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Supercapacitor power unit for an event-driven wireless sensor node

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Abstract—**This paper discusses supercapacitor based power unit for event-driven wireless sensor network node. In such nodes, most of the energy is consumed when transmitting or receiving data. Sleep-wake scheduling mechanism is an effective way how to prolong node's lifetime. However, this mechanism can result in delays because a transmitting node has to wait until his neighbor wakes up. Another solution is event-driven communication model, where nodes communicate in case an event occurs. Although, events occur asynchronously, the node needs to send a keep alive message periodically. An event can be caused by very high temperature (indicating fire), or presence of movement in a surveillance system. Good communication pattern can reduce energy consumption. However, the main issue remains the design of network node power unit. We propose supercapacitor power unit circuit which is charged from solar cells and discuss a sensor node energy balance.**

I. INTRODUCTION

THE principles of wireless sensor networks (WSN) are known for some time. But only technology advance in last decades allowed development of new, interesting applications of WSNs. Such applications are property surveillance, various diagnosing systems (for example for a production line), illegal forest logging detection and traffic monitoring or even wearable electronics. It is critical to operate such networks unattended for a long time. Therefore, extending network lifetime through the efficient use of energy is a key issue in the WSN development [1].

The fraction of total energy consumption in event based systems for data transmission and reception is relatively small, because events occur rarely. The energy required to sense events is usually constant and cannot be controlled. Present microcontrollers (MCUs) are energy saving also when they are fully operational, but their power consumption can be reduced even more switching them into sleep mode. Sleep-wake scheduling mechanism becomes an effective way to prolong the lifetime of energy-constrained event-driven sensor networks. By putting nodes to sleep when there are no events, the energy consumption of the sensor nodes can be significantly reduced. However, the energy expended to keep the communication system on, is the dominant component of energy consumption, which can be controlled in order to extend node's lifetime [1]. In most practical cases the communication possibilities are limited by communication range as well as data rate. Note that increasing communication range can be accomplished only by increasing transmitter power and receiver sensitivity and that always leads to elevated energy consumption. On the other hand, increasing communication range also increases interference between individual network elements and adversely influences throughput of the network. For that reason, the communication range is usually 30-300m with transmission power of 0-10dBm and receiver sensitivity from -90 to -102dBm. WSNs use ISM (industrial, scientific and medical) radio bands for applications at 443MHz, 886/916MHz and 2.4GHz. Shannon - Hartley theorem describes connection between communication channel data rate with limited frequency band and energy consumption of radio frequency (RF) transceiver [1].

Most WSN applications have limited transfer rate from 10 to 250kbps. Thus, WSN belong to category WLRPAN (Wireless Low Rate Personal Area Networks). For information transfer management purpose in WSN, many routing protocols have been developed. Their analysis and basic properties are described in [1], [2] - [4].

Apart from further basic properties of individual network elements that will be mentioned, there are other important parameters such as:

- Sensor node power computing,
- energy management efficiency,
- low power consumption / long lifetime,
- production cost,
- security,
- fault tolerance.

Many of presented requirements are contradictory. Increasing of computational power raises power requirements as well as sensor costs. Enhanced security needs more computing power. Making fault tolerant node usually increases its price. It is not possible to develop versatile element that would be optimal from all points of view. Moreover, different applications have different importance to particular requirements [1].

Event based communication is a pattern promoting production, detection, consumption and reaction to events. An event can be defined as a significant change of state. For ex-

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ample when temperature rises up to a certain point, the system can change its state from “normal” to “burning” and evaluate this significant change of state to be enough to generate an event. An event-driven system typically consists of event emitters (agents) and event consumers (sinks). Sinks have the responsibility of applying a reaction as soon as an event is presented. The reaction might or might not be completely provided by the sink itself. Building applications and systems around an event-driven architecture allows these applications and systems to be constructed in a manner that facilitates more responsiveness, because event-driven systems are, by design, more normalized to unpredictable and asynchronous environments [5].

