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Wireless Sensor Networks: A Survey on Ultra-Low Power-Aware Design

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Abstract**—**Distributed wireless sensor network consist on several scattered nodes in a knowledge area. Those sensors have as its only power supplies a pair of batteries that must let them live up to five years without substitution. That's why it is necessary to develop some power aware algorithms that could save battery lifetime as much as possible. In this is document, a review of power aware design for sensor nodes is presented. As example of implementations, some resources and task management, communication, topology control and routing protocols are named.

Keywords**—**Low Power Design, Power Awareness, Remote Sensing, Wireless Sensor Networks (WSN).

I. Introduction

A distributed wireless sensor network is formed by several scattered nodes, from hundreds to thousands, in a sensor field. Each node contains both processing and communication elements and has as main functionality event-oriented environment monitoring. Collected data from the environment are sent to the base station to be processed. Thanks to the great node density in this kind of networks, collaboration among them allows creating a high quality and failure resistant environment monitoring system [1,2].

Lately it has appeared an increasing interest in developing wireless sensor and actuator networks. These networks can be applied in a large variety of applications, such as:

- Continuous patient monitoring.
- In-building people localization for efficient energy control.
- Aircraft fatigue breakage supervision.
- Dangerous and harmful agents' detection in great traffic density areas
- Tornado evolution analysis.
- Forest fire, earthquake or flooding detection.
- Remote terrains monitoring.
- Environmental danger detection.
- Metropolitan area traffic study for routes planning.
- Free parking spot control.
- Home, mall, public buildings and some others facilities surveillance and security.
- Military applications for detecting, locating or tracking enemy movement.
- Potential terrorist attacks alert.
- Vineyard management.
- Interactive museums or toys.
- Domotics.

As these applications show, embedded electronic devices will be a part of our daily life in applications that go from entertainment to automobile factories. *Power Awareness* plays a vital role in wireless sensor networks life. But not only it is important to manage existing resources correctly in order to avoid wasting them and reserve some of them for critical situations, but also regenerating or *harvesting* consumed energy as much as possible, to make network live longer. The secret to reduce both energy consumption and dissipation so much lies in power aware designing of each layer of the system. In this document, we present a survey on every sensor node's part that is susceptible of power-aware designing.

The rest of the document is organized as follows. In section II, design steps are listed. In section III node consumption is presented and in section IV is optimized. Network management is explained in section V and finally, section VI summarizes and presents conclusions.

II. Power-Aware Design

Sensor network technology has faced several challenges in hardware, communication protocol and application design in order to be a reality [3]. Advances in MEMS (*Micro Electro Mechanical Systems*) technology, radio circuitry and DSPs, have help to overdraw these challenges in a more or less successful way. Some of those challenges are [1,4]:

- Low cost (hundreds to thousands nodes per network).
- Low power consumption (battery supplied lifetime of 3–5 years).
- Network intelligence for data gathering (autonomous networks without human management).
- Resource limited nodes (energy power supply, computational capacity and memory).
- Dynamical reaction to changing network conditions and

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topology modifications.

- Minimum impact (nodes have to be small and go unnoticed).
- Reliability (*Fault tolerance* thanks to high level redundancy).
- Measurement accuracy improvement (processed information from many distributed sensors).

Furthermore, a sensor node has a high consumption element: the radio module. This is an essential module in a wireless sensor network node, but reducing the dissipated energy in communication is the hardest task in developing a highly dense wireless sensor network of scattered micro-nodes. Unlike in other wireless networks, such as MANET, Bluetooth® or HomeRF, sensor networks can have around hundreds or even thousands of nodes, generally stationary, where QoS (*Quality of Service*) is not the first objective, but making sensors' life as longer as possible. In fact, in these kind of networks, network connectivity degradation is not dependent on the mobility of the nodes but on their battery lives. That's why node's and network's global performance highly depends on the energy efficiency of the implemented algorithms [5].

