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Power Management and Energy Harvesting Techniques for Wireless Sensor Nodes

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Abstract – **Wireless Sensor Networks, WSNs, are large networks composed of small sensor nodes, SNs, with limited computer resources capable for gathering, data processing and communicating. Energy consumption represents a barrier challenge in many sensor network applications that require long lifetimes, usually an order of several years. Sensor nodes, as constituents of wireless sensor networks, are battery driven devices and operate on an extremely frugal energy budget. Conventional low-power design techniques and hardware architectures only provide partial solutions which are insufficient for sensor networks with energy-hungry sensors. This paper surveys several techniques used in today's wireless sensor networks with order to surpass the problem of energy consumption, power management and energy harvesting. It provides an insight into how various power reduction techniques can be used and orchestrated such that satisfactory performance can be achieved within a given energy budget.**

Keywords – **Sensor node, Wireless Sensor Networks, power management, harvesting techniques.**

I. Introduction

Collections of tiny, inexpensive wireless sensor nodes (modules), organized in clusters and networks deployed over a geographical area, capable to integrate continuous and unobtrusive measurement, computing and wireless communication, have attracted much attention during the last decade in forming the concept of smart spaces. One of the many challenges associated with sensing multiple parameters from the environment, by using wireless sensor networks, is to how to transmit data and power the sensors. Batteries provide the most obvious power source of sensor nodes. In spite of the fact that battery technology is mature, extensively commercialized, and completely self-contained, even for relatively large battery capacity and moderate communication traffic requirements, the mean time to replacement or recharging is only two or three years. For deployment with hundreds of sensors, this means that a battery will need a replacement every few days, what represents an unsuitable rate for many applications. Several solutions to the power problem exist, such as reducing power consumption to the point where batteries can elongate the sensor module's lifetime. Another solution is energy harvesting–EH (or energy scavenging) - that is extracting energy from ambient sources. Common energy ambient sources for energy harvesting include mechanical energy resulting from vibration, stress and strain; thermal energy from furnaces and other heating sources; solar energy from all forms of light sources, ranging from lighting to the sun; electromagnetic energy that is captured via inductors, coils and transformers: wind and fluid energy resulting from air and liquid flow; human energy which depend of human movement by foot, human skin and blood; and chemical energy from naturally recurring or biological processes. This solution assumes that the wireless sensor node completely alone, can capture and accumulates energy as it becomes available. In most cases, these energy sources provide energy in very small packets that have previously been difficult to capture and use. Because of that, capturing, accumulating, and storing of small packets of electrical energy requires high energy efficiency. The harvesting circuit must stay in active mode permanently, to be ready to capture harvestable energy whenever it becomes available, and to be capable to provide an output as the application requires. The power consumption of the harvester has to be very small so that the energy consumed by this circuit is much smaller than the energy provided by the ambient sources. The second key component of the harvester is its high energy retention, i.e. the capability to store the captured energy for as long as possible with minimal leakage or loss. Energy harvesting circuits must have extremely high energy retention, due to the infrequency of the energy capture activity. Low harvesting activity levels mean that it may be many hours before enough energy has been stored by the energy harvesting circuit to trigger some activities of SNs, such for example data transmission, sensing data, collecting data, etc.. The energy harvesting circuit must also economize the stored energy in order to provide correct operation for the intended application.

This article starts from the fact that WSNs are ideally suited for long-lived applications deployed at large densities for low cost. The article discusses some promising techniques and research directions for alleviating the energy problem in wireless sensor node, including power management, energy aware sensing and environmental energy harvesting. Its aim is to point to some global viewpoint, concerning power reduction and energy harvesting problems, as useful design concepts for sensor node designers with order to provide long-lived sensor networks. The remainder of the article is structured as follows. Section II concentrates on sensor node system architecture. The workload profile of the sensor node is briefly discussed in Section III. Section IV deals with power management techniques currently implemented in sensor nodes. The three main techniques used for energy harvesting

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are shortly presented in Section V. Finally concluding remarks are given in Section VI.

II. System Architecture of a Sensor Node

System architecture of a typical wireless SN is pictured in Fig. 1. The sensor node is comprised of four subsystems: i) computing subsystems consisting of microprocessor or microcontroller; ii) a communication subsystem consisting of a short range radio for wireless communication; iii) a sensing subsystem that links the node to the physical world (external environment) and consists of a group of sensors and actuators; and iv) power supply subsystem which houses the battery, DC-DC converter, and energy harvester.