In [11] there is considered nonlinear or event-dependent sampling. Such sampling depends on the function being sampled. The paper investigates possible nonlinearity of the sampling procedure and associated Lebesgue’s integral scheme.

II. WSN APPLICATIONS

Our department studies focus on possibilities how to utilize WSNs in traffic parameters monitoring, transport infrastructure quality monitoring and monitoring vehicles emissions [6]. Additionally, there are applications such as navigation and tracking systems, property surveillance, illegal forest logging detection, state border monitoring and many other controlling and monitoring applications. The main WSN application areas are as follows [1], [7] and [12]:

- Military,
- traffic monitoring,
- environmental applications,
- flood and forest fire detection systems,
- security applications,
- health applications,
- tracking systems,
- other commercial applications.

In most WSN applications we have to deal with one basic problem - to ensure network operation without any intervention. Unattended operation of the sensor network is required particularly for applications that monitor the state of the environment, objects, or operate on spatially large territory. As an example of such system could be forest fire detection system described in [8] or the application of monitoring military areas [1]. In terms of minimizing operator intervention to the network during its operation, the critical issue is energy self-sufficiency of each network element. Despite undeniable progress in low-power technologies, the question of power supply for sensors remains a serious problem [9].

The application described in this paper focuses on event-driven sensor node’s power supply unit based on supercapacitors. The supercapacitors are becoming dominant in such applications like WSN or energy harvesting. The presupposed energy source for presented application is solar energy. The power unit circuit is described in detail later.

III. SENSOR NODE ENERGY BALANCE

Each sensor node has to have the capabilities to collect data and route them to the sinks or the end users. In order to meet sensor network requirements, each node must be able to provide the following functions [1]:

- Data collection,
- data preprocessing,
- communication.

Standard network element (node) consists of the following basic parts (Fig. 1):

- Sensing unit,
- processing unit,
- communication subsystem,
- power supply unit.

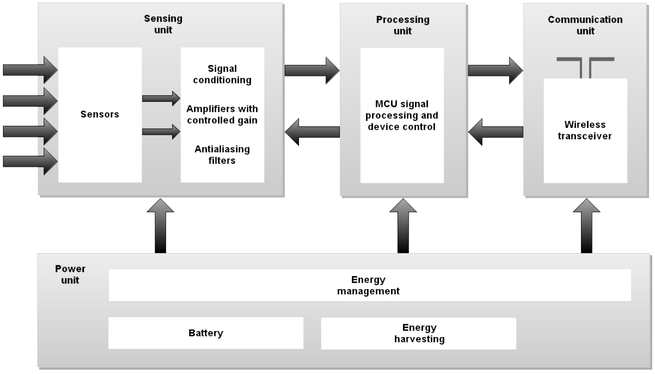

Fig. 1. Sensor node basic parts

In terms of energy consumption, the sensing subsystem depends on the choice of sensing parameters, sensors’ sensitivity, frequency of measurements and other technological limitations [9].

The main task of sensing unit is transformation of chosen parameters to quantity suitable for further processing (usually voltage). This unit is application specific and contains modern electronic elements as probes, operational amplifiers, gain controlled amplifiers, comparators and other microelectronic components. Most often used sensors are sensing temperature, humidity, vehicular movement, pressure, biological and chemical agents, acoustic noise level, lighting condition, the presence/absence of an object, mechanical stress etc. In most applications, sensing subsystem is unit with the lowest energy consumption compared to the communication unit and data processing unit [9].

Basic functions of processing unit are digital processing of measured signals, controlling all parts of sensor node, information transfer and further tasks required by specific application. When designing processing unit, we can use diverse integrated circuits from ASICs (Application-specific integrated circuits) and FPGAs (Field-programmable gate arrays) to universal microcontrollers. At present, the main part of the processing unit is usually a MCU. We must carefully consider required computing power as it is directly related to energy consumption. Widely used processor units with their energy consumption requirements are stated in table 1 [9].