III. Node Power Consumption

The first step in wireless sensor network power aware design is identifying which parts of a sensor node need more power supply than the others:

- Control unit gives intelligence to a sensor node. Its main purpose is controlling the sensing parts and executing the communication protocols and the data processing algorithms [5,6].
- The radio module of a sensor offers wireless communications with its neighbourhood and external world. Several factors have influence in radio module power consumption, such as, modulation scheme, data rate, transmission power and duty cycle. In general, radio modules work in four different stages: Transmission, Reception, Idle (module is on but not transmitting or receiving) and Sleep (switched off). In most radio modules, it is important to take into account that Idle state wastes as much energy as Reception state. Therefore, a very important point is switching off completely the radio module whenever there is no transmission or reception scheduled, instead of leaving it in Idle state. Furthermore, a working state change generates a transitory activity in the radio module's circuitry that leads to a important energy dissipation [7]. There are several researches about how radio module transmitted energy control affects in packet broadcasting in the network and how that would modify its behaviour. As a result, there are some mechanisms that offer power control adjustment, such as COMPOW (COMmon POWer), CLUSTERPOW (CLUSTER POWer), MINPOW (MINimum POWer) and *Flexible Power Scheduling* (FPS) [8].
- Transducers translate physical magnitudes to electric signals and can be classified in active ones and passive ones. Passive sensors do not need power supply for measuring while active ones require a external energy. In general, passive sensors' energy consumption is not significant in comparison with the rest of the components of the node.
- Every node component is battery-powered, so these parts play a very important role in node lifetime. Batteries are not simple devices, and their operation depends on many factors, such as battery dimensions, type of electrode material and some nonidealities that can appear during normal operation and decrease system lifetime. Moreover, for the nodes to be useful and easily deployable, they have to be small, which limits seriously the possibility of including a battery large enough to supply energy for all its lifetime (3–5 years). Taking into account this, a rechargeable battery along with a power harvesting source seems to be the most suitable option. As an example of different power harvesting mechanism, there are photo voltaic, thermoelectric, human, pressure variations and vibration energy [9].

IV. Node Optimization

Now that we know which parts of a sensor node consume a significant amount of the battery current, minimizing power consumption is required. To achieve that, it is necessary to implement power-aware design methodologies and systems architectures that let the network be autonomous.

There are some techniques that offer power consumption reduction, such as:

- *Dynamic Power Management* (DPM) algorithms try to reduce system consumed energy making components go to low power consumption state selectively. This can be achieved thanks to a previous analysis of the system duty cycle and each element's load [10-13]. As a example of this algorithms, there are some real-time implementations, such as, *Resource-constrained Energy-Efficient Utility Accrual Algorithm* (ReUA) [14], (developed from *Energy-efficient Utility Accrual Algorithm* (EUA) [15]), *Uncertainty-Based Scheduling* (UBS) [16] and *Earliest-Deadline First* (EDF) [17,18].
- Both *Dynamic Voltage Scaling* (DVS) and *Dynamic Frequency Scaling* (DFS) algorithms reduce power consumption varying a functional characteristic: voltage or frequency, respectively [19-24]. They have mainly the same philosophy: make computational unit work faster when it has load (with a higher voltage or frequency) and slowly when there is no computational activity. This way, power consumption gets reduced to its minimum. Most interesting implementations are: *Variable Speed Constant Bandwidth Server* (VS-CBS) [25], *Genetic List Scheduling Algorithm for Energy-Efficiency* (EE-GLSA) [26], *General Dynamic Voltage Scaling* (GDVS) [27] and *Real-Time DVS* (RT-DVS) [28-31].
- *Dynamic Thermal Management* (DTM) controls CPU

energy dissipation thanks to a dynamic chip temperature management [32-34] and *Dynamic Modulation Scaling* (DMS), applies to radio transmission modulation the same philosophy as DVS does with supply voltage.

Although these techniques offer power consumption reduction, they increase system latency. However, sensor networks have parallel processing capability so if algorithm calculations are shared among some nodes, allowed latency to each one is higher. This way DVS, DFS, etc can be applied and reduce global network consumption. However, parallel processing demands more inter-node communication with its associated cost.

Furthermore, sensor networks lifetime can be improved drastically if system software, including operating system, application layer and routing protocols, are designed to be power-aware. As the heart of the operating systems lies the *Task Scheduller* that schedules system tasks execution, making sure of fulfilling each one's temporal restrictions. Therefore, it is necessary to apply power-aware concept in organizing task processes [35].