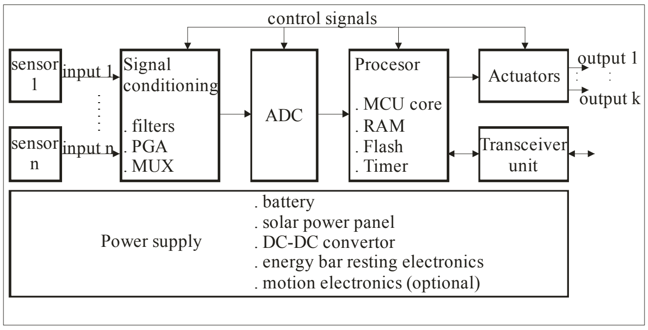

Fig. 1. System architecture of a typical wireless sensor node

A. Computing Subsystem – Microcontroller (MCU)

Most computing subsystems of SNs' are implemented as CMOS MCU fully static devices which operate from very low frequencies from 1 kHz up to 32 kHz, to a maximum speed from 1 MHz at 1.8 V DC up to 100 MHz at 5 V DC that depends on the technology. In spite of a hefty current consumption at 1 mA/ MHz the current draw may still be 100 µA at 32 kHz, when the MCU is running continuously, what is not sufficient to achieve multi-year battery life [1]. In this approach, the MCU is put into a power-savings mode, such as idle, sleep or stop mode.

Early MCUs required an external event to toggle a pin. Modern MCUs can wake-up from internal-timer events or external I/O pin events. Using the wake-up timer allows the MCU to enter in the power-savings mode for 99.9% while running 0.1% of the time.

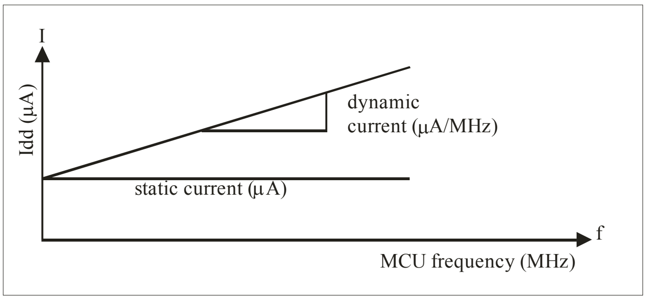

Fig. 2. Dynamic versus static current

When the MCU is built entirely of clocked CMOS logic circuitry, the current consumption is perfectly linear of clock speed, with zero offset current. This was the case when there were simple ROM-based MCUs without any analog circuitry.

Today's modern mixed-mode MCUs are flash-based and packed with analog circuitry. The active mode current is composed of two elemental components: static current and dynamic current. The dynamic current consumption is the increment current change versus a change in clock frequency (see Fig. 2).

The static current is a current component that is independent of operating frequency and is composed of analogue-block currents, flash-module current and leakage current.

TABLE I
Power consumption for some common CPU

CPU	Power suplay [V]	Power Active [mW]	Powe down [µW]	Sensor Node
4-bit CPU				
EM6603	1,2-3,6	0,0054	0,3	
EM6605	1,8-5,5	0,012	0,9	
8-bit CPU				
ATtiny 261V/ 461V/861V	1,8-5,5	*0,38 mA @ 1,8V 1MHz	*0,1	
PIC16F877	2-5,5	1,8	3	CIT
MC68HC05PV8A	3,3-5	4,4	485	
AT90LS8535	4-6	15	45	WeC Rene
ATmega163L	2,7-5,5	15	3	Rene2 Dot
ATMega103L	2,7-3,6	15,5	60	Mica IBadge
C8051F311	2,7-3,6	21	0,3	Parasitic
ATmega128L	2,7-5,5	26,7	83,15	Mica Mica2Dot Mica2 BTnode
PIC18F452	2-5,5	40,2	24	EnOcean TCM
80C51RD+	2,7-5,5	48	150	RFRAIN
16-bit CPU				
MSP430 F149	1,8-6	3	15	Eyes,BSN
MSP430F1611	1,8-3,6	3 1,5	15 6	Telos SNoW[5]
MC68EZ326	3,3	60	60	SpotON
32-bit CPU				
AtmelAT91 ARM Thumb	2,7-3,6	114	480	
Intel PXA271	2,6-3,8	193	1800	iMote2
Intel StrongArm SA1100	3-3,6	230	25	WINS µAMPS