TABLE I

MCU ENERGY CONSUMPTION OVERVIEW

MCU NAME	MCU FAMILY	POWER CONSUMPTION
StrongARM (CPU)	32-bit	300 mW@1.5V/200 MHz
Atmel ARM7	32-bit	90 mW@3.3V/48 MHz
TI MSP 430F5437	16-bit	1 mW@ 3.0V/8MHz
Atmel ATmega 644	8-bit	0.72 mW@1.8V/1MHz

Note that the given data in TABLE 1 are only informational. The table demonstrates that various MCUs have different power consumption requirements, but still very low. When deciding which MCU to use, one must take into account much more parameters than just power consumption. The size of program and data memory, set of integrated peripherals, development tools availability and others are important as well [9].

Each sensor node must be able to communicate with neighboring nodes and/or with the base station using wireless communication channel. For this, we have communication unit. As the RF data transmission is very energy intensive, it is desirable to perform most of the data processing right in the sensor node and then send out only relevant data. Consumption of this unit mainly depends on the required communication range (receiver sensitivity and transmitter output power), baud rate and frequency band. In general, this sensor node unit is the most power consuming unit of all. This means that the choice of communication unit and communication mechanism is a key issue in designing a reliable WSN working without any intervention [9].

The resulting energy consumption of the sensor node is given by the sum of the energy requirements of above mentioned three main parts (sensing unit, processing unit, data collection unit) [9].

If we understand the life of the sensor node as the operation time without operator intervention and the node is powered by a portable power source, then its life is determined by the capacity of this source and power consumption of the node. It is clear that in this case life of the node can be extended by increasing the energy resource capacity, or by reducing device consumption. Another option is to power the sensor system using some kind of energy harvesting device [9]. Today we see MCUs with active mode consumption below 100µA/MHz @ 3V. The single battery with a capacity of 1000mAh could power such processing unit for up to 1 year [8].

In real applications the microcontroller is often in sleep mode with the consumption approximately one hundred times lower than in normal mode. The limiting factor becomes the above mentioned consumption of the communication module and battery / supercapacitor self-discharge process.

The old-school way for powering WSN is a battery. Despite recent significant improvements in battery parameters, particularly energy density increase and self-discharge current reduction, batteries have strict lifecycle and therefore, they limit WSN performance and long term sustainability.

The second alternative that lately attracts the design engineers more and more are systems able to acquire energy from the environment (energy harvesting) in collaboration with supercapacitors [9].

The supercapacitor differs from a regular capacitor in having very high capacitance. This capacitance is rated in farads, which is thousands of times more than regular electrolytic capacitor. The supercapacitor is ideal for energy storage that undertakes short and frequent cycles of charging and discharging at high currents [10].

There is a voltage limit for every single capacitor. The supercapacitor is designed to operate at 2.5V to 2.7V. Higher voltages can be achieved by linking supercapacitors in series, but this has disadvantages. This technique reduces the total capacitance. For example, two capacitors with the same capacitance connected in series act as one with quarter capacitance of the sum of both original capacitors. Additionally, series of more than three supercapacitors need voltage balancing in order to prevent any cell (supercapacitor) to run into over-voltage. Similar protection applies in lithium-ion batteries [10].

Comparing to Li-ion battery (table II), which delivers steady voltage in the usable power band, the supercapacitor's discharge curve decreases linearly from full voltage to zero. This fact reduces the usable power spectrum and much of the stored energy is left behind [10]. The supercapacitor can be charged and discharged virtually an unlimited number of times. Unlike the electrochemical battery, which has a defined cycle life, there is little wear and tear by cycling a supercapacitor. Nor does age affect the device, as it would a battery. Under normal conditions, a supercapacitor fades from the original 100 percent capacity to 80 percent in 10 years. Applying higher voltages than specified shortens the life. The supercapacitor functions well at hot and cold temperatures as well [10].

The self-discharge of a supercapacitor is substantially higher than that of an electrostatic capacitor and somewhat higher than the electrochemical battery. The organic electrolyte contributes to this. The stored energy of a supercapacitor decreases from 100 to 50 percent in 30 to 40 days. A nickel-based battery self-discharges 10 to 15 percent per month. Li-ion discharges only five percent per month [10]. Advantages and limitations of the supercapacitors are summarized in the table III.

