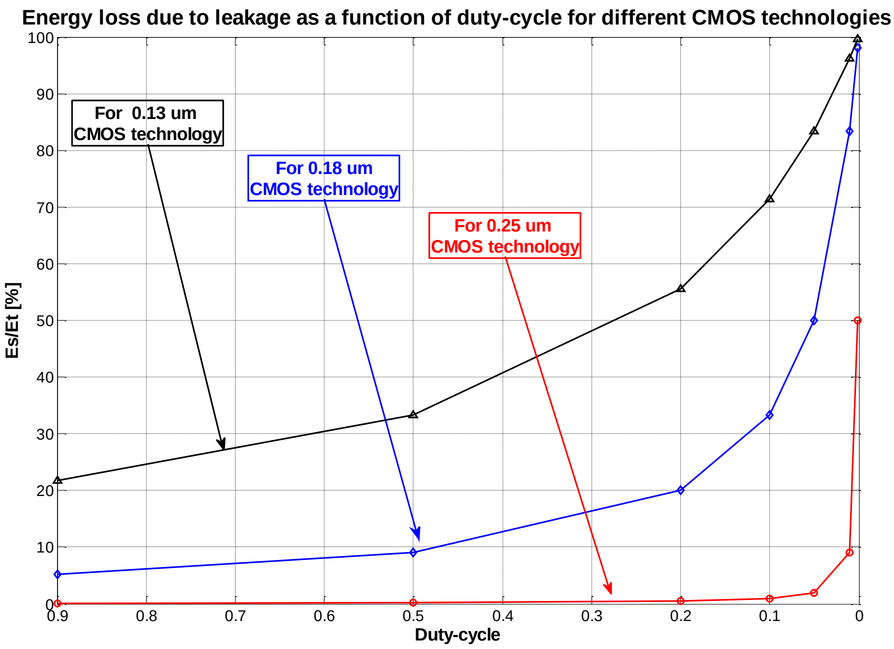

Fig. 3 Energy loss due to leakage as a function of duty-cycle for different *CMOS* technologies

For digital components of the *SN*, similarly as in reference [44], we assume that P_d / P_s is ≈ 1000 for 0.25 μm technology, ≈ 20 for 0.18 μm technology, and ≈ 4 for 0.13 μm technology. By analyzing Fig. 3 we can conclude the following:

[1] For the sake of clarity, the reference [18] defines the power consumption in active state ($P_a = P_d + P_s$) and the power consumption in inactive state ($P_i = P_s$)

1. With CMOS technology, scaling the energy loss due to static power increases. In other words, the static power loss is comparable to dynamic power loss (high amount of power is lost due to the leakage currents of CMOS circuitry [45]).
2. In standard applications a DC factor of the *SN* is low ($<1\%$), which makes the total system power dominated by the standby power, i.e. static power losses.
3. Theoretically, better energy efficiency (achieved by decreasing E_D) can be obtained by further decreasing the DC factor. However, in this case the influence of the clock system, as components of SN, on the overall time synchronization accuracy of the WSN becomes critical [46], [47].

Namely, the impact of variations in environmental temperature on clock drift in highly duty-cycled wireless SNs is emphasized [47].

3.2. Power gating

With the aim to switch-*off* the leakage currents of inactive sensor elements we decide to implement power-gating, because as a design technique it is primarily used to reduce the overall static power loss in a circuit [48]. The efficiency of power gating depends on the activity profile of *SN's* components. By adapting an event-driven control mechanism we will first present the activity model of a *SN* at a general level (see Fig. 4), and then in Section 4 we will study energy consumption issues of sensor elements units (constituents of the sensing subsystem – see Fig. 2) that switch-*on* and –*off* during the sensing period.

