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Node's Power Source Type Identification in Wireless Sensor Networks

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***Abstract*—Contemporary Wireless Sensor Network (WSN) nodes can use one of the three options for their power supply: the electricity grid, the batteries or the wide range of energy harvesting systems. The possibility of identification for power source type used on the WSN node provides valuable information on the node potential resources, that could be used e.g. for the improvement of the whole WSN lifetime. Additionally, the possibility of WSN node Power Source Type Identification (PSTID) allows unifying the node's software through implementing the methods for WSN node operation adaptation based on the information about identified power source type and allows the support of efficient WSN node power source changeability without node reprogramming. To the best of our knowledge, this article is the first one which focuses on the problem of WSN node PSTID and suggests the appropriate solution. The suggested method allows implementing efficient PSTID with minimum resource consumption while not requiring any hardware components added to the WSN node. The suggested method has been implemented and tested in practice using different WSN node platforms and power source options. The evaluation results are presented in the paper as well.**

***Keywords*-WSN; embedded systems; power source; identification;**

I. Introduction

During the recent years, the introduction of new low-power microcontrollers and radios together with the development of numerous simple and cheap sensors allowed to significantly broaden the range of the WSN applications. Additionally, the development and demonstration of the efficient environment energy harvesting methods and their application to WSN allows to further increase the autonomy of the WSN systems.

Meanwhile, the standardization activities for the used in WSN communication protocols, namely the introduction of IEEE 802.15.4 [1] and 6LowPAN [2] and the emerging Bluetooth Low-Energy standard [3] enable to unify the communication within WSN. This allows one to expect in future the introduction of the new WSN, which would get the features of suggested "Internet-of-Things" [4] paradigm and would consist of numerous nodes, which would have different architecture and sense different parameters using the common radio channel resources for data exchange. The development of such systems in practice, introduces the new challenges for the node's interoperability and for the efficient usage of different platforms within the same WSN. One of such challenges is the requirement of having a mechanism for WSN power supply source identification.

Indeed, the WSN nodes can nowadays have several different options for power supply and each of them has special features and requires from the node the special working mode for the most efficient resources utilization. Although it is always possible to use the traditional approach and to hard-code the required operations for efficient power source usage inside the actual node software distributive, however this approach has numerous limitations, the main of which are:

- It is necessary to support the separate embedded software version for each power supply option, which complicates the manufacturing and deployment of the WSN as well as the network maintenance (e.g. reprogramming);
- The change of the node source of power is impossible without node reprogramming.

Additionally, the information on the WSN node's available energy is often required by different higher layer protocols, e.g. for energy efficient data routing or by the application for measurement correctness estimation and the whole network lifetime prediction. Therefore, to solve the described problem, the WSN node requires to have some additional intelligence to be able to identify its source of power supply and to adjust its working mode to use the available energy resources in the most efficient way.

During recent years, there have been discovered the ways, which can be used for the adaptation of a WSN node to the available power supply and for increasing the overall system operation energy efficiency and lifetime. So in [5] and further works have been presented the experimental studies results, showing the influence of the radio operation on the discharge rate of the batteries in WSN nodes and were suggested some ideas on the possible ways to increase the system lifetime. In [6] and [7] were evaluated the influence of microcontroller parameters on the WSN node energy consumption and were suggested the ways for improving the energy efficiency of WSN node data processing.

Nevertheless, for the existing researches it is usually assumed that the WSN node power source is known in advance (e.g. [6], [7]), which is not always possible in practice. Therefore, later in this paper we will introduce the method for power source type identification (PSTID), which could be used by a WSN node or by any other similar embedded system for identifying its source of power.

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II. WSN NODE'S POWER SUPPLY OPTIONS

To the best of our knowledge, nowadays WSN nodes are mostly using the following power supply options:

- the power supply from the electrical grid using AC/DC converter or external stabilized power source,
- batteries or accumulators,
- energy from environment harvesting systems with capacitive storage,
- or the combination of the options above.

The WSN nodes with power supply from the electrical grid usually do not have any strict limitations on the energy they consume. This is the reason, why this power supply option is often used in practice for the devices with the high duty cycle, e.g. the routers and access points(AP) in WSN (e.g. [8]). For most of the WSN node platforms, as they usually require the level of supply voltage in the order of 2-5 V DC, an external AC/DC power adapter is used for getting the required supply voltage level from the electric grid.