TABLE III

ADVANTAGES AND LIMITATIONS OF SUPERCAPACITORS

ADVANTAGES	DISADVANTAGES
Virtually unlimited cycle life (can be cycled millions of times)	Low specific energy (holds an energy fraction of a regular battery)
High specific power (low resistance enables high load currents)	Linear discharge voltage (prevents using the full energy spectrum)
Charges in seconds (no end-of-charge termination required)	High self-discharge (higher than most batteries)
Simple charging (not subject to overcharge)	Low cell voltage (requires serial connection with voltage balancing)
Excellent temperature charge and discharge performance	High cost per watt

IV. SUPERCAPACITOR POWER UNIT

From variety of possible power sources, for this application, the solar energy was selected. The supercapacitors are used for saving the energy from the solar cells. In order to charge the supercapacitors, we use Linear Technology LTC3105 high efficiency step-up DC/DC converter. This integrated circuit is ideal for energy harvesting applications and solar powered battery/supercapacitor chargers because it can operate from input voltages as low as 225mV up to 5V.

To preserve the energy from the solar cells, there are two supercapacitors used with a capacitance of 50F/2.3V each. These capacitors are linked in series together forming a virtual capacitor with a capacitance 25F/4.6V. We will call this group of supercapacitors primary supercapacitors.

Total energy the primary supercapacitors can store is 264.5J. Knowing that the supercapacitor's voltage varies in range from 4.6V to 2.2V, the available energy is 204J. The value of 204J is the maximum energy used by the device during the time without the solar source. From [8], we can use the calculation formula to estimate the time needed for extraction of given amount of energy from the solar cell:

$$t = \frac{E}{P_s \cdot S} \qquad (1)$$

where: t is time in [s],

E is energy in [J] or [Ws],

P_s is the power density in [W/cm^2],

S is active area of the solar cell in [cm^2].

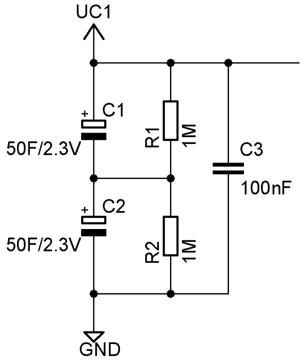

Fig. 2. Circuit detail of primary supercapacitors

Under ideal conditions and assuming active solar cell area of approximately 85cm^2 and power density 5.3mW/cm^2, the solar cell is able to charge primary supercapacitors from 0V to full 4,6V in almost 9 minutes.

If we assume that the average power drawn by the sensor node during the night will be 3.63mW (1.1mA @ 3.3V), then the power supply will be able to power the sensor node for more than 15 hours ($204 / (3.63 \cdot 10^{-3})$). If we count with some losses and nonlinearities the sensor may last about 14 hours (worst case scenario). The sensor's energy consumption is more less 100µA @ 3.3V and during these 14 hours it consumes 15.1J. Note that calculation does not consider power supply unit efficiency of the node, so the results might be slightly less favorable.

Our processing unit is based on STMicroelectronics MCU STM32F103C6T with maximum consumption in active mode 4.5mA @ 3.3V (14.85mW) at 8MHz when code running from RAM. In stop mode, the power consumption is 24µA @ 3.3V (79.2µW). This unit can be activated from stop mode in two ways. Either the RTC (real-time clock) unit wakes up the MCU, or the sensor generates an interrupt request. Real time unit is a part of the MCU and is active also in sleep mode and stop mode. During the 14 hour operation, without primary supercapacitor's charge, the energy flown from the primary supercapacitors is 10.5J (this value strictly depends on active to inactive time ratio).

