Power Management Technologies to Enable Remote and Wireless Sensing

May 2010

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Executive Summary

The true autonomy of sensor systems depends on their reliable operation for extended times without human intervention. Energy supply is a critical factor in this design. The growing power demand of feature-rich applications cannot be satisfied by the improvement levels in battery technology, and therefore sensor systems need to become leaner, and more energy-efficient. Power management is an active research topic aiming to control power consumption in sensor systems, while providing a reasonably good output or service.

The Power Management Action Group was established as a joint activity between the Sensors & Instrumentation KTN and the Electronics KTN. The Power Management Action Group complements the work of the Energy Harvesting Action Group as it became evident that existing sensing systems cannot operate efficiently by just adding energy harvesting modules. In the Power Management Action Group we take the view that the entire system [System = hardware platform + software (operating system & applications)] needs to be optimised in a holistic way from the design of the architecture to power management at the application and networking levels.

The main goals of Power Management Action Group were to:

- Investigate the state of the art in power management techniques and identify the best practice and key centres of expertise.
- Support KTN members interested in exploring opportunities, applications and successful deployment of energy harvesting & power management technologies.
- Determine recommendations for funding agencies on the challenges that they could support. The Power Management Action Group produced this report on the findings of the study in Spring 2010 and organised a conference on 27th May 2010 to disseminate the results.

This study briefly introduces the problems power management technologies trying to alleviate. Significant focus has been given to examining the barriers to application through consultation with both developers and potential users of the technology. Power management has become a systems problem and being addressed by all engineers involved in system design process and techniques are invented and deployed in both hardware and software. As a result of this increasing complexity, optimising power consumption is no longer confined to the scale of the device but embraces its environment through the networks it accesses. Such a challenge is similar to the one encountered for large mobile communication/multimedia networks, where devices commonly integrate photo and video camera sensors and wireless connectivity.

The main focus of the study is on establishing best practices and identifying remaining performance barriers and therefore on a set of key questions or issues that the potential user community have posed. These questions were arrived at by consultation with members of the Sensors & Instrumentation KTN and others expressing an interest in implementing self-powered wireless sensor networks. They have been grouped in 3 sets depending on the level the optimization focuses on. Issues explored related to the themes of:

Microprocessor level Power Management
- Issue 1 – Causes and metrics of power dissipation in microprocessors

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1  http://www.tinyurl.com/ktnpmc
Node level Power Management

- Issue 4 – Power analysis of sensor nodes
- Issue 5 – Optimization of radio Components
- Issue 6 – Energy Harvesting Aware Power Management

Network-level Power Management

- Issue 7 – Measuring energy/performance trade-offs
- Issue 8 – Power consumption and node density
- Issue 9 – Condition of a battery system

For each level the technical context for power management is reviewed. The power requirements of wireless sensor nodes are discussed. The study identifies some commercial and academic centres of expertise advancing power management technologies. The emphasis here is on UK and Europe although others are identified. An intellectual property landscape analysis is also performed to show which organisations and countries are claiming the bulk intellectual property in the field.

Finally, the study makes recommendations aimed at improving or achieving the goal of practical implementation of power management to enable remote and wireless sensing in applications of interest to industry. These include:

- Current energy harvesting devices are largely inefficient and will continue to be so unless tailored for particular applications and combined with efficient power management.
- Efficient power management demands a systems approach where software techniques exploit architectural features rather than relying only upon advances in low power circuitry or slow improvements in battery technology.
- Although many studies have evaluated power management techniques through simulation, experiences with prototype implementations have not always achieved the predicted levels of energy usage because of interactions with the rest of the system. Taking a whole-system approach as well as knowledge of the application profile can yield improved results.
- Power budgets must be set at the beginning of design rather than at later stages as trades-offs can be quite high at latter stages and result to additional complexity.
- There are significant opportunities to improve energy consumption by revising application programs to eliminate waste and configure them by employing available power management features. This can be achieved by promoting more awareness among application software engineers about the power management techniques available to them. Today’s engineering skills where every engineer has his own area of expertise and knows only vaguely the alternatives and what is connected to his part of the system are very far from the multidisciplinary skill-sets needed for adjusting today’s and tomorrow’s demanding products. Networking engineers at different levels of the supply chain is an essential task and KTNs have a key role to play in it.
- R&D funding in power management is essential towards supporting the widespread adoption of WSN systems, which otherwise could seriously damage their commercial viability. Academic researchers focus on power efficiencies while industry is demanding related
standards. An area that research is urgently needed is the accurate measurement of battery power density and standardisation of energy metrics so as to minimise the inconsistencies between data provided by vendors and experienced by systems integrators.

- The importance of skills required in developing more energy-efficient sensing and actuating devices will increase due to the proliferation of more demanding usage scenarios, creating significant opportunities for organisations and individuals with rare skills such as analogue electronics.
Introduction

The Sensors & Instrumentation KTN

The Sensors & Instrumentation KTN is a network of more than 2,700 organisations covering the whole of the UK’s sensing community and supply chain, from technology developers, systems integrators, instrumentation manufacturers through to end-users, research councils and government departments. The KTN embraces sensing in its entirety – from the principles of measurement and novel sensor technologies to instrumentation, deployment and data analysis. It works with industry and researchers to stimulate innovation in the development and deployment of sensors and instrumentation.

The Sensors & Instrumentation KTN is financially supported by the following organisations in recognition of the strategic importance of sensing to the UK economy and quality of life.

- Technology Strategy Board
- Science & Technology Facilities Council
- Biotechnology and Biological Sciences Research Council
- Natural Environment Research Council

This study is part of a range of activity to develop new priority areas of focus by engaging with both the suppliers and users of technology to understand the limitations of the state of the art in a particular technology and to address barriers to potential adoption. The topics for Action Group projects are selected by the Advisory Board of the Sensors & Instrumentation KTN.

The Sensors & Instrumentation KTN will be merging with the Electronics KTN and Photonics & Plastics Electronics KTN on 1 July 2010 to create the Electronics, Sensors and Photonics KTN.

Background and Objectives

The Sensors & Instrumentation KTN has for some time now had considerable activity in the area of wireless sensing and wireless sensor networks (WSN). It has also founded a network within its community to focus specifically on this topic – the Wireless Sensing Interest Group (WiSIG). The powering of remote and wireless sensors is widely cited within this group and elsewhere as a critical barrier limiting the uptake of this technology.

Increasingly dense microelectronic solutions underpin a new wave of non-invasive wireless sensing systems in commercial, military, space and medical applications for monitoring, control and surveillance. The driving features of this technology are self-power, long life, wireless telecommunication and sensing-control functionality. Integration however, in spite of its progress over the years limits the growth of such applications because energy and power are scarce when conformed to microscale dimensions. The fact is, even with the most energy-dense state of the art battery, the operational life of a miniaturized system capable of sensing, storage and wireless telemetry is relatively short, requiring periodic maintenance by personnel, which is costly and in many cases prohibitive and/or dangerous.

Unfortunately, practical realities challenge and limit its viability and ability to penetrate the market. The power delivered is not necessarily in the form required, as loading applications often demand specific voltage and impedance characteristics. Transferring energy and conditioning power also
require energy and power, substantially reducing the already limited capabilities of the system.

Many of the advantages of wireless sensor networking disappear if individual nodes require an external power source. Ongoing power management developments enable electronic circuits to operate longer for a given power supply however this has its limitations and power harvesting is a complementary approach. Energy harvesting is a means of powering wireless sensor nodes by converting many low grade ambient energy sources such as environmental vibrations, human power, thermal sources, solar, wind energy and their conversion into useable electrical energy. Energy harvesting devices are attractive as replacements for batteries in low power wireless electronic devices. The goal is to achieve power sources that operate over a wide range of operating conditions and for extended time periods with high reliability.