The other option, which is often used for the WSN AP, is the node power supply using the available supply lines of USB or other data exchange interface. This allows one to combine the interfaces for the node power supply and for data exchange with an external device (e.g. laptop or hand-held device). Often (e.g. [9] or [10]) the 5V of USB supply voltage is down converted on node to lower voltage (3.6 V or around).

The second option, which is commonly used for the WSN end devices (ED) and for installations in places without the access to the electrical grid is usage of rechargeable or not rechargeable batteries. Such systems have limited energy capacitance that depends as well on the parameters for the used battery, the environment parameters (e.g. working temperature) and the node current consumption (which depends on the system working mode). The influence of these parameters on the node's available energy and the methods for such system lifetime maximization is a very complicated problem, which is out of the scope for this article. Some of the corresponding data, can be found e.g. in [11], [12] and [5]. Sometimes (e.g. [13]), for increasing the WSN node lifetime, in parallel to the battery itself is connected an additional capacitor which is used for buffering the energy, that is consumed during the peak load (e.g. during radio operation).

The third option, which became possible due to recent years technology advances and that is currently gaining popularity is the usage of energy, harvested from the environment for WSN node operation support. Currently, such introduced and demonstrated methods include the energy harvesting from the following energy sources [14]:

- light,
- temperature difference,
- vibration and movement,
- water, air or gas flow,
- electrical or magnetic fields,
- and chemical reactions (e.g. [15]).

For all these methods, the energy is initially harvested from the environment and buffered using a special storage system and later is consumed by the WSN node. Usually, the amount of energy, which can be collected from the environment at a period of time, is rather small. Thus, the energy harvesting methods require the energy storage system to be able to accumulate the energy over relatively long periods of time, before the WSN node would get enough energy for its operation. The collected from environment energy is most often stored using different capacitors, which typically, (e.g. [16], [17], [18]) are having rather limited capacity and are unable to store the energy over the long period of time without harvested energy availability. Therefore, the nodes using this option can suffer from often forced restarts due to energy unavailability and require the most energy efficient communication protocols and very low duty cycle [14].

Finally, depending on the application requirements, several of the described power supply options can be combined, although this solution is not really widespread due to increase of the system price, size and complicity which goes against the "minimum cost" nature of the most WSN. This option is not considered in the article in detail, although the suggested PSTID method could be modified also for this scenario.

Regardless of the actual used power supply option, most of the WSN nodes already have the mechanism to monitor the level of node supply voltage. This feature is mostly used for:

- estimating the available energy if the node has limited energy resources (the lower the voltage of the battery - the lower energy is left),
- controlling the system operation (e.g. checking the possibility of launching some operations, which require a certain level of supply voltage, like e.g. writing to the microcontroller Flash or launching sensor operation).

This mechanism for node supply voltage control is usually implemented by the supply voltage connection to one of the inputs for WSN node controlling device in-build Analog-to-Digital Converter (ADC).

Thereby, the WSN nowadays could use several power supply options and, as it has been shown e.g. in [7], each of these options requires from the WSN node the different working mode for the most efficient energy resource utilization. The development of such methods for the WSN workmode adaptation to the used power source option is a very complicated problem which requires to consider numerous environment factors and application requirements and which, to the best of our knowledge, has not been yet solved. Some of the initial information and methods for the WSN node working mode adaptation to some of the power supply options can be found e.g. in [6] and [7].

III. IDENTIFICATION OF POWER SUPPLY SOURCE FOR WSN

As it has already been noted, numerous WSN are having very limited resources due to the "low cost and low power" nature of the systems [19]. Thus the identification of the source of the power for this system must be as simple as possible and

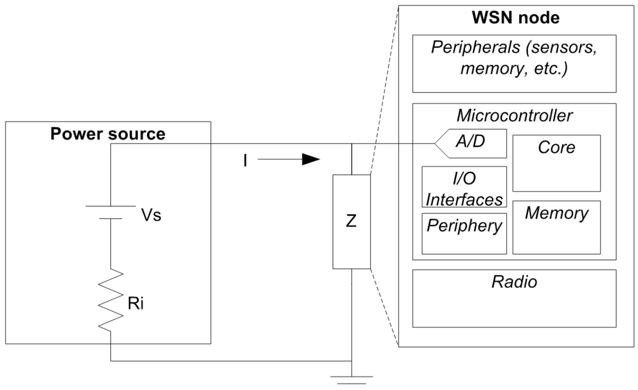

Fig. 1. Equivalent circuit of a WSN node

should be done, whenever possible, with the very limited use of the additional hardware components.