Most analogue blocks, independently of the MCU clock frequency, have a significant current drain while the analogue block is powered. The flash memory typically draws current to power the array and read from flash cell. In some cases memory blocks draw more current than the CPU, especially at low clock speed. The leakage current depends very much on the process technology. The active-mode static current might be 10 times the current in a power-savings mode. To minimize the active static current the SN must operates at a low duty cycle, what means that faster speed results in substantial power savings. In addition, as the lithography advances the dynamic current goes down, but the static leakage current (for low-voltage submicron technology) tends to increases. Thus, low duty-cycle operation is more beneficial for the more advanced technologies.

Table I shows power consumption of the most popular CPU installed in some standard sensor nodes [2-4].

Performances of analogue peripherals represent also important consideration in managing power consumption. For example, a high-performance 300 ksamples/s 10-bit SAR ADC can complete 12 acquisitions in about 40 µs. The faster the ADC, the shorter the acquisition time and the sooner the MCU can go back to sleep. High-end ADCs also reduce the effective duty-cycle required for data-acquisition. In general, as technologies move toward deep-submicron (< 90 nm), performance will continue to increase, while power savings modes become more important.

By analyzing Table I we can conclude that CPUs with 4-, 8-, 16-, and 32-bit data bus width are implemented in SNs. 4-bit CPUs were used in first SN`s generation, mainly intended for acquiring on/off signals (light detection, temperature, movement). The second generation of SNs is typically realized with 8-bit CPU. In average the power consumption in active mode of operation varies from 3 mW up to 30 mW, and in power down mode is about 10 µW. Modern SNs use 16/32-bit CPU with larger number of power down modes, and are intended for multimedia data acquisition (voice, image). The power consumption of 32-bit CPUs in active mode is >100 mW.

B. Communication Subsystem – Radio

The SN's radio provides wireless communication with neighboring nodes and the outside world. Several factors affect the power consumption characteristics of a communication subsystem, including the type of modulation scheme, data transfer rate, transmit power, and the operational duty cycle. Table II shows power consumption of the most popular radio modules (transceivers) used by sensor nodes [2], [5], [6]. From communication aspect of wireless SNs operation, the physical layers can be considered to be in one of the five states:

a) Off- the only power consumption is leakage current, but coming out of the off-state can take a long time (many ms).

b) Sleep/ Standby- the SN may be consuming as little as (100-300) µW and can wake-up quickly unless the main crystal oscillator is turned off.

c) Listen- the SN is listening for a packet to arrive, so most of the radio receiver must be on. State-of-the-art power numbers for SN communication modules in this mode are within a range from 9 mW up to 40 mW, respectively.

d) Active Rx- similar to the Listen state, but use of additional circuitry may push power consumption for transceiver to 50 mW.

TABLE II
POWER CONSUMPTION FOR SOME COMMON RADIOS MODULES

Type	Clock [MHz]	Rx power [mA]	Tx power [mA/dBm]	Power down [µA]
low-power radio modules				
MPR300CB	916	1,8	12	1
SX1211	868-960	3	25/10	
TR1000	916	3,8	12/1,5	0,7
CC1000	315-915	9,6	16,5/10	1
medium-power radio modules				
nRF401	433-434	12	26/0	
CC2500	2400	12,8	21,6	
XE1205	433-915	14	33/5	0,2
CC1101	300-928	14,7	15	0,2
CC1010	315-915	16	34/0	0,2
CC2520	2400	18,5	17,4/0	<1
CC2420	2400	19,7	17,4/0	1
CC1020	402-915	19,9	19,9	0,2
CC2430	2400	19,9	19,9	
PH2401	2400	20	20	
nRF2401	2400	22	10/0	0,4
CC2400	2400	24	19/0	1,5
CC2530F32	2400	24	29/1	
RC1180	868	24	37/0	
LMX3162	2450	27	50	
STD302N-R	869	28	46/0	
MC13191/92	2400	37	34/0	1
hugh-power radio modules				
ZV4002	2400	65	65/0	140

e) Active Tx- in the transmit state, the SN's active components include the RF power amplifier, which often dominates in high-power transmit systems. State-of-the-art power consumption for SN transceiver module is in average 40 mW at 0 dBm Tx power.