Although there is a considerable body of research into power management, this is a rapidly growing area with many recent developments. Nevertheless, a number of limitations are evident when considering the growing demand for additional features and low maintenance. Therefore the Sensors & Instrumentation KTN and Electronics KTN have supported an Action Group project to focus on this technology area and particularly the barriers limiting its current uptake. It is intended that this study becomes the basis for a further activity to be delivered by the new Electronics Sensors & Photonics KTN and other collaborating organisations.

The main focus of the study is on establishing best practices and identifying remaining performance barriers therefore on a set of key questions or issues that the potential user community has posed. These questions were arrived at by consultation with members of the Sensors & Instrumentation KTN and others expressing an interest in implementing self-powered wireless sensor networks. They have been grouped in 3 sets, depending on the level the optimization focuses on as per Figure 1. Issues explored related to the themes of:

Microprocessor level Power Management

- Issue 1 – Causes and metrics of power dissipation in microprocessors
- Issue 2 – Dynamic voltage scaling (DVS)
- Issue 3 – Selection of a Microprocessor
Node level Power Management
- Issue 4 – Power analysis of sensor nodes
- Issue 5 – Optimization of radio Components
- Issue 6 – Energy Harvesting Aware Power Management

Network-level Power Management
- Issue 7 – Measuring energy/performance trade-offs
- Issue 8 – Power consumption and node density
- Issue 9 – Condition of a battery system

Scope and Limitations
The field of power management R&D is large and very diverse. It is therefore neither possible nor sensible to include a detailed technical review of all aspects of power management technologies within this report. Such information may be found in various reviews referenced at the end of the report and by consulting with the organisations described in the section on Centres of Expertise.

The primary focus of the study is on establishing best practices and identifying remaining performance barriers so most attention is devoted to addressing industry’s questions and concerns. These issues are those raised by a selected group of organisations that are either involved in attempting to adopt power management techniques or are assessing it for specific applications. The question set developed (see Section Key Issues: Barriers and Limitations) is only as representative as the diversity of the organisations consulted. The composition of this group is however diverse and the consultation process specifically asked for input on any major issues that weren’t captured by the question set.

Methodology
The approach taken was driven by the focus on industrial application and the perceived performance barriers. The initial activity was to form a steering board for the project from those organisations on the Sensors & Instrumentation KTN that had an active interest in power management technologies. This board then recommended a set of questions on key issues. These issues/questions were further developed by consultation with other interested organisations.

A programme of meetings, telephone interviews and an online survey was then used to gather input structured around the question set and to provide supporting information on the state of the art. In parallel, desk based research was used to widen the technical and geographical reach of the study. In developing the report the community of researchers, core technology developers and end users of the technology were engaged to validate the findings and provide comment on the text as it developed through the various iterations.

The report is therefore the collection of the views of the parts of the research community and the potential user community that were willing and available to get involved in this study.

Who should read this?
The target audience for this report is primarily those with an interest in applying power management technologies in practical applications. These may be systems integration organisations wishing to understand how likely the technology is to be able to address their clients’ needs. They may also
be those power management technology developers wishing to understand where the systems integrator community sees barriers or issues that they might then address.

The academic community most likely to be interested in this report will be those involved in research on wireless sensor networks. This report should help them to identify remaining problems and to find collaboration partners. It is anticipated that the findings of this study will also be of interest to the various funding agencies e.g. Technology Strategy Board, European Commission and UK Research Councils. It should inform them on gaps in R&D coverage of relevance to their particular remits. Specific recommendations will be prepared for each in separate summary papers.

Structure of the Report

This document first introduces the technical context within which power management technologies must operate. The core of the report revolves around the review of the limitations of the technology and establishing best practices as approached via the key question set. The various centres of expertise are then highlighted with a particular emphasis on UK and Europe and coverage of both academic groups and companies developing and/selling power management products or solutions. The report then concludes with a number of recommendations. Further reference information is organised in various appendices.
The Technical Context

Evolution of Electronic Components
Modern CMOS technologies has allowed manufacturers to greatly enhance a wide variety of circuits and systems by integrating signal conditioning, signal processing, digital output options, diagnostics and communications (Figure 2).

Sensor Networking Background
The purpose of this section is to place power management in context with the technical issues of using it for powering wireless sensors and nodes in a network and with the alternative approaches with which it competes. Recent advances in VLSI, MEMS, as well as in wireless communication technologies have made it possible to build sensor networks, enabling a paradigm shift in the science of monitoring — whether of buildings, transport systems, soil moisture, industrial equipment, healthcare, or myriad other applications. Sensor networks can significantly improve the accuracy and density of scientific measurements of physical phenomena because they can be deployed in large numbers directly where experiments are taking place. These networks consist of a large number of densely deployed nodes that gather local data and communicate with each other and do not have a fixed architecture. Their nodes integrate sensing, computational and communication capabilities and as a result the resources scale with network size.

Designing applications for sensor networks is challenging due to their large scale, communication volatility, and power consumption constraints at each node. Examples of experimental and commercial nodes (aka motes) are depicted in Figure 3. Several companies such as Picotux, Moteiv (now Sentilla), Gumstix, MEMSIC (bought the WSN lines of Crossbow in Dec 2009) and Libelium offer such nodes in the market. In addition, many companies (e.g. GE Energy, Pruftechnik, RLW) now design and build complete wireless sensor systems from basic components including wireless chipsets, microprocessors and sensors without using proprietary motes.
Some specific examples of wireless sensor networks include ExScal (a 1000+ node wireless sensor network and a 200+ node peer-to-peer ad hoc network of 802.11 devices in a 1.3km by 300m remote area in Florida)\(^2\), Argo (a global array of 3,000 free-drifting profiling floats that measures the temperature and salinity of the upper 2000m of the ocean)\(^3\) and GLACSWEB: a wireless sensor network to monitor glacier behaviour\(^4\). In the security and defense domains, it is not uncommon to have remotely deployed nodes with imaging capabilities (e.g. either IR or EO). In terms of operational longevity the state of the art for products used here is 5 months of continuous system operation between battery replacement and or recharge (because such device could be deployed in a covert manner it is not usually possible to implement an energy harvester).

The design of the system architecture is crucial to the longevity of the sensor networks, but the major constraints are introduced by the low power characteristics of wireless sensor network components. These low-power wireless sensor nodes provide a real incentive for investigating novel types of power sources.

**Powering up Sensors and Actuators**

An active sensor/component requires an electrical power source to work, while a passive one does not. Ultrasonic sensors, gas detectors, radar, and video cameras are active. A strain gauge (whose resistance changes with pressure applied) is passive. Some types of microphones are active while others (like piezoelectric microphones) are passive. They generate an output with only the input energy they are sensing. They do not need a power source to generate an output (though the output will usually be very low and need to be amplified with an active device). Thermocouples and thermopiles are passive. They generate a voltage output using the temperature energy they are sensing. They do not require an external power source to make their output. But it is very weak and probably needs to be amplified. Some RFID tags are passive, others are active. The active ones need a battery present to work. The passive ones take the RF energy being transmitted by the base unit, modify it somehow, and reflect it back out to be received by the base station, but they have a much shorter range than the active ones.

Typically, wireless communication systems aim for long range and high bandwidth efficiency (more bits/second/Hz), while wireless systems interfacing sensors and actuators aim at optimising a utility function (more bits/£/Joule). It is of vital importance to properly specify the measurement that the WSN must carry out to fulfill the user requirements. Factors such as sample rates, precision, synchronisation accuracy etc. all have a significant impact upon power consumption. Users often over-specify the system (e.g. sample more often than needed) if they have not properly defined the measurement.