Radio modules can not be treated as CPU was in the former paragraphs because in radio communications it is better to transmit as soon as possible. If we analyze the consumed energy in transmitting one information bit in comparison with the required power for executing one instruction, we would realize that radio module designing needs special attention. If radio module is switched on longer than strictly necessary, a great amount of power is wasted. There are several approximations, such as *Power Aware Multi-Access protocol with Signaling* (PAMAS) that lets nodes switch off its own radio module when neither it nor its neighbours have packets to send. Moreover, packet overload can be reduced to just 16 bits if internal processing is done and furthermore, if reusable, short and Huffman codified ones are used, MAC addresses can be reduced up to 10 bits [36].

The most evident way to make communication efficiency higher is reducing transmission time. This can be achieved codifying more than one bit per symbol, that's it, implementing M-ary modulation. In standard situations, 16-QAM is the best way to save energy in wireless communications, because it is adjusted to the optimal parameters. Moreover, as radio module's start up draws a significant amount of current in comparison with the whole consumption, module's awake status has to be exploited as much as possible instead of wake up the module every now and then [7]. Furthermore, good error control mechanisms have to be implemented as they minimize packet retransmission and consequently power consumption [37].

Apart from monitoring its environment by means of its sensors and transmitting its own data to the rest of the nodes, a wireless sensor network node has to act as router, broadcasting packets received from other nodes. In fact, in a typical sensor network, a great percentage, around 65%, of all the received packets in a node have to be redirected to other destinations. In most node architectures, protocol functionality is implemented in the central processing unit. Therefore, every received packet, regardless its destination, goes to the processing subsystem and is processed. This generates a great and unnecessary power consumption. An intelligent radio hardware would be able to identify packets that have to be forwarded and would not bother the central unit. This way, these packets will not pass through the processing unit and the latter could keep on sleeping, saving as much energy as possible [38].

V. Network Management

Traffic routing from data source to data destination, usually known as *sink*, is another obstacle in the way of power-aware designing. Node's multi-hop ability has to be used wisely: nodes cannot know in advance the optimal route as network topology changes continuously. So route discovery and tracking management protocols are needed. However, traditional implementations are not feasible in sensor networks because they waste more energy in maintaining routes updated than in transferring information packets.

In order to reduce discovery cost, researchers have developed different routing protocols, specific for wireless sensor networks, that can be classified into *proactive*, *reactive* (or *on-demand*) and *hybrid*. These protocols are presented below.

- *Proactive* protocols, where each node has routing information of every node in the network in storage tables and refreshes these tables periodically or whenever the network changes, such as, *Destination-Sequenced Distance Vector* (DSDV), *Wireless Routing Protocol* (WRP), *Global State Routing* (GSR), *Fisheye State Routing* (FSR), *Source-Tree Adaptive Routing* (STAR), *Distance Routing Effect Algorithm for Mobility* (DREAM), *Multimedia support in Mobile Wireless Networks* (MMWN), *Cluster-head Gateway Switch Routing* (CGSR), *Hierarchical State Routing* (HSR), *Optimised Link State Routing* (OLSR) and *Topology Broadcast Reverse Path Forwarding* (TBRPF) [39].
- *Reactive* or *on-demand* protocols were designed to decrease proactive protocols overload and that's why they just keep information about active routes, such as *Adaptive On-Demand Distance Vector* (AODV), *Dynamic Source Routing* (DSR), *Routing On-demand Acyclic Multi-path* (ROAM), *Light-weight Mobile Routing* (LMR), *Temporally Ordered Routing Algorithm* (TORA), *Associativity-Based Routing* (ABR), *Signal Stability Adaptive* (SSA), *Relative Distance Micro-discovery Ad hoc Routing* (RDMAR), *Location-Aided Routing* (LAR), *Ant-colony-based Routing Algorithm* (ARA), *Flow Oriented Routing Protocol* (FORP), *Cluster Based Routing Protocol* (CBRP) [39], *Associativity-Based Multicast* (ABAM) *On-Demand Multicast Routing Protocol* (ODMRP) y *Adaptative Demand-Driven Multicast protocol* (ADMR) [40].
- And *hybrid* protocols, whose behaviour is both *proactive* and *reactive*. This type of protocols divides the network in *clusters* or trees and uses *proactive* and *reactive* methods at different stages: maintain intra-zone routing information

refreshed in a proactive fashion whereas inter-zone routes are only updated when are needed. Some of them are: *Zone Routing Protocol* (ZRP), *Zone-based Hierarchical Link State* (ZHLS), *Scalable Location Update Routing Protocol* (SLURP), *Distributed Spanning Trees based routing protocol* (DST), *Distributed Dynamic Routing* (DDR) [39], *Geographical Routing Algorithm* (GRA) [41] and *Directed Diffusion Routing* [42].