To understand, how it is possible to implement the PSTID, let us consider the simple equivalent circuit for the WSN node connected to the battery. This equivalent circuit is presented on Fig.1.

As can be seen from Fig.1, the source of power is represented by the source voltage V_s in series with the internal resistive impedance R_i. For representing the whole WSN node is used a generalized impedance Z, the value of which depends on the WSN node work-mode. The battery internal impedance R_i depends on the actual battery and is usually in the order of 0.1-0.5 Ohm for AA batteries [11]. The voltage V_{AD}, which appears across the WSN node connectors, as it has already been discussed in II, is measured by the WSN node microcontroller ADC and can be represented as (1):

$$V_{AD} = V_s - I \cdot R_i \tag{1}$$

The level of consumed current for a general WSN node is defined by the actual used peripherals and their working modes. For illustration, in Table I are presented the values for the current, consumed by the different core and peripheral components for Texas Instrument (TI) eZ430-RF2500 development board [9], which includes low-power MSP430 microcontroller [20] and CC2500 2.4 GHz radio chip [21].

As it is possible to see from Table I, depending on the active components, the current consumption for eZ430-RF2500 node could be in the range from $1\mu A$ for the node in the deep sleep mode and up to around $400\mu A$-$30mA$ in active mode, depending on the clock frequency of the microcontroller and the modes for the radio and other peripherals. Such level of current consumption is rather typical for current technology state-of-the-art and is reported for numerous existing WSN node platforms. Therefore, as it is easy to see using (1), these levels of current consumption could result in the voltage drop over the R_i of around 0.52 mV for 2mA system current consumption and 5.2 mV for 20mA current consumption with the corresponding change of V_{AD}, suggesting that the node is supplied using two AA batteries and thus R_i is equal to 0.28 Ohm and V_s is 3 V [11]. Although, this change is rather small, usually it can be detected using A/D converter. This fact, we are using to implement the PSTID for the WSN nodes.

TABLE I
CURRENT CONSUMPTION BY COMPONENTS FOR TI EZ430-RF2500 NODE

Peripheral	Workmode	Consumed current[a], mA
MSP430 microcontroller	sleep mode (LPM4)	0.0005
	active, 1MHz clock	0.4
	active, 8MHz clock	2.7
	active, 12MHz clock	4
	ADC10 conversion using internal reference	2
	write to internal Flash	1
CC2500 radio	sleep mode	0.0004
	RX (input at sensitivity level, 250 kbit/s)	18.8
	TX (0 dbm, 250 kbit/s)	21.2
LED green	ON	1.85
LED red	ON	3.4

[a] the supply voltage is 3V

The reasoning above was done for the simple batteries as the WSN node power supply source option. Nevertheless the same approach can be applied to other types of power sources. So, for the case when the WSN is connected to the power grid, in most cases the supply voltage is stabilized and thus the described increase of WSN node current consumption is not likely to result in the change of the supply voltage value. On the contrary, the systems using energy from environment harvesting with its storage using capacitors would have higher difference for the values of available node supply voltage(V_{AD}) for the cases of low and high current consumption modes. Additionally, due to reasons discussed above, the usage of capacitors with low capacitance for energy storage in such systems could result in significant supply voltage level decrease after the period of high current consumption due to capacitor discharge.

IV. IMPLEMENTATION AND EVALUATION OF THE DEVELOPED POWER SUPPLY SOURCE IDENTIFICATION METHOD

For evaluating the practical applicability for the suggested PSTID method, it has been implemented and tested using different power supply options. For testing, we used two different platforms: the TI eZ430-RF2500 [9] and CC2510-mini [22] development boards. The decision about the available source of power was made by the WSN microcontroller basing on three supply voltage measurements:

- The first measurement (V_{ll}) has been done during the node running in low current consuming mode (all systems except the ADC were switched off);
- The second measurement (V_{hl}) was done with the node running in high current consuming mode (the measurement has been done with the radio running in receive mode and microcontroller in active mode);