\(^2\) http://cast.cse.ohio-state.edu/exscal/

\(^3\) http://www-argo.ucsd.edu/

The system architecture of a typical wireless sensor node is depicted in Figure 4. The node is comprised of four components: a) a power supply component, which includes a power source and the converter that powers the rest of the node, b) a sensing component that links the node to the physical world and consists of a set of sensors and actuators, c) a computing component consisting of a microprocessor or microcontroller that processes measurement data and stores them in the memory and d) a communication component consisting of a short range radio for wireless communication with neighbouring nodes and the outside world.

Several factors can affect the power consumption characteristics of such a wireless sensor node, the main of which are listed in Table 1 below.

**Table 1** Factors affecting the power consumption or longevity of a wireless sensor node.

<table>
<thead>
<tr>
<th>Power supply</th>
<th>Sensors</th>
<th>ADC</th>
<th>Microprocessor</th>
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<tr>
<td>• discharge rate</td>
<td>• physical to electrical signal conversion</td>
<td>• sampling rate</td>
<td>• core operating frequencies</td>
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<tr>
<td>• relaxation effect</td>
<td>• complexity of supporting components</td>
<td>• aliasing</td>
<td>• power proportional to process and computational load</td>
</tr>
<tr>
<td>• battery dimensions</td>
<td>• signal sampling</td>
<td>• dither</td>
<td>• ambient temperature</td>
</tr>
<tr>
<td>• supply voltages</td>
<td>• signal conditioning</td>
<td></td>
<td>• application code</td>
</tr>
<tr>
<td>• type of electrode material used</td>
<td>• dynamic range (ratio between the smallest and largest possible measurements)</td>
<td></td>
<td>• peripheral utilisation</td>
</tr>
<tr>
<td>• diffusion rate of the active materials in the electrolyte</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>• ratio and duty-cycle of peak to average current</td>
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For instance, air pumps in some gas sensors.
Power Sources / Energy Harvesting

Power sources are fundamentally energy reservoirs. Energy reservoirs have a characteristic energy density, and how much average power they can provide is then dependent on the lifetime over which they are operating. Energy harvesting is a means of powering wireless electronic devices by scavenging many low grade ambient energy sources such as environmental vibrations, human power, thermal and solar and their conversion into useable electrical energy.\(^6\) The energy provided by an energy harvesting source depends on how long the source is in operation.\(^7\) Therefore, the primary metric for comparison of scavenged sources is power density, not energy density.

Generally energy harvesting suffers from low, variable and unpredictable levels of available power. Figure 5 depicts the amount of power generated by an energy harvesting device and consumed by a mote at two duty cycles.

![Figure 5](image.png)

**Figure 5** Power generation from an energy harvester vs power consumption of a mote at two different duty cycles (left). Current consumption of a mote in active mode (receive and transmit) (right). (Graphs courtesy of Tyndall Institute).

The harvester, because of its unlimited energy supply and deficiency in power, can be used as a lifetime extender for a primary battery (i.e. no recharging) or to recharge a secondary battery (Figure 6). In the latter case the secondary battery yields higher output power but stores less energy so it functions as a power cache, supplying power when required but otherwise regularly receiving charge from the harvester.

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\(^6\) Energy harvesting tends to describe systems where the characteristics of the ambient energy available are known, while energy scavenging more opportunistic systems for which the operating environment can vary.

\(^7\) For example, if you hit a vibration harvester with a hammer you can get very high instantaneous power but a very small amount of energy.
The current state-of-the-art in commercial off-the-shelf energy harvesting technologies, for example in vibration energy harvesting and indoor photovoltaics, yield power levels of the order of a mW in typical operating conditions. While such power levels may appear restrictively small, the operation of harvesting elements over a number of years can mean that the technologies are broadly comparable with long-life primary batteries, both in terms of energy provision and the cost per energy unit provided. Systems incorporating energy harvesting will typically be capable of recharging after depletion—a feature that is lacking in systems powered by primary batteries. There are other advantages of using energy harvesting, including the ability to monitor more closely the amount of energy being used by a system and hence deliver an improved level of energy-awareness, as may be required for state-of-the-art sensor network management algorithms.

**Power Management**

Much like in large power-generation and transmission systems, it is crucial to convert and condition the available energy so it can be delivered in a useful form. Any inefficiency in the conversion electronics associated with an energy harvesting device can dissipate the hard-won energy. Here efficient converter topologies such as intelligent dynamic charge pumping are becoming more common place.\(^8\) Traditionally, digital circuits have relied on the steady improvement of semiconductor processes to solve the power consumption problem. However, the sky-rocketing cost and complexity of designing, verifying and manufacturing using the latest process nodes is putting limits on who and which applications can use the latest processes. Recent industry experience shows simply using the latest semiconductor process does not guarantee low power performance unless power management is taken into consideration from the beginning.

There are several tasks the power management is responsible for in energy harvesting power supplies. The first task is matching the energy harvesting transducers voltage level with those of the electronic circuit or system to supply. This task can enable an indefinitely long lifetime, limited only by the hardware longevity. The next function is the regulation of the supply voltage, to generate a constant voltage independent of source or load variations. Furthermore, the power consumption of the application devices has to be minimized by the power management so that a maximum of functionality, performance and operation time is achieved with the minimum of energy provided by the energy harvesting module. Another task for the power

---

\(^8\) A charge pump is a DC to DC converter that uses capacitors as energy storage elements to create either a higher or lower voltage power source. Charge pump circuits are capable of high efficiencies, sometimes as high as 90-95% while being electrically simple circuits.
management is the management of the energy and the required storage units such as capacitors or rechargeable batteries.

No matter the type of power source or energy harvesting mechanism, careful integration of hardware and peripherals is crucial. A systematic analysis of the power consumption in a sensor node is important to identify power bottlenecks in the system, which can then be the target of aggressive optimisation. Conventional low-power design techniques only provide partial solutions which are insufficient for these highly energy-constrained systems. Optimising the power consumption in sensor networks is much more complex as the reduction of the energy consumed by a single device can affect the lifetime of the rest of the network.

Since harvested energy manifests itself in irregular, random, low-energy bursts, a power-efficient, discontinuous, intermittent charger is required to transfer the energy from the sourcing devices to the battery. Referring to Figure 4, some of the most prominent ways to realise efficient power management in the three major components of a sensor node (ADC, microprocessor and radio) are described below:

**ADC**

An ADC is an electronic device that converts an input analogue signal to a digital number proportional to the magnitude of the voltage or current. The digital output may use different coding schemes, such as binary, Gray code or two’s complement binary. A low efficiency factor leads to significant energy loss in the converter, reducing the amount of energy available to the other sensor node components. Also, the voltage level across the battery terminals constantly decreases as it gets discharged. As a result, the converter draws increasing amounts of current from the battery to maintain a constant power supply to the sensor component, which leads to depletion in battery life.

**Microprocessor / Microcontroller**

Low energy processors and controllers have been designed and used, especially in the area of embedded systems. The choice of microprocessor is dictated by the application scenario, to achieve a close match between the performance level offered by the microprocessor unit and that demanded by the application. Several modern processors support scaling of voltage and frequency, avoiding external oscillators where possible. Programmers can have a great impact on power consumption based on their choice of operating system and middleware. For example, an application might be able to isolate and switch off certain individual circuits if it knows it will not need it in the next time period or instead run auxiliary hardware components from low speed oscillators. Complex and common functions such as encryption can be implemented in hardware to save resources. The radio interface can also be switched off if it is not used for an extended period of time. In other approaches, data is aggregated within a cluster and then sent to the cluster head that takes care of sending it to the appropriate recipient. However, most of these solutions only work in certain conditions, for specific types of algorithms, etc. and lack a generic solution that can be used in a wide variety of application domains.

Importantly, for some applications/functions, it is more power efficient to use analogue techniques (e.g. for filtering - which is relatively power hungry if

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implemented digitally but can be done at very low power in analogue form). For example, complex Matlab algorithms can be implemented on low power MSP430 series processors by using analogue for appropriate parts of the signal processing. This can reduce the power consumption by an order of magnitude or more.