The communication unit is based on Microchip MRF24J40MA transceiver, which can operate from 2.4V to 3,6V. At receive mode, the power consumption is 19mA @ 3.3V (62.7mW), at transmit mode 23mA @ 3.3V (75.9mW) and at sleep mode the power consumption is 2µA @ 3.3V (6.6µW). Within these 14 hours the consumption is more less 11.8J.

From these values it is clear that using appropriate network behavior strategy can ensure that network elements will be capable of 14-hour operation from energy conserved in primary supercapacitors.

The total power consumption of mentioned modules is 37.4J in 14 hours. The remaining energy is 166,6J. This value is sufficient enough to provide energy for continuous operation for:

- Transmitter only – 36.6 min,
- receiver only – 44.3 min,
- processing unit only – 3h 7 min (active mode),
- processing unit only – 24 days (stop mode),
- sensing unit only – 12h 51 min.

The values assume ideal conditions and ideal efficiency of power systems, but these informational values give direction of network communication strategy.

Although, events are generated asynchronously and the sensors are operational permanently, the communication pattern remains synchronized. This means the nodes need to send keep alive messages regularly (let's say every 10 minutes) and with that, increasing energy consumption. After the 10 minutes the MCU wakes up for about 2 minutes to send out all data it needs to send and receive everything it has to – updated sensing parameters from an operator. It is necessary to find out the reasonable ratio between active and inactive time of communication unit. Another problem becomes the time synchronization – any situation when a node wakes up too early or too late and is not able to send/receive any data successfully because every single node in its range is in power saving mode, should not occur. It is clear, that due to limited energy resources, transfer of data cannot be initiated immediately after event detection. Each sensor needs enough time to evaluate the measured value and, if necessary, to send out the results during the next time slot.

The proposed power unit circuit is given on Fig. 3. It consists of three main functional parts. The first is supercapacitor circuit with primary supercapacitors shown on Fig.2. The

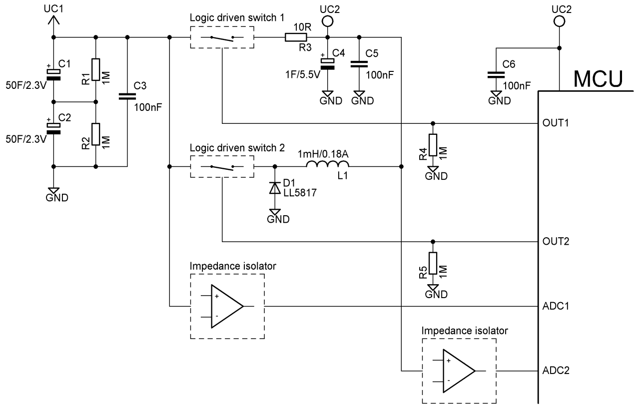

Fig. 3. Power unit circuit

two resistors with 1MΩ resistance serve as simple voltage balancing circuit to prevent any of the supercapacitors to run into over-voltage. The small 100nF capacitor (C3) filters high frequency current peaks. The second main part is MCU powering circuit (Fig. 4) with secondary supercapacitor.

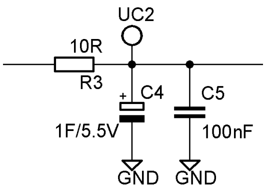

Fig. 4. MCU powering circuit

The 1F capacitor (C4) is being charged via MCU driven switches. The first switch (Fig. 5) is always on when the MCU is inactive (in stop mode). As a result, during MCU inactivity supercapacitors C1 and C2 charge C4 capacitor. When MCU becomes active, the C4 capacitor is (or should be) fully charged to a maximum voltage 4.6V (maximal voltage of series C1 and C2) and the MCU can close logic driven switch 1.