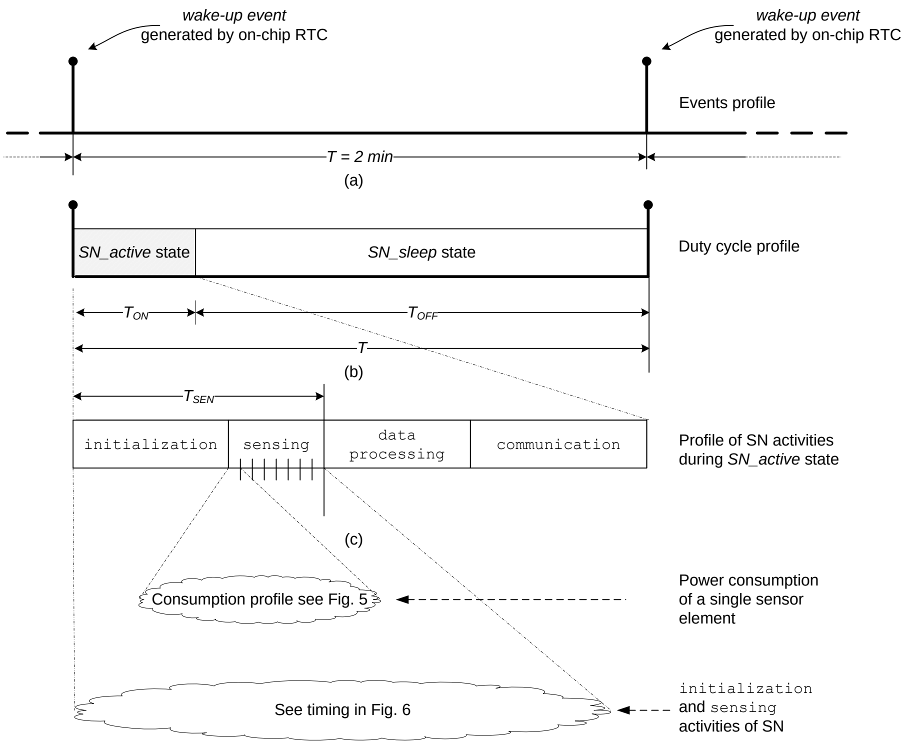

Fig. 4 Activity profile of a sensor node

As can be seen from Fig. 4 a), the *RTC* circuit, as a building block of the *MCU*, periodically generates an interrupt signal called *wake–up*. The period of *wake–up* is *T*, in our case *T* = 2 min. The appearance of the signal *wake–up* initiates a *SN* and it enters into *SN_active* state (see Fig. 4b)). During *SN_active* state (Fig. 4c)) four sequential activities are performed, `initialization`, `sensing`, `data processing`, and `communication`. Activity `initialization` deals with restoring the content of *MCU* registers to the preceding *SN_active* state and setting peripherals (*LDO* regulator, Controllable load switches, and Transceiver – see Fig. 2) into the corresponding operating mode. The `sensing` activity is responsible for information collection and analog-to-digital conversion. The energy consumption during this activity comes from multiple operations, including power-*on* (-*off*) switching of sensor elements, signal sampling, and analog-to-digital conversion/SPI communication. If we assume that n sensor elements are connected to the *MCU* (see Fig. 2), then the total energy consumption of the *sensing subsystem*, E_{ST}, can be expressed as:

$$E_{ST} = N * \sum_{i=1}^{n} (e_{FOi} + e_{OFi} + E_{wi} + E_{Ci}) \quad (4)$$

where:

- e_{FOi} (e_{OFi}) is the one time energy consumption of opening (closing) sensor element operation – switching sensor element *i* from *OFF* (*ON*) to *ON* (*OFF*) state;
- E_{wi} – energy consumption during *warm-up* time period of sensor element *i*;
- E_{Ci} – energy consumption during analog-to-digital conversion period;
- *N* – number of *SN* active states during lifetime of a *SN*, and
- *n* – number of sensor elements in a *SN*.

Power consumption profile of a *SN* during single `sensing` activity of a sensor element is sketched in Fig. 5.