Radio

Power management of the radio component is extremely important since this is known to be a big power consumer during system operation. Radios can operate in four distinct modes: transmit, receive, idle, and sleep. An important observation in the case of most radios is that operating in idle listening mode results in high power consumption, almost equal to the power consumed in the receive mode. There is a trade-off between high data rates and low power consumption and reducing the number of transmitted messages is not the only way of saving energy at the nodes. Also as the radio’s operating mode changes, the transient activity in the radio electronics causes a significant amount of power dissipation as well as a latency overhead. The key factors to low duty cycle operation are to sleep the majority of the time, to wakeup quickly, start processing and return to sleep. Power level in wireless transmission also influences the range (subject to the type of antenna), determines the level of interference and also the routes. It is known that many systems (particularly development kits) have extremely lossy antennas, so this is an area for quick gains by users. Directional antennas for static deployments is also an idea for saving on transmit power usage.

Below is a summary of the most commonly used power management techniques used from the application all the way down to the physical layer of the hierarchical OSI networking protocol stack.

Application Layer

A technique known as load partitioning allows an application to have power intensive computations performed at central nodes rather than locally. For some applications though, i.e. distributed detection, monitoring or tracking, it is better to process locally because communication is generally more expensive than processing. The wireless device simply sends the request for the computation to be performed, and then waits for the result. Another technique uses proxies in order to inform an application about changes in battery power. Applications use this information to limit their functionality and only provide the most essential features. Other approaches use 2-tier architectures, with more powerful nodes (which are not necessarily centralised) or use context information, e.g. completely shutting down the radio, when no activity is expected.

Transport Layer

Techniques try to reduce the number of retransmissions necessary due to packet losses from a faulty wireless link. In a wired network, packet losses are used to signify congestion and require back off mechanisms to account for this. In a wireless network, however, losses can occur sporadically and should not immediately be interpreted as the onset of congestion.

Network Layer

Power management techniques at the network layer are concerned with the design of routing protocols, and most often routing through a multi-hop network. The simplest way to reduce power consumption is to allow each node to schedule sleeping periods. Moreover other techniques such as data aggregation, overhead reduction, proactive and reactive routing or data updates, (aka pull vs push approaches) and cluster heads reduction can be used to reduce energy waste.

Data Link Layer
The two most common techniques used to conserve energy at the link layer involve reducing the transmission overhead during the Automatic Repeat Request (ARQ) and Forward Error Correction (FEC) schemes. Both of these schemes are used to reduce the number of packet errors at a receiving node. By enabling ARQ, a routing node is able to automatically request the retransmission of a packet directly from its source without first requiring the receiver node to detect that a packet error has occurred. Other power management techniques at the link layer are based on some sort of packet scheduling protocol. By scheduling multiple packet transmission to occur back to back, it may be possible to reduce the overhead associated with sending each packet individually.

**MAC Layer**

Energy efficiency is considered in several MAC protocols employed in wireless sensor networks. Power saving techniques at the MAC layer consist primarily of sleep schedulers that are used to duty cycle a radio between its on and off power states in order to reduce the effects of idle listening. Other power saving techniques at this layer include battery aware MAC protocols in which the decision of who should send next is based on the battery level of all surrounding nodes in the network. Power level information is included in each packet that is transmitted, and individual nodes base their decisions for sending on this information. Sleep scheduling protocols can be broken up into two categories: synchronous and asynchronous. Synchronous sleep scheduling policies rely on clock synchronisation between all the nodes in a network, while asynchronous scheduling techniques do not require clock synchronisation and use a continuous transmission (a preamble) to wake up the receiving node when needed.

**Physical Layer**

At the physical layer, proper hardware design techniques allow one to decrease the level of parasitic leak currents in an electronic device. These smaller leakage currents ultimately result in longer lifetimes for these devices, as less energy is wasted while idle. Variable clock CPUs, CPU voltage scaling and flash memory can also be used to further reduce the power consumed at the physical layer. A technique known as Remote Access Switch (RAS) can be used to wake up a receiver only when it has data destined for it. A low power radio circuit is run to detect a certain type of activity on the channel. Only when this activity is detected does the circuit wake up the rest of the system for reception of a packet. A transmitter has to know what type of activity needs to be sent on the channel to wake up each of its receivers.

Another approach is to separate the hardware for data communication and channel monitoring (PicoRadio). A separate wake up radio monitors the channel and wakes up the main unit when it detects activity. The disadvantage is that it still consumes energy. Another approach is to use the energy in the radio signals (radio triggered wakeup). This is more like RFID type approach, when the receiver is powered by inducted energy generated by a powerful transmitter. This approach requires a powerful transmitter and provides a smaller operating range.
Key Issues: Barriers and Limitations

I. Microprocessor level Power Management

Microprocessors handle the logic operations in digital systems by executing a stored set of instructions, such as accessing memory, adding, subtracting, and copying. They may be designed to perform general purpose tasks (the kind used in a PC) or can also be more specialized (aka microcontrollers) in order to deliver self-sufficient and cost-effective electronic components. According to one report, only 2 percent of the approximately 8 billion microprocessor units produced ended up in conventional computers in 2002. The rest end up in all sorts of embedded systems including automobiles, office machines, toys, and appliances. It is anticipated that the portion used in conventional computers is considerably more dramatic now. As well standard processing and control functionality for real world applications we are starting to see a need for microprocessors with true DSP functionality and here highly integrated low power devices such as the PIC DSP may become very relevant for WSN solutions.

![Microprocessors' usage](image)

*Figure 7 Only a tiny fraction of microprocessors are used in conventional computers.*

Upgrading microprocessor performance requires packing more transistors into an integrated circuit (chip), which necessitates operating at a lower voltage to reduce power loss during switching. Advanced process technology is used to maximize integration while minimizing the cost:

- 90nm (shipping)
- 65nm (mature design)
- <45nm (preliminary)

However, in order to keep up with Moore's Law it is becoming increasingly challenging as dominant chip-making technologies approach their physical

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11 Rejeski, Anticipations. In “Sustainability at the speed of light”, 2002
12 A PIC microcontroller is a single-chip package that combines a microprocessor, ROM program memory, and RAM variable memory, along with several input and output logic gates. This makes them a one-chip computer, with an operating system supplied by the programmer.
A different approach to increase the processing performance is to add extra processors, as in symmetric multiprocessing designs, which have been popular in servers and workstations since the early 1990s. Most microprocessor-based systems have a time-varying computational load, and hence peak system performance is not always required. Several modern processors support scaling of voltage and frequency. Energy, power, voltage variation, thermal hotspots and related design topics have emerged as key microprocessor design issues over the past few years. Although this is the case across the entire computing range, from low-end embedded systems to high-end supercomputers, power in wireless networks is a particularly valuable commodity. Microprocessors that utilise less power can be more highly appreciated in these areas than microprocessors with more capability and better performance. The legacy of components such digital libraries and support tools is difficult to change for the low energy paradigm. A detailed understanding of these issues is of primary importance for designing microprocessors able to carry out the processing and communications within the power and thermal constraints of the energy harvester or battery power source.

Issue 1 – Causes and metrics of power dissipation in microprocessors

What are the dominant causes of dynamic power dissipation in microprocessors and how could it be measured?

When a current flows through a component, that component will heat up and the heat will then be conducted or radiated away. This process is called power dissipation and is measured in Watts. This conversion to heat energy is a function of the size of the wires and transistors, and the operating frequency of the processor.

There are two types of power dissipation in an integrated circuit: a) static power (aka leakage power) and b) dynamic power dissipation. The former is characterized mostly by leakage current and the latter is by the charging and discharging the capacitance on the output of the hundreds of millions of gates in today’s circuits.