TABLE II
EVALUATION OF PSTID METHOD

Power source	eZ430-RF2500			CC2500-Mini		
	V_{ll}, mV	V_{hl}, mV	V_{ll2}, mV	V_{ll}, mV	V_{hl}, mV	V_{ll2}, mV
DC power adapter from grid	3.579	3.584	3.579	NA	NA	NA
DC power adapter from laptop	3.579	3.584	3.579	3.367	3.358	3.367
2xAAA batteries(new)	2.962	2.933	2.962	3.056	3.025	3.054
2xAAA batteries(old)	2.499	2.420	2.493	2.582	2.494	2.574
2xAAA accumulators (Ni-MH, new)	2.555	2.525	2.555	2.646	2.618	2.646
2xAA batteries(new)	3.091	3.066	3.086	3.193	3.171	3.190
2xAA accumulators(Ni-MH, new)	2.587	2.528	2.587	2.673	2.622	2.673
2xAA accumulators(Ni-MH, old)	1.758	1.749	1.752	1.870	1.857	1.864
CR2032 battery(new)	2.971	2.344	2.921	3.076	2.655	2.845
2xAG4 alkaline batteries(new)	2.977	2.725	2.953	3.073	2.856	3.016
2xAG10 alkaline batteries(new)	2.909	2.742	2.909	3.047	2.964	3.034
2xAG13 alkaline batteries(new)	3.027	2.930	3.027	3.137	3.041	3.131
Solar energy harvesting [16]	4.033	3.965	3.984	3.505	3.446	3.457
Vibration energy harvesting [18]	3.228	2.559	2.554	3.292	2.948	2.862

- The third measurement (V_{ll2}) has been done after the second one, once the node returned to low current consuming mode.

The results of the measurements for different power supply options are presented in Table II. In each case for the both platforms the same sources of power were used. The difference in the absolute supply voltage values for different platforms is caused by the internal ADC reference voltage instability (which could reach 6% [20]) and ADC errors. Nevertheless, from presented results it is possible to see that there are some common features for different types of power sources, which can be used to identify them. For this purpose, can be used the simple algorithm, presented on Fig. 2.

Here, dV_1 and dV_2 are calculated according to (2) and (3) respectively. The threshold values Thr_{vcc1},Thr_{vcc2} and Thr_{bat} should be tuned for each platform. For tested platforms, as it can be seen from Figs.3-4, which are showing the dispersion and average value (marked with bold) for dV_1 and dV_2 using different types of power supply, it is possible to use the following values for thresholds: $Thr_{vcc1} = 0.5\%$, $Thr_{vcc2} = 99.5\%$ and $Thr_{bat} = 30\%$.

$$dV_1 = \frac{V_{ll} - V_{hl}}{V_{ll}} \cdot 100\% \qquad (2)$$

$$dV_2 = \frac{V_{ll2} - V_{hl}}{V_{ll} - V_{hl}} \cdot 100\% \qquad (3)$$

As can be seen from the presented results, the suggested PSTID method enables for all tested options to recognize the type of used source of power. The suggested method allows quite reliably recognizing the system using DC power supply from the ones with batteries or energy harvesting. The recognizing of battery-supplied and energy harvesting supplied systems, as possible to see from presented results, can be done rather reliably, especially for the new batteries and for batteries with high energy capacitance, while for old discharged batteries there can be some errors.

The amount of resources, consumed by the program, implementing presented on Fig.2 algorithm, appeared to be very