By analyzing Table II we can conclude that radio modules are used for all three ISM bands: 433.05 - 434,79 MHz, 902 - 928 MHz i 2400 - 2483,5MHz. Having in mind that the duty cycle ration between transmit (Tx) and receive (Rx) mode is usually 1:1000, we decide to classify radio modules according to the current consumption in receive mode (Rx power). The first group, called *low-power* is characterized by current consumption less then 10 mA. For the second group, called *medium-power*, the current consumption is within a range from 10 mA up to 50 mA. In the last group, referred as *high-power*, the current consumption is >50 mA.

C. Sensing Subsystem

Sensor transducers translate quantities from the non-electrical (physical) domain into the electrical domain (electrical signals). According to the type of output they produce sensors can be classified as analogue or digital circuits. There exists a diversity of sensors that measure environmental parameters such as temperature, light intensity, humidity, proximity, magnetic fields, etc.

There are several sources of power consumption in a sensor including [7]: i) signal sampling and conversion of physical signals to electrical ones; ii) signal conditioning; and iii) A/D conversion. Table III lists power consumption of some common of-the-shelf sensors [2], [8].

Several factors need to be considered when selecting sensors for use in tiny wireless SNs: a1) volume; a2) power consumption; a3) suitability for power cycling; a4) fabrication and assembly compatibility with other components of the system; and a5) packaging needs, as sensors that require contact with the environment, such as chemicals, add significant packaging considerations.

TABLE III
POWER CONSUMPTION FOR SOME COMMON SENSORS

Sensor type	Sensing	Power [mW] consumption
micro-power		
SFH 5711	Light sensor	0,09
DSW98A	Smoke alarm	0,108
SFH 7741	Proximity	0,21
SFH 7740	Optical Switch	0,21
ISL29011	Light sensor	0,27
STCN75	Temperature	0,4
low-power		
TSL2550	Light sensor	1,155
ADXL202JE	Accelerometer	2,4
SHT 11	Humidity/temper.	2,75
MS55ER	BarometricPressure	3
QST108KT6	Touch	7
SG-LINK(1000Ω)	Strain gauge	9
medium-power		
SG-LINK(350Ω)	Strain gauge	24
iMEMS	Accelerometer	30
OV7649	CCD	44
2200-2600 Series	Pressure	50
high-power		
TI50	Humidity	90
DDT-651	Motion Detector	150
EM-005	Proximity	180
BES 516-371-S49	Proximity	180
EZ/EV-18M	Proximity	195
GPS-9546	GPS	198
LUC-M10	Level sensor	300
CP18,VL18,GM60	Proximity	350
TDA0161	Proximity	420
ultra high-power		
FCS-GL1/2A4-AP8X-H1141	Flow control	1250
FCBEX11D	CCD	1900/2800
XC56BB	CCD	2200

In principle, due to diversity of sensors there is no typical power consumption number. In general, passive sensors such as temperature, touch, seismic, etc., consume negligible power relative to other SN's subsystems. However, active sensors, such as level sensors, proximity, pressure, humidity, flow control, imagers, etc., have usually acquisition times longer than transmission times, and accordingly they consume significantly more energy then the radio.

We divide sensors (see Table III) into five groups. The on/off sensors belong to the *micro-power* group with power consumption <1 mW. The second group, referred as *low-power*, characterizes power consumption less than 10 mW and small amount of linear signal processing. Sensors of m*edium-power* group have consumption within the range from 10 mW up to 50 mW and are realized with mixed circuits (analogue and digital electronics). In high-power group of sensors, some kind of dedicated signal processors are implemented. This possibility makes the sensor of this group to be SMART devices. The power consumption of this group is from 50 mW up to 1 W. The last group, *ultra high-power*, characterize consumption > 1 W. Due to higher power consumption for the last two groups harvesting electronics is usually obligatory.

D. Low-power versus Ultra-low-power Sensor Node Design

As it was previously mentioned the top consideration in the design of wireless sensor node is that energy consumption is paramount. During this, one possible differentiation between low-power design and ultra-low-power sensor node design is that the former tries to maintain performance while reducing power, but the latter has very minimal performance requirements and sacrifices everything to minimize power consumption.

E. Energy Sources

Usually, wireless sensor nodes utilize a combination of energy storage and energy scavenging devices.