Until recently, only dynamic power has been a significant source of power consumption, and Moore’s law helped control it. However, power consumption has now become a primary microprocessor design constraint; one that researchers in both industry and academia will struggle to overcome in the next few years. Microprocessor design has traditionally focused on dynamic power consumption as a limiting factor in system integration. As feature sizes shrink below 0.1 micron, static power is posing new low-power design challenges.\(^\text{14}\)

The dynamic power dissipation is calculated using \(P=nfCV^2\), where \(n\) is the activity factor (how many transistors are switching), \(f\) is frequency, \(C\) is circuit capacitance and \(V\) is supply voltage. As transistor dimensions are decreased (as a result of new fabrication processes), the leakage consumption increases. Smaller process technologies typically bring higher performance at the cost of higher power consumption.

\(^{13}\) Projections in the International Technology Roadmap for Semiconductors (ITRS) published by the Semiconductor Industry Association (SIA) point to lower voltages and higher current. out to be true, microprocessors will operate at 0.6V and 300A with 15GHz clock rates. complicating further the task of power management in microprocessors.

As device size reduces to deep submicron, static power dominates. Low power processors normally targeting applications with low duty cycle where leakage power will have high impact on overall power consumption. Hence, there is some merit in low-power processors using larger process technologies in order to reduce the static power. Static power becomes more important for sensor nodes operating at a low duty cycle.

Numerous design techniques have been investigated for both logic and memory circuits to address the growing issues with power and variations. Low-power and process-tolerant designs, however, impose new test challenges and may even have conflicting requirements for test - affecting delay fault coverage, parametric yield, and even stuck-at tests. Hence, there is a need to consider test and yield, while designing for low-power and robustness under variations.  

Techniques have been experimented to minimize energy dissipation through a) selection of better algorithms for the application e.g. DSP algorithms that require fewer number of operations to perform a task such as filtering and, b) reducing the operating supply voltage by changing the architecture of the system e.g. through the use of pipelining. However power dissipation is often neglected when developing the software for embedded systems. Software optimization techniques can be used to reduce the cost, size, and power dissipation in embedded systems without adding to system overheads.

The power dissipation may be measured at three levels as listed in the table below.

Table 2 Approaches to measure power dissipation.

<table>
<thead>
<tr>
<th>Level</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Microprocessor/Board Level | Most accurate  
Perhaps the fastest, if setup and tools exist  
Too late to change hardware details  
Software/Load control is still possible  
Typically used for software optimizations |
| Transistor Level (estimation) | Simulation of transistor level netlist  
Most accurate in the simulation world  
Requires complete implementation details  
Unmanageable time complexity even for simpler designs  
Typically used for cell/component characterization |
| Cell Level (estimation) | After logic synthesis  
Requires RTL implementation  
Simulation to capture switching activity  
Characterized cells – empirical formulas or table look-up  
Interconnect power  
- Either unaccounted or  
- Using estimated wire load models (typically based on experience) or  
- Extracted layout (if done after physical synthesis)  
Still unmanageable time complexity especially to use in design space exploration  
Netlist, interconnect capacitance, cell power library |

Dynamic Voltage and Frequency Scaling (DVFS)

The microprocessor system in micro-sensor node devices often has a time-varying computational load which is comprised of: a) compute-intensive and low-latency processes, b) background and high-latency processes, and c) system idle. The key design objectives for the processor systems in these applications are providing the highest possible peak performance for the compute-intensive code (e.g., image decompression) while maximizing the battery life for the remaining low performance periods. If clock frequency and supply voltage are dynamically varied in response to computational load demands, then energy consumed per process can be reduced for the low computational periods, while retaining peak performance when required.\(^\text{16}\)

Hence, many modern microprocessors are designed to operate at different voltage and frequency settings as an effective way to manage power usage. As the processor frequency is reduced, the supply voltage can also be reduced. DVS refers to runtime change in the voltage levels supplied to various components in a system so as to reduce the overall system power dissipation, while maintaining total computation time and/or throughput requirement. Implementation of DVS require substantial software support such as development of scheduling techniques with a dynamic recalculation

of tasks priorities based on average energy dissipation.\textsuperscript{17} Although DVS implementations on processor are now readily available the same is not true for other components found in WSN nodes, and it is not always feasible to combine DVS and non-DVS components.

A complementary, sometimes even alternative, approach to obtaining an acceptable power-performance level is the use of Dynamic Voltage and Frequency Scaling (DVFS) and the active and passive leakage management of systems. These techniques can reduce power significantly, especially when combined with fine-grained power management architecture.\textsuperscript{18}

Other trends in DVS include:

- Logic Delay Measurement Circuit (LDMC) and Power Driven Partitioning algorithms.
- Transition-Aware Dynamic Voltage Scaling
- Exploiting Synchronous and Asynchronous DVS
- Processors and supporting electronics implemented using below threshold CMOS technology.

### Issue 3 – Selection of a Microprocessor

**What are the key criteria for device designers and system integrators in choosing a microprocessor for power optimization?**

The choice of microprocessor is dictated by the intended application, as ultimately in an efficient setting one has to achieve a close match between the performance level demanded by the application and that offered by the microprocessor. The other important factor is the microprocessor’s cost.

There are three primary areas of interest when benchmarking the characteristics of ‘low power’ systems employing power management techniques to achieve low power goals:

- Actual power consumption of the system under typical user conditions
- System operability or usability under power management conditions – it is clear that one could achieve remarkable power characteristics at the cost of system performance and the response time
- Impact of power management techniques on system reliability.

An appropriate benchmarking strategy for power managed systems must address these three areas in order to put forward an overall system figure merit, low power without sacrificing system operability or reliability. It would be one that characterizes the system power consumption while the system was carrying out some useful task.

Microprocessors usually support various operating modes for power management:

**Active mode:** in this mode, the microprocessor is executing code, scheduled tasks are being executed. In brief, the system is receiving and processing input. As soon as there are no tasks to be executed, the system changes into idle mode. If the system does not have any tasks schedule for certain period of time, it will change into sleep mode.

\textsuperscript{17} The other main technique for reducing the energy consumption of embedded systems is Dynamic Power Management (DPM). According to DPM energy efficiency can be achieved by selectively turning off (or reducing the performance of) system components when they are idle, partially unexplored or when battery level or device temperature requires a reduction in the consumption.

\textsuperscript{18} Juha Pennanen; Advanced Power, National Semiconductor; Electronic product Design, 01.03.2007 available from www.epdonthenet.net;
Idle mode: in this mode, there are no tasks scheduled to be executed, therefore all non-essential parts of the system are disabled, the system is typical waiting for user input.

Sleep mode: in this mode, the device is in power-down state. The contents of volatile memory are preserved, and the real-time clock is ticking in order to preserve time and date. The system is waiting for the user to power it up, or for an alarm to wake it up.

Power consumption in the various states should be assessed so as to reduce the overall power draw of the system. For example, running a processor at a higher frequency and lower duty cycle may be more efficient than reducing the overall clock speed. It is also good to look at variable power supplies – running at a lower voltage can significantly reduce the power draw. Hence, a designer should look for:

- Ability to turn off power domains e.g. peripherals which are not currently in use;
- Wake-up methods available when device is asleep or dozing;
- Different power saving modes - ability to doze when not doing anything useful, but all clocks active to allow rapid response to wakeup event such as interrupt;
- Availability of sleep mode using slow speed or no clock (static design required) and fast start-up of main oscillator from this mode to get to full speed operation as quickly as possible after wakeup event.

While values of power consumption of an off-the-shelf microprocessor take into account supporting circuitry, power specifications of processor cores are based on simulations as vendors are free to delete or ignore any number of power-dissipating functions when reporting power numbers. Some vendors do not include specific functions when they measure the power consumption. They often specify in their datasheets what they did not take into account. However, sometimes, these functions are vital for the microcontroller. For example, when a supplier does not include the clock tree, the customer has to appreciate the consequences of this omission: indeed, the clock tree includes the gates operating at the highest frequency of the core. This function dissipates much of the CPU power. It is not possible to design a microcontroller without clock tree. Obviously, it would be unfair to compare the power specifications of two processors and omit the clock tree from one of them.