Dense sensor networks would generate too much redundant information that in some cases would not be necessary and consumed power could have been saved. That's why topology management protocols appeared. Moreover, always routing through the best route is not the optimal decision, because that route's nodes will get their resources depleted much faster than the rest of the network's and this would compromise global connectivity. Nevertheless, it is not simple to determine the optimal traffic distribution when network activity is unknown. *Geographical and Energy Aware Routing* (GEAR) [43] and *Cell based Energy Density Aware routing* (CEDA) [44] base their routing decisions upon nodes' power resources, avoiding nodes with little energy left whereas distributed protocols, such as GAF, *Cluster-based Energy Conservation* (CEC) [45], SPAN [46], *Low-Energy Adaptive Clustering Hierarchy* (LEACH), centralized LEACH (LEACH-C), *Power Efficient Gathering in Sensor Information Systems* (PEGASIS) and *Base-station Controlled Dynamic Clustering Protocol* (BCDCP) [47] need nodes to change their behaviour periodically to assure homogeneous power consumption distribution. On the other hand, *Sparse Topology and Energy Management* (STEM) [48], exploits the fact that this kind of networks spends most of the time monitoring and waiting for events to happen whereas *cluster* based algorithm *Ad hoc Network Design Algorithm* (ANDA) [49] manages its cluster-heads to dynamically adjust cluster size (number of cluster nodes) through power control. There are some other protocols such as, *Geographic Ramdom Forwarding* (GeRaF) [50], that starts sending packets without knowing previously which route will take, XTC, that does not need exact geographical information and, *Local Information No Topology* (LINT), *Local Information Link-State Topology* (LILT), CONNECT and BICONN-AUGMENT [51] that are zero-overload protocols.

Although every node processes its own collected data, information from several adjacent nodes could be redundant, if known in advance, packet quantity in the network may be dramatically reduced. There is a technique that combines different sensor nodes' measurements into coherent data flows, known as *Data fusion*, *aggregation* or *gathering*. It has two types *Early aggregation* and *Late aggregation* [52] and several implementations: SMACS (*Self-organizing Medium Access Control for Sensor networks*), EAR (*Eavesdrop-And-Register*) [53], SAR (*Sequential Assignment Routing*), SWE (*Single-Winner Election*), MWE (*Multiple-Winner Election*) [3] and PEGASIS *Power-Efficient GAthering in Sensor Information Systems*. Although this mechanism tries to reduce the amount of flowing information through the network and consequently power consumption, in some situations the consumed energy in data aggregating is higher than the saved energy in packet sending [53].

In contrast with traditional way of reprogramming micro-controllers (In-System Programming, (ISP)), sensor networks need a way to update node's firmware without human intervention. That's why University of California at Berkeley developed XNP, a one-hop protocol that offered firmware update through the wireless link [54]. Nevertheless, its code dissemination does not allow multi-hop fashion and Deluge [55], MOAP [56] and MNP [57] appeared. These are based upon CSMA technology and offer a reliable way of code updating. In order to solve some CSMA problems with communication collisions, a TDMA based protocol appeared, Infuse [58]. Furthermore, protocol shown in [59] and Trickle are some more elaborated mechanisms that do not send the whole new program code, but just a summary of the differences between the current code and the new one.

VI. Conclusions

As shown in this paper, low power wireless sensor network design is not a trivial task. Almost every node part is susceptible of being power aware designed and this possibility adds one more variable to the problem. However, one degree of freedom in a problem solution also offers more flexibility and design improvement capability. Moreover, there are so many little improvements that it is difficult to decide which one to implement and that's why wireless sensor networks have to be designed very carefully and always with the capacity-power consumption trade-off borne in mind. Nevertheless, current applications show that low power aware design is the basis of wireless sensor networks development.

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