Capacitors may also be used in these systems to effectively lower the impedance of a battery or energy harvester in order to allow larger peak currents or to integrate charge from energy harvester to compensate for lulls, such as night-time, for a solar cell. Current capacitors, such as Ultra-capacitors, store up to 10 mJ/mm^3, which is less than 1 % of the energy density of lithium cells.

F. Batteries Issues

From the system's perspective, a good micro-battery should have the following features [9]: 1) high energy density; 2) large active volume to packaging volume ratio; 3) small cell potential (0.5 – 1.0 V) so digital circuits can take advantages of the quadratic reduction in power consumption with supply voltage; 4) efficiently configured into series batteries to provide a variety of cell potentials for various components of the system without requiring the overhead of voltage converters; 5) rechargeable in case the system has an energy harvester.

A number of small batteries are being developed until now for wireless communications. It seems that three cell chemistries currently dominate the growing wireless sensor network application market: Nickel-Metal Hydride (NiMH), Lithium Ion (Li-Ion), and Lithium Polymer (Li-polymer).

Each battery type has unique characteristics that make it appropriate, or in-appropriate, for a SN. Knowing the specific characteristics of each cell chemistry in terms of voltage, cycles, load current, energy density, charge time, and discharge rates is the first step in selecting a cell for a SN. The following discussion gives a short overview of the characteristics, strengths, and weaknesses of each of the three cell chemistries.

Nickel-Metal Hydride (NiMH): Characteristics of NiMH batteries include a nominal voltage of 1.25 V, 500 duty cycles per lifetime, less than 0.5 C optimal load current, an average energy density of 100 Wh / kg, less than four-hour charge time, typical discharge rate of approximately 30 percent per month when in storage, and a rigid form factor. NiMH Battery systems excel when lower voltage requirements or price sensitivity are primary considerations in cell selection. NiMH Systems can be configured with up to ten cells in a series to increase voltage, resulting in a maximum aggregate voltage of 12.5 V [10].

Lithium Ion (Li-Ion): Li-ion battery characteristics include a nominal voltage of 3.6 V, 1000 duty cycles per lifetime, less than 1 C optimal load current, an average energy density of 160 Wh / kg, a less-than-four-hour charge time, typical discharge rate of approximately ten percent per month when in storage, and a rigid form factor. These characteristics make Li-Ion battery systems a good option when requirements specify lower weight, higher energy density or aggregate voltage, a greater number of duty cycles, or when price sensitivity is not a consideration. Li-Ion battery systems can be configured up to seven cells in series to increase voltage, resulting in a maximum aggregate voltage of 25.2 V [10].

TABLE IV
BATTERY PARAMETERS

Voltage	Nominal cell voltage
Capacity	The amount of electrical charge that can be stored
Specific Energy	The volume-related content, measured in energy/weight
Energy Density	The volume-related content, measured in energy/volume
Internal resistance	Characterizes the ability to handle a specific load
Self discharge	The internal leakage, and aging effects
Re-charge cycles	The number of charge cycles before performance degrades
Charging procedure	Type of charge circuit required

Lithium Polymer (Li-polymer): Li-polymer cells have similar performance characteristics when compared with Li-Ion cells, but have the advantage of being packaged in a slightly flexible form. However, this flexibility is often misleading, as Li-polymer cells should remain flat when installed in a device, not even bending for installation in the battery system. Characteristics of Li-polymer cells include a nominal voltage of 3.6 V, 500 duty cycles per lifetime, less than 1 C optimal load current, an average energy density of 160 Wh / kg, less than four-hour charge time, typical discharge rate of less than ten percent per month when in storage, and a semi-rigid form factor. Li-Ion cells can be configured up to seven cells in series to increase voltage, resulting in a maximum aggregate voltage of 25.2 V [10].

The crucial battery parameters are given in Table IV and V [11].