Another example of frequent omission is the static consumption (see Issue 1). It will depend on the fabrication technology, the Vt flavour selected (i.e. Nominal, High or Low Vt), the temperature range and the operating frequency. Indeed, down to 180 nm technology, static power consumption is not considered because it is insignificant compared to the dynamic power consumption. However, in advanced fabrication technology, from 90 nm and beyond, the static power consumption cannot be ignored anymore. It could represent a significant part of the total consumption but most of the time, vendors do not indicate the static power consumption.

Even if the datasheet clarifies all the items listed above, one more important detail tends to remain unclear: What is the processor doing while the power simulations run? If the program being run during the power simulation is a loop of NOPs (i.e. no operation), the customer would expect to get lower power numbers than if the processor were exercising its function units. Thus even the benchmark program being run during power simulation can influence the core’s power consumption specifications.

Data contained in datasheets will give a global idea of the dynamic consumption. Thanks to that, it will help to have an overview of the consumption of competitors’ solutions, but since no standardized power-benchmarking program for processor cores has emerged and since the measurement conditions can be far from the customer’s application.
conditions, it seems unrealistic to have accurate power consumption estimation for a microcontroller without running its own power simulations. Thus, such partial data will not enable an accurate model of the consumption, which is essential to the system designer for proper sizing of the power grid to meet voltage-drop and electro-migration criteria. Users are encouraged to run their own power simulation for two reasons. They could have a full control of the evaluation conditions and they could assess the power consumption of the rest-of-SoC, especially the memory system, in the mean time. This last point is important and often underestimated: an embedded processor is just one part of the system and a processor that enables to reduce the number of accesses to the memory system is a better processor for low power optimisation.\(^{19}\)

Organisations such as Berkeley Design Technology (BDTI), EDN Embedded Microprocessor Benchmark Consortium (EEMBC) and Standard Performance Evaluation (SPEC) support benchmark suites that highlight a processor’s performance when performing application specific tasks.

Another key activity that is just starting in the US which has benefit to future WSN implementation is a DARPA project to revisit analogue computing, this approach promises to have significant energy benefits compared to today’s more common place digital solutions. The focus on the proposed DARPA project is to produce the analogue equivalent of an FPGA.

\(^{19}\) Aurélie Descombes, Dolphin Integration ; Design and Reuse Industry Articles (www.design-reuse.com); accessed 15.03.2010
II. Node level Power Management

As described earlier in Figure 3, a node is a device capable of performing some processing, gathering sensory information and communicating with other connected nodes in a network. Power management performed at the node level is about adapting node performance in response to temporal variations.

Energy consumption in a node has in general the following components depending on the operations performed by the node:

1. Sensing energy: Sensing energy must be dissipated in order to activate sensing circuitry and gather data from the environment. The magnitude of this energy depends on the task that is assigned to the sensor. Different sensors require different levels of energy for their operation.

2. Communication energy: A node consumes communication energy while sending or forwarding data packets to the base station. The communication energy includes transmission energy and receiving energy.

3. Computation energy: To operate the sensor node, the sensor’s processor/microcontroller must be activated. Whenever data aggregation is performed, additional computations must be realized. Compared to the previous items, computation energy is usually relatively low.

While the sensing energy is dependent on the sensing requirements in different applications, in general passive sensors such as temperature, seismic, consume negligible power relative to other components of sensor node. However, active sensors such as rangers, array sensors such as imagers, and field-of-view sensors that require repositioning cameras with pan-zoom-tilt can be large power consumers. A lot of real world measurement in the environmental and security domains can involve high dynamic ranges. High dynamic range conversion can be a significant consumer of node energy. To overcome the deficiencies of high dynamic range conversion people are now exploring non ADC type approaches such as Time over Threshold (ToT) techniques, which can significantly reduce the energy require of the conversion function (in its basic form the converter could come down to 2 comparator and a clocked latch). A useful benefit of ToT is that it can have a very good timing resolution and this would be invaluable for applications where localization may be important.

Various approaches have been proposed to reduce the computation and communication energy consumption. The two main approaches carried out to save power in connection to each of the above: CPU is switched to a low power mode when no computation is required and radio transceiver is powered down when unused.

To meet a high degree of energy efficiency, these kinds of devices used to be driven by a Real Time Operating System (RTOS) with special features. Among these kernels, we can find open source solutions like: TinyOS, Contiki, Nut/OS. Independently of the kernel used, even if they lack it, applications running on these devices always follow the same execution model, behaving as event-driven systems. These reactive systems are characterized for remaining most of the time in a sleep mode. Whenever an event is detected, the system switches to a higher power mode to process it (measuring variables via sensors, processing data and communicating results via radio). Then, as fast as possible the system returns to the

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20 To overcome this, it is possible to exploit network centric system approaches such as node to node queuing (e.g. lower energy consuming node could be used to awaken and queue high energy consumers on the network).
previous low power state. In general, saving a few micro watts is crucial to extend a node’s operational mode for several years.

**Standardisation**

Large organisations procuring WSN systems currently employ heterogeneous nodes to meet the needs of their applications. Efforts are underway in standardisation of sensor nodes by integrating various components. The big motivation is that they really want to mix and match (i.e. plug and play) sensors from different vendors without having to invest significantly in system integration.

In the defense domain, for instance, timely dissemination of relevant information is needed in the form of classification of terrestrial events, occurrence times, their trajectories and direction of movement of adversarial activities. Component technologies such as Radio frequency interference (RFI) extraction, Optimization of algorithm code, High-precision position location systems, Beam-forming techniques, tracking and classification algorithms etc are available but they are not readily available on a single sensor node. The Army Research Lab (ARL) is moving towards an architecture known as ‘Family of UGSs’ that will standardize communications so as to help to mitigate the heterogeneous Unattended Ground Sensor (UGS) network problem. Honeywell got a contract from US Department of Defense in 2009 to “design and build an ‘Open Architecture’ Unattended Ground Sensor (UGS) Controller to serve as the backbone of the Terra Harvest UGS System” which is a step towards standardisation of sensor nodes.21, 22

### Issue 4 – Power analysis of sensor nodes

What does the power analysis of sensor nodes reveal about the power consumption by the different parts (radio, memory, DSP, sensors, ADC etc) and how the energy accounting can be carried out?

As sensor nodes consist of several components such as microcontrollers, radios, sensors, and memory, a detailed low-level model of all these devices is necessary to enable accurate prediction of energy consumption. Systematic power analysis of a sensor node is important to identify power bottlenecks in the system, which can then be the target of aggressive optimization.

Unless particularly specialised applications are being targeted (for example requiring power-intensive sensors or peripherals), communication is usually the dominant consumer of energy on a sensor node. For most 2.4GHz nodes, this stands at ~50-100mW for transmitting, receiving, and in idle receive mode. Most sensors that are used (for example those sensing temperature or light) tend to be less significant, particularly if they are also being duty-cycled. Early research in sensor networks proposed distributed information processing and the use of nodes purely as data loggers. However, as the power consumed by a microcontroller to execute a single instruction is usually many orders of magnitude smaller than the power required to communicate a single bit across a wireless channel, this is

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21 FedBizopps.gov; Unattended Ground Sensor (UGS) Controller; Solicitation Number: HHRM402-09-R-0077
clearly unrealistic. Hence, sensor nodes tend to be designed around processing data as much as possible on the node. There has been continuing debate around the practicality of mesh networking in sensor networks with limited energy supplies – the difficulty of synchronising communications means that a substantial amount of time must be spent in the power-hungry receive mode. Few true ‘mesh’ deployments have been documented; most monitoring applications simply have point-to-point networking, with nodes communicating directly with a powered ‘sink’.