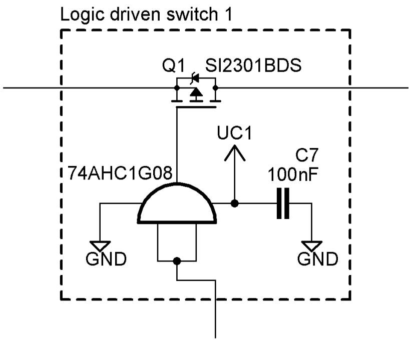

Fig. 5. Logic driven switch 1

Logic driven switch 2 (Fig. 6) works as complementary switch to logic driven switch 1 when MCU is in stop mode. This means, all output MCU pins are in high impedance and the logic driven switch 2 is always off when MCU is inactive. If MCU is active, this switch works as fast charging switch for capacitor C4, which powers the MCU. The inductor L1 limits C4 charging current to prevent any damage.

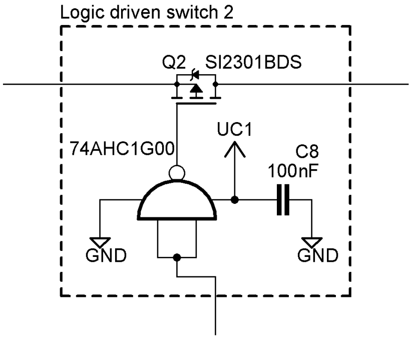

Fig. 6. Logic driven switch 2

Impedance separator consists of an operational amplifier from Texas Instruments OPA2369. This part separates the analog to digital converter pins (ADC1 and ADC2) of the MCU from direct supercapacitor's voltage levels. This is due to potential very high currents that could flow from supercapacitors to these ADC pins. These high currents would cause quick discharge of either MCU powering capacitor C4 but also main supercapacitors C1 and C2. Common values of input impedance of an operational amplifier are very high. This particular, OPA2369 has input impedance 10TΩ according to datasheet. Therefore, we can say that the input impedance is practically infinite and effect on energy consumption is negligible.

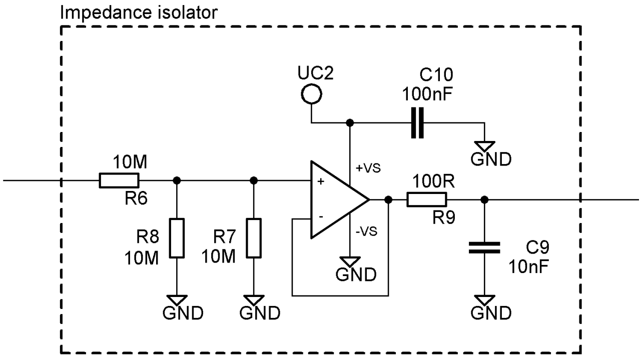

Fig. 7. Impedance isolator circuit

MCU output pins (OUT1 and OUT2) drive switches. These switches are basically responsible for charging C4 and energy balancing between C1, C2 and C4.

MCU analog to digital converter pins (ADC1 and ADC2) are detecting the voltage level of primary supercapacitors C1 and C2 (ADC1) and voltage level secondary supercapacitor C4 (ADC2). When critical low voltage level is detected, the MCU can charge C4 to desired (when C4 is at low voltage level) voltage level from primary capacitors by switching logic driven switch 2 with PWM (Pulse Width Modulation) signal up to 10kHz or MCU can run into sleep mode or even better stop mode and wait until solar cells charge primary supercapacitors and secondary supercapacitor to a desired voltage level (or full voltage).

V. CONCLUSIONS

In this paper, we discuss basic units of wireless sensor node with its energy requirements, some applications, where WSNs are widely used and event-driven communication to extend node's lifetime. In comparison to the asynchronous sleep-wake scheduling mechanism, according to which transmitting node needs to wait until the receiving node wakes up, the event-driven communication mechanism saves the energy until it is necessary to transmit any data. As it was presented, the most energy consuming part is the communication unit. We can save significant portion of energy and extend the lifetime of a wireless sensor node when designing efficient power supply unit.

The basic principle of the proposed power unit circuit is simple. Primary supercapacitors are being charged from solar cells continuously. When MCU is in stop mode, by default, the secondary supercapacitor is being charged from the main supercapacitors. When MCU is in active mode, it can control voltage level at C4 by switching logic driven switch 2. The circuit was designed to work with minimal energy losses and to be simple as well.

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