TABLE V
BATTERY TYPES

Type	Voltage	Energy density	Specific energy	Self discharge
Lead-acid	2.0 V	60-75 Wh/dm^3	30-40 Wh/kg	3-20%/ month
Nickel Cadmium	1,2 V	50-150 Wh/dm^3	40-60 Wh/kg	10%/ month
Nickel Metal Hydrid	1.2V	140-300 Wh/dm^3	30-80 Wh/kg	30%/ month
Lithium-Ion	3.6 V	270 Wh/dm^3	160 Wh/kg	5%/ month
Lithium-polymer	3.7V	300 Wh/dm^3	130-200 Wh/kg	1-2%/ month

III. WORKLOAD PROFILE OF SENSOR NODE

As is shown in Fig. 3 a typical workload profile for a SN consists of two distinct phases [12]:

1. low workload - corresponds to the state of a wireless SN in the absence of intruders. SNs periodically wake-up, sample their sensors in order to detect any intruders, and, in their absence, go back to sleep. To cope with high energy efficiency in this phase a SN should provide: a) ultra low power sleep mode; and b) rapid wake-up capability.

2. high workload - represents the state when intruder activity is detected. During this phase the SN performs significant amount of computation and communication with other SNs.

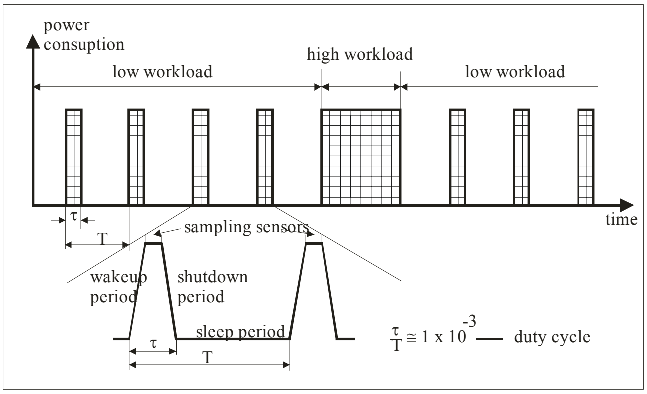

Fig 3 Two phases of SN's operation

A. Node Level Energy Minimization

The following two approaches are used for reducing energy consumed by a SN [13]:

1. duty cycling - consists of waking-up the SN only for the time needed to acquire a new set of samples and then powering it off immediately afterwards

2. adaptive-sensing strategy - is able to dynamically change the SN activity to the real dynamics of the process.

In designing the SN software modules (OS drivers) intended for manipulation with duty cycle control, special care should be devoted to a choice of the following two operating parameters:

a) wake-up latency: it is a time required by the sensor to generate a correct value once activated. For example, if the sensors' reading is performed before the wake-up latency is elapsed, the acquired data is not valid.

b) break-even cycle: is defined as the rate at which the power consumption of SN with implemented power management policy is equal to that of one with no power management.

More details concerning the hot-topic, problematic, how to extend the lifetime of sensor units with energy-hungry sensors, the readers can find in [14].

IV. POWER MANAGEMENT

One of the biggest problems in SN design is management of energy and/or power management.

In general most wireless sensor nodes have at least two modes of operation: a) an active mode, useful processing (sensing, digital signal processing and/or communication) takes place, and b) an idle mode - when the system is inactive. It is acceptable to have higher power consumption in active mode as a trade-off to increased performance, but any power consumed when the system is idle is a complete waste and ideally should be avoided by turning some parts of the sensor node off.

Conventional low-power design techniques and hardware architectures only provide point solutions which are insufficient for WSN's operation as a typical representative of highly energy-constrained systems. Energy optimization, in the case of sensor networks, is specific and much more complex, since it involves not only reducing the energy consumption of a single sensor node but also maximizing the lifetime of an entire network.

Designers address the energy problem at three levels: hardware, operating system, and application. At the hardware level, low-power circuit designs are used in order to reduce energy consumption. In addition, hardware devices can include some specific power management policies at the system's higher levels. At the operating system (OS) level, we can observe the applications' and devices' combined resource demands. Existing OS-level energy management tends to focus on individual devices. At the application level, you can save energy by making the applications energy aware. An energy-aware application can decrease its power consumption by reducing its activity, and it can give hints to the device manager or change its device-access pattern to create energy-saving opportunities for hardware.

Until recently most strategies for energy management assumed that data acquisition part of the sensor node consumes significantly less than data transmission. But, when this assumption does not hold, effective energy management strategies should includes policies for an efficient use of energy-hungry sensors, too.