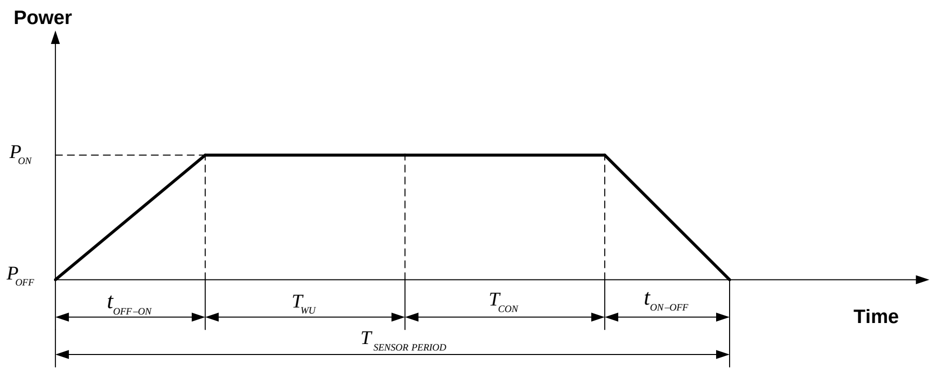

Fig. 5 Power consumption profile of a single sensor element

Notice: A time interval t_{OFF-ON} (t_{ON-OFF}) *includes transient time of Controllable load switch* CLS_i, $i = 1,...,8$, *and transient time of a sensor element* SE_i

As is marked in Fig. 5, t_{OFF-ON} (t_{ON-OFF}) corresponds to a time interval needed for switching the sensor element from *OFF* (*ON*) to *ON* (*OFF*) state, T_{WU} to *warm-up* time interval, and T_{CON} to analog-to-digital conversion time interval.

Basic constituents of most sensor elements are analog circuits (input and output amplifiers, active filters, etc.). In analog circuits, the power gates must be turned-on long enough before the active system operation in order to allow the circuits to reach a stable dc state. This implies that both the sensor elements and their coupling with the source of stimulus cannot always respond instantly. Namely, the sensor is characterized with a time-depended characteristic, and a delay (latency) appears in representing a true value of a stimulus. In Fig. 5 this delay corresponds to the *warm-up*time T_{WU}. In essence, *warm-up* time is the time between applying to the sensor power or excitation signal and the moment when the sensor can operate within its specified accuracy [48].

The *warm-up* time depends on the type of sensor. Many sensors may have a negligible short *warm-up* time (in the range from $100\,\mu s$ up to $1\,ms$), but those that operate in a thermally or humidity controlled environments, such as a thermostat and humidity sensor, may require from several hundred up to seconds or minutes of *warm-up* time after powering-up only the sensor elements. From the aspect of energy consumption, a sensor with a shorter *warm-up* time causes a lower amount of power loss.

Let us assume that all sensors are homogenous. This means that for $\forall i$, $i = 1,...,n$, the following is valid $E_{Wi} = E_W$, $E_{Ci} = E_C$ and $e_{FO} = e_{OF} = e_S$. According to the aforementioned, the eq. (4) now has the form

$$E_{ST} = N * n * (2 \cdot e_S + E_W + E_C) \tag{5}$$

The total energy consumed during *warm-up* time is

$$E_{TW} = N * n * E_W \tag{6}$$

If we take that in average, $e_S = 0.1 \cdot E_C$, then a portion of energy due to the *warm-up* is

$$\frac{E_{TW}}{E_{ST}} = \frac{N * n * E_W}{N * n * (2 \cdot e_S + E_W + E_C)} = \frac{1}{1 + \dfrac{1.2 \cdot E_C}{E_W}} \tag{7}$$

If we further take that $E_W = k \cdot E_C$ where k is an real number, the portion of energy loss, E_{TW} / E_{ST}, in terms of E_W is presented in Table 2.

Table 2 A portion of energy lost in term of k

k	0	0.1	0.2	0.5	0.8	1	2	5	10	20	50	100	1000	∞
E_{TW} / E_{ST}	0	0.077	0.143	0.294	0.400	0.454	0.625	0.800	0.892	0.943	0.976	0.989	0.999	$\rightarrow 1$

By analyzing the results presented in Table 2 we can conclude that as *warm-up* time increases the portion E_{TW} / E_{ST} asymptotically brings closer to value 1. This means that at the lower limit, $T_{WU} = 0$, the total energy loss is $E_{ST} = N * n * (2 \cdot e_S + E_C)$, and at the upper limit $T_{WU} \to \infty$, the total energy loss is $E_{ST} \sim N * n * E_W$, i.e. E_W becomes dominant. In general, better design solution concerning E_{TW} is one in which $T_{SW} \to 0$, but in this case the sensor elements are all time active. As a direct consequence of this approach the power consumption of a sensing subsystem will be high. To cope efficiently with this problem, involving of power gating technique represents a good compromise. But in such a solution, the sensor warm-up time cannot be ignored when SN's energy model is considered.