There are definitely advantages with aggregating data and transmitting less frequently. In this way, the effect of the packet header can be reduced and the effective transmission time per bit can be reduced. Work has been proposed for runtime power accounting (effectively breaking down the power consumption by each thread being executed), though these are usually targeted at larger more powerful sensor nodes (often Linux based) that are not particularly suited to energy harvesting. Monitoring of the energy being consumed by physical peripherals tends to be performed by measuring the voltage and current that each device is consuming, often using lab instrumentation.

Some salient features of power analysis of sensor node are:

1. Using low-power components and trading off unnecessary performance for power savings during node design can have a significant impact, up to a few orders of magnitude.
2. The node power consumption is strongly dependent on the operating modes of the components.
3. Due to very short transmission distances, the power consumed while receiving data can often be greater than the power consumed while transmitting packets.
4. The power consumed by the node with the radio in idle mode is approximately the same with the radio in receive mode.

There are various ways of energy accounting that can be carried out. There are scalable simulating environments that are developed or being developed which can carry out energy accounting quite accurately.

Some known energy accounting tools are PowerTOSSIM (developed at Harvard University) and AEON (developed at University of Tubingen). PowerTOSSIM provides estimation of power consumption for a range of applications and scales to support very large simulations. The trace of each node’s activity is fed into a detailed model of hardware energy consumption, yielding per-node energy consumption data. This energy model can be readily modified for different hardware platforms. Table 3 shows the resulting power model for the Mica2 node. The different CPU power modes cover a wide range of current levels, from 103 μA in the “power down” state up to 8mA when actively executing instructions. Likewise, the choice of radio transmission power affects current consumption considerably, from 3.7mA at -20dBm to 21.5mA at +10dBm. However, in many of applications the radio is almost always listening for incoming messages, which consumes 7mA regardless of transmission activity.

One of the experimental setup with PowerTOSSIM reveals following result:
AEON (Accurate Prediction of Power Consumption) is an evaluation tool to quantitatively predict energy consumption of sensor nodes and whole sensor networks. The energy model, based on measurements of node current draw and the execution of code, enables prediction of the energy consumption of sensor nodes. Consequently, it prevents erroneous assumptions on node and network lifetime. Moreover, detailed energy model allows comparing different low power and energy aware approaches in terms of energy efficiency. Thus, it enables an estimation of the overall lifetime of a sensor network.

Table 3 Power analysis of the Mica2 node using PowerTOSSIM.\textsuperscript{23}

<table>
<thead>
<tr>
<th>Mode</th>
<th>Current</th>
<th>Mode</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>8.0 mA</td>
<td>RX</td>
<td>7.0 mA</td>
</tr>
<tr>
<td>Idle</td>
<td>3.2 mA</td>
<td>Tx (-20 dBm)</td>
<td>3.7 mA</td>
</tr>
<tr>
<td>ADC Noise Reduce</td>
<td>1.0 mA</td>
<td>Tx (-19 dBm)</td>
<td>5.2 mA</td>
</tr>
<tr>
<td>Power-down</td>
<td>103 μA</td>
<td>Tx (-15 dBm)</td>
<td>5.4 mA</td>
</tr>
<tr>
<td>Power-save</td>
<td>110 μA</td>
<td>Tx (-8 dBm)</td>
<td>6.5 mA</td>
</tr>
<tr>
<td>Standby</td>
<td>216 μA</td>
<td>Tx (-5 dBm)</td>
<td>7.1 mA</td>
</tr>
<tr>
<td>Extended Standby</td>
<td>223 μA</td>
<td>Tx (0 dBm)</td>
<td>8.5 mA</td>
</tr>
<tr>
<td>Internal Oscillator</td>
<td>0.93 mA</td>
<td>Tx (+4 dBm)</td>
<td>11.6 mA</td>
</tr>
<tr>
<td>LEDs</td>
<td>2.2 mA</td>
<td>Tx (+6 dBm)</td>
<td>13.8 mA</td>
</tr>
<tr>
<td>Sensor board</td>
<td>0.7 mA</td>
<td>Tx (+8 dBm)</td>
<td>17.4 mA</td>
</tr>
<tr>
<td>EEPROM access</td>
<td></td>
<td>Tx (+10 dBm)</td>
<td>21.5 mA</td>
</tr>
<tr>
<td>Read</td>
<td>6.2 mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read Time</td>
<td>565 μs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Write</td>
<td>18.4 mA</td>
<td></td>
<td></td>
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<tr>
<td>Write Time</td>
<td>12.9 ms</td>
<td></td>
<td></td>
</tr>
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</table>

\textsuperscript{23} Shnayder, Hempstead, Allen, Welsh; Simulating the Power Consumption of Large Scale Sensor Network Applications, Proc. 2nd international conference on Embedded networked sensor systems, Baltimore, MD, USA, 2004
Most radios operating in idle mode result in significantly high power consumption. Why is it so and how the radio component can be optimized?

In general, radios can operate in four distinct modes of operation (Transmit, Receive, Idle, and Sleep) and the power consumed by radio depends on two main components:
- An electronic component that accounts for the power consumed by the circuitry that performs frequency synthesis, filtering etc.
- An RF component that depends on transmission distance and modulation parameters

Factors affecting the power consumption characteristics of a radio include:
- Modulation scheme used
- Data rate
- Transmit power (determined by the required transmission distance)
- Operational duty cycle.
- Digital control aspects

**Case Study: Saving energy on the Waspmote platform**

Waspmote is an open source ZigBee sensor platform developed by Libelium. The product features seven different radio communication modes with a minimum consumption (0.7 μA in the Hibernate mode).

An effective technique to save energy in Waspmote is changing the threshold of the sensors events when they are triggered too many times in a short time to avoid being continually treating these interruptions and to be able to return to the sleep mode. This means that dynamic thresholds can be set in order to change the behaviour of the mote using digital potentiometers (digipots) controlled by the microprocessor itself.

Another technique used by Libelium in order to keep as low as possible the consumption in the mote is to disconnect the main battery using a digital switch and switch it on after a certain time using a Real Time Clock (RTC) programmed with an alarm time. All this tasks are performed by the microprocessor.

Regarding the encryption mechanisms such as AES 128b, it is important they are implemented using specific hardware components (normally integrated in the same transceiver) and never using software encryption as it is not as energy efficient.

![The Waspmote platform](source: Libelium)

In many radios, including most ZigBee and 802.15.4 transceivers, the idle power consumption is the same as (or often higher than) the transmit power consumption. This is because such idle modes are effectively receiving.

Ideally, this type of consumption is optimised by never operating the radio in idle mode (i.e. the radio is only ever on when it is transmitting or receiving, and it is in a low-power of off state at all other times). This is based around the concept of duty-cycling the node, as discussed in ‘Issue 6’. In practice, ensuring that the radio is always ‘useful’ when it is ‘active’ can be near impossible, requiring very accurate time synchronisation (challenging in low-power low-cost devices) and MAC protocols. Communication protocols and algorithms have been proposed to address these issues (for example low-power listening algorithms), and emerging work has been proposed into wakeup radios (whereby a transmitter is able to generate an interrupt in a sleeping receiver to wake it up to receive).

Power reduction strategies for the RF transceiver elements of nodes may include:
• Reduce the amount of data transmitted through data compression/reduction
• Lower the transceiver duty cycle and frequency of data transmissions
• Implement strict power management – use power down and sleep modes
• Implement an event-driven transmission strategy - transmit only on certain event(s).
• Use high sensibility radios to avoid retransmission due to loss of packets.
• Forwarding nodes in a mesh network will be the nodes with the higher battery levels.
• Use variable TX Power so that we can set the minimum value needed to talk to the nearby nodes (minimum radio of action).
• Interference avoidance algorithms: channel change for DSSS protocols and channel hopping for FHSS ones.
• It is also useful to use the Received Signal Strength Indicator (RSSI) in order to detect good and bad quality nearby nodes.