A. Techniques for Power Management

Many techniques have emerged for saving active and leakage power in SNs. It is not uncommon to find multiple techniques at use in different parts of a SN design. In the sequel we will give a quick overview of these approaches:

a) Clock gating: is one of the earliest techniques for reducing dynamic power. It can increase static power because the clock-gating cells need to be fast and designers implement them with large, low-threshold transistors. This method simply shuts off the clock to portions of the SN that are inactive. Originally, designers used clock gating at the block level as a way of creating a standby mode. More recently, designers have employed fine-grain clock-gating, down to the level of individual latches. Control circuitry can simply decide not to issue a clock pulse on a cycle when the data in latch does not change.

b) Voltage islands: if some blocks can be slower than other, it make senses to run the slower blocks at lower frequency and turn down the supply voltage until these blocks just meet timing.

c) Power gating: involves turning off the supply voltage to a block in order to stop both static- and dynamic-power consumption. This technique involves a relatively complex mechanism which relate to determining how to sequence the shutdown and power-up cycles and whether it is possible to anticipate activity of the block early enough with aim to perform the power-up sequence. The designer must isolate the block from surrounding circuitry during power transitions.

d) Dynamic voltage frequency scaling: is a mixture of voltage islands and power gating. The designer adjusts the voltage and clock frequency of each block in the fly so that it is just meeting its deadlines for the current task. This technique requires fairly detailed knowledge of the application's performance requirements. The whole SN system must meet timing at every legal combination of block operating frequencies.

e) Dynamic threshold voltage control: dynamically controls the threshold of individual sets of transistors, thereby choosing a leakage-versus-speed point that just matches the requirements of the block on the selected path. Today, this approach is primarily used by only a few advanced-processor vendors.

In general, to achieve efficient energy reduction in SN it is necessary:

i) Reduce at an absolute minimum the energy needed for data transmission.

ii) All processes running in the SN should be optimized for speed and duration.

iii) Component not needed to support the process running at any point should be switched off, while for processes that have to run continuously, the focus is on reducing energy consumption.

Basic components of energy management blocks are:

1. Threshold detector- is responsible for monitoring whether spontaneous sensor information is available.

2. Timer- periodical processes are controlled by efficient timers.

3. Control logic- implemented as a FSM (*Finite State Machine*) intended for controlling the available energy sources, i.e. generating control signals for clock/power switching on/off, adjusting voltage/clock frequency, etc, on a block-by-block basis.

V. SOURCES OF ENERGY HARVESTING

Batteries can only store a limited amount of energy, which places an upper bound on network lifetime. An emerging technique that promises to circumvent this limitation is environmental energy harvesting (scavenging). The process of extracting energy from the surrounding environment and converting it into consumable electrical energy is termed as energy harvesting or power scavenging [16]. In general, harvesting sources are used to increase the lifetime and capability of SNs by augmenting the battery usage.

Energy harvesting is most applicable to applications that demand small amounts of continuous power or that have short periods of high-power use, which previously harvested and stored energy can provide for. SNs are typical candidate devices for such applications. Scavenging energy from the environment will allow the wireless SNs to operate nearly indefinitely, without their battery dying.

The added advantage of using energy scavenging devices is that they are usually small. For example, there are SNs which do not use any self-contained energy source; they only scavenge energy from the surrounding. Such nodes can be very small since they do not have to carry their energy sources with them. However, the supply of energy may be interrupted at a period of time since the power obtained from the surrounding can not be guaranteed all the time.

There are many types of energy harvesters each offering differing degrees of usefulness depending on the application [13]. The various sources for energy harvesting are wind turbines, photovoltaic cells, human body, thermoelectric generators and mechanical vibration devices such as piezoelectric devices or electromagnetic devices [15]. Table VI shows power outputs for typical energy scavenging devices [2]. The classification of energy harvesting can be organized on the basic of the form of energy they use to scavenge the power, and in general, we can distinguish three types of harvesting sources from surrounding [16]:

1. Photovoltaic Cells - Perhaps the best known harvesters (transducers) are solar or photovoltaic cells. This is a device that converts light energy into electrical energy. The form of energy exploited is typically light energy obtained usually from sunlight. From locations where the availability of light is guaranteed and usage of batteries and other means of power supply are not feasible or expensive, usage of solar cells is a convenient solution. While designing sources which scavenge solar energy the first thing which we must consider is the power supply requirements for SNs. The second, we must have in mind such factors as availability of day light, period of dense cloud and snow cover, effects of operation at higher latitudes, characteristics of the solar cells used and the intensity of the incident light. Solar radiation is the most abundant energy source and yields around 1 mW/mm^2 (1 J/day/mm^3) in full sunlight or 1 μW/mm^2 under bright indoor illumination. Solar cells have conversion efficiencies up to 30 %.