4. Power Estimation

In this article we continue our work [49], and present a complete energy consumption profile of the wireless sensor node during the activities `initialization`, and `sensing`, only within the `SN_active` state.

In our case, the *sensing subsystem OCSE* (see Fig.2) is composed of eight sensor elements, SE_1, ..,SE_8. Sensor elements from SE_1up to SE_7 are of analog type and drive the *on-chip ADC* (as a component of *MCU* (MSP430FR59xx)). These sensor elements are used for sensing temperature (LMT87), humidity (SHT21S), acceleration (ADXL377), ambient light (ISL76671), position (SS345PT), motion (L3G3250A), and audio microphone (MP33AB01), respectively. The last sensor (T5400) is used for measurement pressure and it transfers data to *MCU* via an *SPI* interface. For more details about electrical and time specifications of sensor elements see Farnell website [50]. The power supply voltage $out\,2 = 3\text{V}$ (marked as V_{OUT2} output of a low-drop out dual-channel voltage regulator TLV716 [51]). A*CLSi* is implemented as a P-channel MOSFET transistor TPS22908 [52] (see Fig.2).

Electrical and time specifications (found in the devices documentations and determined by direct measurements) and energy consumption per sensor element (determined by calculation and direct measurements) are presented in Table 3.

Table 3 Electrical and timing specifications, and calculated energy consumption per sensor element

Sensor element	Type sensor	*out*2[V]	SEiav. current [mA]	t_{OFF-ON}[ms]	e_{FO} [uJ]	T_{WU}[ms]	E_W [uJ]	T_{CON}*[ms]	E_C [uJ]	t_{ON-OFF} [ms]	e_{OF} [uJ]
1	LMT87		0.0041	2.01	0.012	–	n.a.		0.000043		0.000031
2	SHT21		0.1811	150.11	40.778	8000	4346.400		0.001902		0.001358
3	ADXL377		0.3011	5.11	2.308	–	n.a.		0.003162		0.002258
4	ISL76671	3	0.0361	0.205	0.011	0.350	0.038	0.0035	0.000379	0.005	0.000271
5	SS345PT		3.0011	0.11	0.495	0.0015	0.014		0.031512		0.022508
6	L3G3250A		6.3011	0.11	1.040	0.3	5.671		0.066162		0.047258
7	MP33AB01		0.3011	0.11	0.050	–	n.a.		0.003162		0.002258
8	T5400		0.7911	2.61	3.097	10	23.733	16	37.9728		0.005933

Notice: Conversion time T_{CON} is determined by SAR-ADC, as constituent of MCU, and for 12-bit resolution and it is 3.5 μs *(identical for all sensor elements); n.a. stands for not available data from catalog*

According to eq. (4) and data presented in Table 3, under the assumption that $N = 1$ and $n = 8$, the estimated energy consumption of our design during powering-up of sensor elements (initial phase of sensing activity) can be expressed as

$$\begin{aligned} E_{ST} &= \sum_{i=1}^{8} (e_{FOi} + e_{OFi} + E_{wi} + E_{Ci}) \\ &= 47.791 + 0.081875 + 4375.856 + 38.07912) \\ &= 4461.808\,\mu J \end{aligned} \tag{8}$$

Let us note that this value corresponds to the worst-case of energy consumption for all *CLSi* and *SEi* during the `sensing` activity (Namely, after powering-up of sensor elements this activity happens only once during the life-time of the sensor node. It is typical for sensor element stabilization to environment conditions. Therefore, its impact, concerning power estimation, can be neglected).