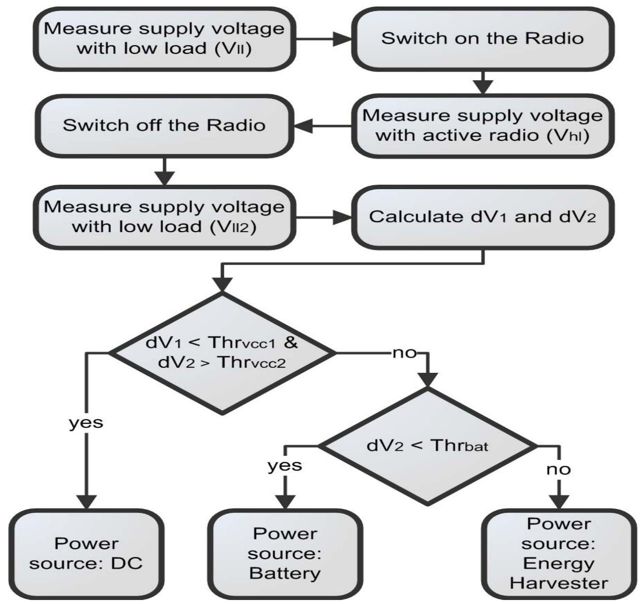

Fig. 2. Suggested algorithm for PSTID on WSN node

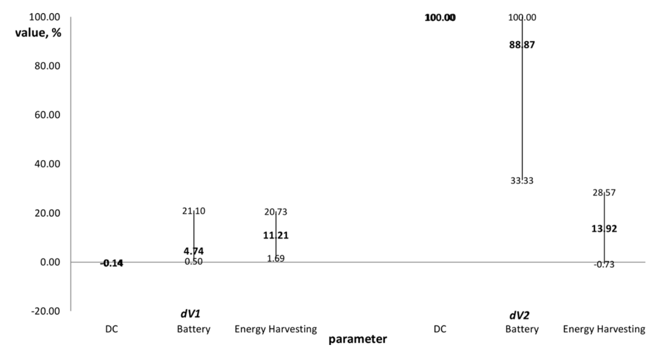

Fig. 3. Values of dV_1 and dV_2 for eZ430-RF2500 node with different power supply options

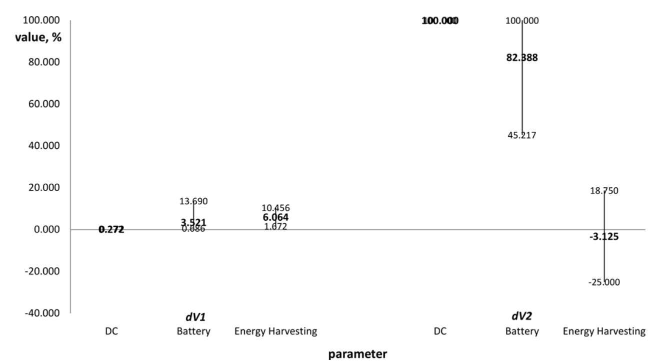

Fig. 4. Values of dV_1 and dV_2 for CC2510MINI-DK node with different power supply options

moderate - the size of program code, was as low as 822 bytes for eZ430-RF2500 and 721 bytes for CC2510 platform without using any further IDE code optimization options. The time, required for PSTID was less than 1.7 ms and caused the consumption for around 70 μJ of energy, most of which was required for radio switching to receive mode and back and which could be neglected if the measurements of V_{hl} and V_{ll2} would be combined with normal system work radio operations.

While developing the PSTID method, we were assuming that the sources of power (batteries and capacitors for the energy harvesting systems) are connected directly to the supply line of WSN node microcontroller without using any additional stabilizing circuits. If such stabilizing circuit exists, the supply voltage measurements for PSTID should be done before it.

The identification of nodes using energy harvesting can be also done using the analyze of WSN traffic, as these systems could have periods of enforced inactivity (with the probable node reset) due to the periodical harvested energy depletion [14].

V. Conclusion

To the best of our knowledge, this paper is the first one which is focusing on the new problem of PSTID for the WSN nodes. The recent technology advances allow contemporary WSN nodes to use three main sources of power: the power supply from the electrical grid or other external stabilized power source, different types of batteries and accumulators or the energy harvested from the environment. The identification of used by the node source of power provides valuable information about one of the most important resources of WSN node - the energy. This information can be used e.g. by the wide range of energy aware routing protocols, which can effectively route the data within the network to maximize the whole network lifetime. Additionally, the suggested PSTID method allows one to develop for WSN nodes the novel methods for adapting their working mode according to the available source of power. This would enable one to eliminate the necessity of upkeeping the different software versions for the same WSN node platform which is using different power supply options. This method also supports the possibility to change the power supply source the WSN node is using without the WSN node reprogramming, upkeeping the high level of energy efficiency, which, to the best of our knowledge, has not been implemented before.

The suggested PSTID method is based on the measurement of the system supply voltage for the different WSN node working modes. Thus, this method provides a simple and quite reliable way of power source type detection without requiring any additional hardware components. According to the presented practical evaluation results, the suggested method can be used as well for different power source options and for various WSN node platforms. The implementation of the suggested PSTID method, using Texas Instruments eZ430-RF2500 and CC2510-mini development platforms, showed that the suggested method has very insignificant resource requirement both for the required WSN code memory and computational power and for the time and energy for PSTID execution.

Although we developed the described PSTID method aiming for its application for the WSN nodes, it can as well be applied to any other embedded system, which requires this feature. In that case, for changing the system current consumption during PSTID execution it is possible to switch between different microcontroller modes (e.g. changing the clock frequency) or switch on and off different peripherals.

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