2. **Mechanical Vibration –** When a device is subjected of some movement, three type of energy can be generated: vibration, kinetic or mechanical. All types of this energy can be harvested, because they may be converted into electrical energy using the following mechanisms:

a.) piezoelectric – piezoelectric materials convert mechanical energy from pressure, vibrations or force into electricity. This property is considered by many researchers in order to develop various piezoelectric harvesters in order to power SNs in different WSN applications. Crucial property of piezoelectric materials is that it varies with age, stress and temperature. The possible advantages of using this kind of harvesters are the direct generation of desired voltage since they do not need a separate voltage source and additional components. But, they have some disadvantages because piezoelectric materials are brittle in nature and sometimes allow the leakage of charge [16].

b.) electrostatic – the principle of harvesting is based on changing the capacitance of vibration-dependent varactors. Vibrations separate the planes of an initially charged varactor, and the mechanical energy is converted into electrical energy. Electrostatic generators are in essence mechanical devices that produce electricity by using manual power. The main benefit of using the electrostatic converters is their ability to integrate them into microelectronic-devices, what means that they do not need any smart surrounding components. From the other hand, disadvantage of using electrostatic converters is that they need an additional voltage source intended for initial charging of the capacitor [16].

c.) electromagnetic – electromagnetic induction is the main principle in electromagnetic energy harvesting. Electromagnetic induction is defined as the process of generating voltage in a conductor by changing the magnetic field around the conductor. One of the most effective ways of producing electromagnetic induction for energy harvesting is with the help of permanent magnets, a coil and a resonating cantilever beam. Electromagnetic induction provides the advantage of improved reliability and reduced mechanical damping as there would not be any mechanical contact between any parts and no separate voltage source is required. However, the great disadvantage of this type is that electromagnetic materials are bulky in size and are complicated to integrate with SNs.

The electrostatic and piezoelectric harvesters are capable of producing voltage from 2 to 10 V, whereas the electromagnetic harvesters have limitation of producing a max. 0.1 V voltage amplitude [16].

3. **Thermoelectric Generators** – thermoelectric generators use the principle of thermoelectricity in order to produce a required electrical energy. The phenomena of creating electric potential following a temperature difference and vice-versa can be termed as thermoelectricity. It is well known that a voltage is generated when there is a temperature difference between two junctions of conducting material. Thermal energy harvesting uses temperature differences or gradients to generate electricity, e.g. between the human body and the surrounding environment. Devices with direct contact to human body can harvest the energy radiated from the human body by means of thermoelectric generator.

For applications where duty-cycling is acceptable, solar cells or other power scavenging sources can be used to trickle-charge a capacitor or battery after which the stored energy can be used at much higher-power rates than the charging pace. However, the supply of energy may be interrupted at a period of time since the power obtained from the surroundings cannot be guaranteed all the time.

TABLE VI
POWER OUTPUT FROM VARIOUS ENERGY SCAVENGING TECHNOLOGIES

Harvesting technology	Power Density
Solar cells – direct sun	15 mW/cm^2
Solar cells – cloudy day	0,15 mW/cm^2
Solar cells – indoors	0,006 mW/cm^2
Solar cells – desk lamp < 60 W	0,57 mW/cm^2
Piezoelectric – shoe inserts	330 μW/cm^2
Vibration – microwave oven	0,01-0,1 mW/cm^2
Thermoelectric – 10 °C gradient	40 μW/cm^2
Acoustic noise – 100 dB	9,6-4 mW/cm^2
Passive–human powered system	1,8 mW
Nuclear reaction	80mW/cm^3 1E6mWh/cm^3

VI. CONCLUSION

The rapid development of low power electronics has made it possible to create wireless networks of hundreds or even thousands of devices of low computation, communication and battery power. The networks can be used for example as distributed sensors to monitor large geographical areas in remote surroundings. In these applications, devices have their own batteries to provide energy. Since every message sent and received, input quantity sensed, and computation performed drains the battery, special care is required in the utilization of power. Achieving sensor lifetime of several years and providing nontrivial application functionality represents one of the highest challenges for designers. This article present research directions for alleviating the energy problems in development of wireless sensor networks, including wireless sensor architecture, power management techniques, and environmental energy harvesting approaches.

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