4.1. Energy profile during `initialization` and `sensing` activities

With the aim to determine the total energy consumption during the `active` state of a sensor node it is necessary to take into account the energy loss of other building blocks (*MCU* and *BSU* (see Fig. 1 and 2)) during the time period T_{SEN} (see Fig. 4).

A detailed timing diagram during `initialization` and `sensing` activities is presented in Fig. 6.

As can be seen from Fig. 6a) the `initialization` activity begins at $T_{START-ON}$ and ends with T_1. The activity `sensing` deals with the right part of Fig 6 a), time interval from T_1 to T_2, continues with Fig. 6 b), time interval from T_2 to T_3, and ends with the left part of Fig. 6c), time interval from T_3 to T_{END-ON}. The right part of Fig. 6c) includes `data processing` and `communication` activities, time interval from T_{END-ON} to $T_{START-OFF}$, and *SN_sleep* state, time interval from $T_{START-OFF}$ to $T_{END-OFF}$. Duration of a time interval from $T_{START-ON}$ to $T_{END-OFF}$ is 2min.

In Table 4, details concerning time interval durations of all activities during `initialization` and `sensing` activities (defined in Fig. 6) including the average current and energy consumption for each time-subinterval are given. Total time duration of `initialization` and `sensing` activities is $T_{SEN} = 191.036ms$ and the corresponding energy consumption during this period is $278.31\mu J$.

Timing diagrams and power consumption profile during `initialization` and `sensing` activities (obtained by MATLAB,) are presented in Fig. 7. Figure Subplot 1 (down-left part of Fig. 7) deals with the `initialization` activity and acquiring data from SE_1 and SE_2. Figure Subplot 2 (down-right part of Fig. 7) refers to acquiring data from SE_3 to SE_8.

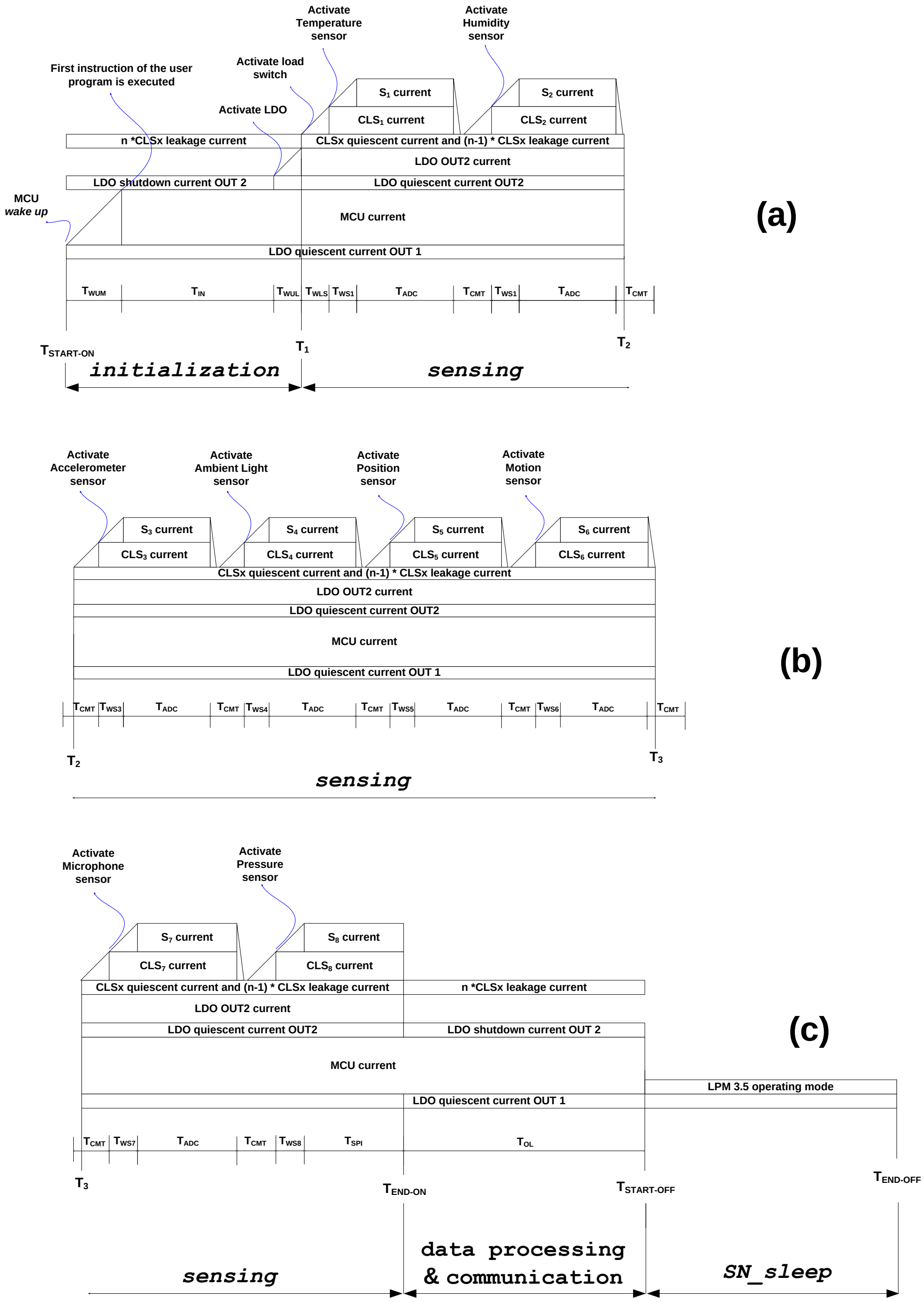

Fig. 6 Profile of power consumption during sensing activity

Table 4 Time interval duration, average current and energy consumption during `initialization` and `sensing` activities for each *MCU* and *OCSE* sub-interval

Time interval	Duration [ms]	Average current [mA]	Energy [μJ]
T_{WUM}	0.3500	0.290	0.1522500
T_{IN}	1.0000	0.495	1.4850000
T_{WUL}	0.9000	0.495	0.6682500
T_{WLS}	0.1600	0.570	0.1368000
T_{WS1}	1.9000	0.590	1.6815000
T_{ADC}	0.0035	0.720	0.0075600
T_{CMT}	0.0050	0.075	0.0005625
	0.1600	0.078	0.0187200
T_{WS2}	150.000	0.729	164.02500
T_{ADC}	0.0035	0.877	0.0092085
T_{CMT}	0.0050	0.075	0.0005625
	0.1600	0.235	0.0564000
T_{WS3}	5.0000	0.869	6.5175000
T_{ADC}	0.0035	1.017	0.0106785
T_{CMT}	0.0050	0.075	0.0005625
	0.1600	0.375	0.0900000
T_{WS4}	0.4450	0.604	0.4031700
T_{ADC}	0.0035	0.752	0.0078960
T_{CMT}	0.0050	0.075	0.0005625
	0.1600	0.110	0.0264000
T_{WS5}	0.0015	3.569	0.00803025
T_{ADC}	0.0035	3.717	0.0390285
T_{CMT}	0.0050	0.075	0.0056250
	0.1600	3.075	0.7380000
T_{WS6}	1.0000	6.869	10.303500
T_{ADC}	0.0035	7.017	0.0736785
T_{CMT}	0.0050	0.075	0.0056250
	0.1600	6.375	1.5300000
T_{WS7}	3.0000	0.869	3.9105000
T_{ADC}	0.0035	1.017	0.0106785
T_{CMT}	0.0050	0.075	0.0056250
	0.1600	0.078	0.0187200
T_{WS8}	10.000	1.359	20.385000
T_{SPI}	16.000	1.373	65.904000
T_{OL}	0.1000	0.496	0.0744000

Notice: Where T_{WUM} – wake-up time of the MCU; T_{IN} – MCU initialization; T_{WUL} – out2 wake-up time of the LDO; T_{WLS} – wake-up time of the CLS; T_{WSx} – warm-up time of a sensor *x*={1,2, ..,8}; T_{ADCx} – conversion time *x*={1,2, ..,7}; T_{CMT} – switching time which includes $T_{turn\text{-}off(LSx+Sx)}$ + $T_{turn\text{-}on(LSx)}$; T_{SPI} – SPI time; T_{OL} – time-off LDO

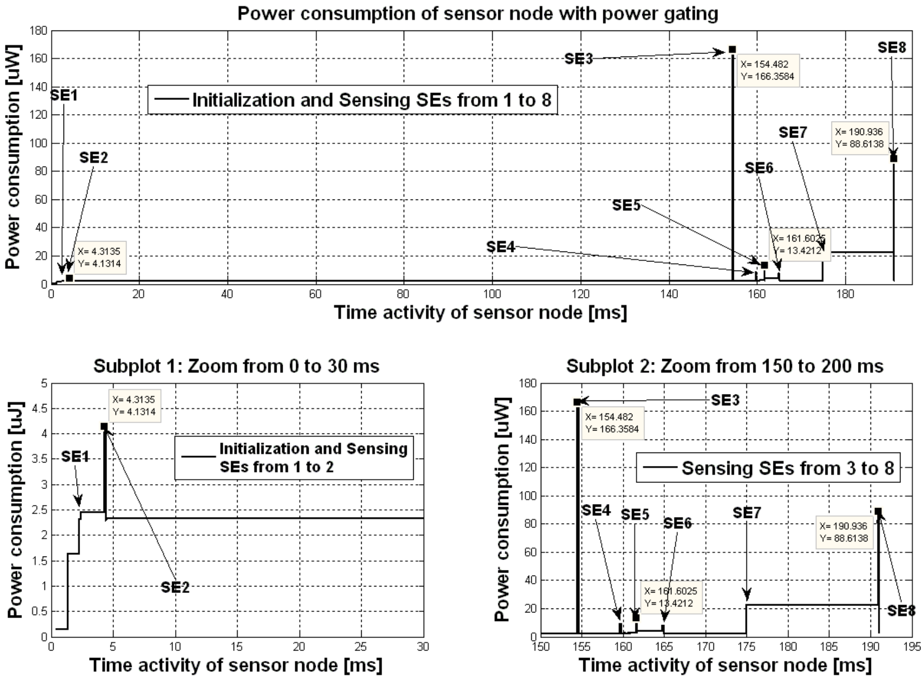

Fig. 7 Diagrams of power consumption during `initialization` and `sensing` activities for *MCU* and *OCSE* blocks

In order to evaluate the performance of our design concerning energy reduction, we have compared the following two design solutions: a) total energy consumption of a sensor subsystem E_{pg} during `initialization` and `sensing` activities, with the implemented duty-cycling and power-gating techniques ($E_{pg} = 638 \mu J$); and b) total energy consumption of a sensor subsystem E_{wpg} without implementation of duty-cycling and power-gating techniques ($E_{wpg} = 3.92\ J$). The estimated ratio is $E_{wpg} / E_{pg} = 6146$. The obtained result justifies the involvement of both power saving techniques in a sensing subsystem of a wireless sensor node.

5. Conclusion

Wireless sensor nodes place sensor elements in the physical world in order to gather information. This activity consumes energy. Due to the limited battery capacity, energy conservation becomes a goal. This paper attempts to provide a comprehensive insight into aspects of energy consumption of a sensing subsystem within a sensor node architecture. In order to achieve reduction in energy consumption in a sensor node operation, we propose using a combination of two power saving techniques. The first one, called duty-cycling, is used for power reduction at a system level, i.e. switching *on/off* the sensor node architecture between `active` and `sleep` state. The second one, referred to as power gating, is intended for switching *on/off* the sensor elements (constituent of the *sensing subsystem* within *SN*), during acquiring information from the external environment. The obtained results based on the analysis and validation by MATLAB show that on average, three order of reduction in energy consumption can be achieved when the mentioned two techniques intended for power saving are implemented with respect to the case when they are turned *off*.

For the time period of two minutes the energy consumption when the two techniques are used is $\approx 638\ \mu J$ compared to $\approx 3.92\ J$ in the case when the duty-cycling and power-gating techniques are turned *off*.

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