Case Study: Low Energy Wireless Sensing over GSM

Apoideas have developed a GSM based wireless sensing system optimized for low energy consumption. To send an SMS, one needs >3.22V; 50mA average; 2A peak for 20s. The system consists of a small device (a bee) powered with a AA battery or a solar cell which connects via SMS to a server (or hive). The protocol between the device and the server is optimized for low power and the bee is a ground up low power design.

The device supports interfaces to a variety of sensors and actuators and works over a wide range of temperatures. It can also provide power to sensors for a limited period of time. The performance derived from measurements for the system is shown below assuming 10 years of operation and making allowance for standby current and 100 sensor measurements per SMS.

![Figure 11 Performance by the Apoideas system and various battery capacities at 20°C.](image)

Source: Apoideas
Issue 6 – Energy Harvesting Aware Power Management

Which are the most efficient Energy Harvesting Aware Power Management techniques?

This is still a very open area of research. Several considerations in using an environmental energy source are fundamentally different from using batteries. Rather than a limit on the total energy, harvesting transducers impose a limit on the instantaneous power available. Further, environmental energy availability is often highly variable and a deterministic metric such as residual battery capacity is not available to characterize the energy source. The different nodes in a sensor network may also have different energy harvesting opportunities. Since the same end-user performance may be achieved using different workload allocations at multiple nodes, it is important to adapt the workload allocation to the spatio-temporal energy availability profile in order to enable energy-neutral operation of the network.

The use of harvested energy leads to several research issues which are different from conventional power management based on only stored battery energy. Not only is the design of the hardware different to account for the harvesting source, but workload scheduling now depends on the nature of the environmental source. The scheduling is also different in case of distributed systems with multiple harvesting nodes. Harvesting theoretic techniques can be used to determine the sustainable performance levels and additional resources required for achieving requisite performance. These techniques also facilitate the design of distributed scheduling methods. An ideal system would utilize its starting battery resources and harvested energy to achieve the maximum possible application throughput with the available resources. Such power management for harvesting networks is an open problem with a rich set of research challenges.

The most energy efficient method for reducing power consumption is to turn off peripheral devices. This can take the form of putting the radio transceiver, microcontroller, sensors and other peripherals to a low-power sleep mode, quite often devices operate in this mode for >99% of their time. Such methods can be controlled by power management algorithms that offer varying profiles or levels of service based upon the energy that the device has available to it. Furthermore, algorithms have been proposed for the runtime prediction of energy harvesting (suitable for sources with periodic variation), where a node is able to control its activity and behaviour as a function of not only the amount of energy that it currently has and is harvesting, but also the amount of energy it is likely to get in the near (or distant) future.

Kansal, Hsu, Srivastava, Raghunathan; Harvesting aware power management for sensor networks; Design Automation Conference, 43rd ACM/IEEE, 2006
A new embedded software architecture has been developed which simplifies the interface between the application and the sensing and energy hardware on the node. While, conventionally, the communications interface is formally structured, other interfaces (such as sensor processing and energy management) are normally unspecified and often integrated into a large and complex application layer. This is not ideal for intelligent sensing and energy management, which are arguably as important as communications to the functionality of a node. The new embedded architecture specifies the structure of multiple interfaces on sensor nodes. A number of stacks are combined via a shared application layer, and this forms a 'unified' stack. The architecture, shown in Figure 13, includes stacks for sensor interfacing and energy management, as well as communications.

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Case Study: Modular plug-and-play power resources

Researchers at the University of Southampton have developed a plug-and-play architecture for the energy subsystems of wireless sensor nodes. The system allows the microcontroller to monitor its energy devices, and permits multiple energy devices (e.g., energy harvesting devices, supercapacitors, and batteries) to be connected to a single sensor node. The system can be plugged together on deployment and each energy module has an electronic datasheet that can be read by the microcontroller. The architecture permits the development of systems that are energy-aware but agnostic with regard to the type of energy resources that they can interface with.

Figure 12 A sensor node connected to a range of energy devices.

The team have also developed a localised technique to extend the lifetime of a wireless sensor network, referred to as IDEALS/RMR (Information manageD Energy aware ALgorithm for Sensor networks with Rule Managed Reporting). The extension in the network lifetime is achieved at the possible sacrifice of low importance packets.

Source: University of Southampton

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The advantage of this new architecture is that the application running on the sensor node can be written in a generalised way, and does not need to be adapted to interface with different energy resources. The stacked architecture also means that individual elements can be re-used, with increasing levels of abstraction at the higher levels of each stack.

**Case Study: LTC3108 - Ultralow Voltage Step-Up Converter and Power Manager**

Using a small step-up transformer, the LTC3108 provides a power management solution for wireless sensing and data acquisition. The LTC3108 is a highly integrated DC/DC converter aimed at harvesting and managing surplus energy from low input voltage sources such as thermoelectric generators, thermopiles and small solar cells. The step-up topology operates from input voltages as low as 20mV.

![LTC3108 on demo circuit](attachment:image.png)

*Figure 14 The LTC3108 with dimensions 3mm x 4mm is shown on the centre of a demo circuit, which been used in various domains including aircraft structural monitoring.*

The 2.2V LDO powers an external microprocessor, while the main output is programmed to one of four fixed voltages to power a wireless transmitter or sensors. The power good indicator signals that the main output voltage is within regulation. A second output can be enabled by the host. A storage capacitor provides power when the input voltage source is unavailable. Low quiescent current and high efficiency design ensure fast charge times of the output reservoir capacitor.

*Source: Linear Technology*
III. Network-level Power Management

Having studied the power characteristics of wireless nodes, we now focus our attention to the issue of minimising the power consumed by these nodes when performing communication tasks. Data routes can be chosen for uniform routing load. The key lies in synchronizing the sleep/wake-up cycles of the nodes to each other. This means a node wakes up when it expects a message from a neighbouring node. As a result the routing nodes too will be in a nearly powerless sleeping state most of the time, achieving low-power operation. The better the wakeup schedule can match the communication expectations, the less power is consumed by ‘in void’ wakeup periods.

A typical architecture to power management is as shown in Figure 15, where the power management module/algorithm sits between the application, the network layer and the data link and physical layer.

![Figure 15 The power management module algorithm sits between the application, the network layer and the data link and physical layer.](image)

Issue 7 – Measuring energy/performance trade-offs

A lot of metrics exist to establish energy/performance trade-offs in networked systems. What factors should be taken into account towards the standardisation of those metrics?

The choice of metrics reflects the diversity of power management approaches to target for optimisation. Average power (Watts) and energy (Joules) are often used interchangeably to measure effectiveness in conserving energy for a particular usage scenario. Battery lifetime (hours) is often used to estimate the total energy consumption for a workload. We would caution against the use of battery lifetime as a metric: this is dependent on many factors and difficult to determine in simulation without having a detailed model of the battery and the load (the behaviour of batteries is complex and difficult to predict under ‘pulsed’ load). Work units per joule may be a helpful metric, but this is dependent on the type of ‘work’ that is carried out and the frequency/voltage the processor is run at. A more useful metric may be minimum energy per (stated) operation. Also, sleep power consumption is very important due to the low duty cycle most sensor nodes are operated at; this must also be included as a metric.

As with processing performance, there are no good power consumption metrics. MIPS per Watt is the most common but it actually tells us nothing about performance.

There are other metrics that have been proposed for evaluating the effectiveness of power/energy management. Productivity metrics such as megabytes per Watts (MB/W), MFLOPS/W, or transactions per Watts make the work accomplished (the unit of work defined approximately for the
application) explicit in the metric. These are based upon the average power consumed in performing the work units of interest.

Motorola invented ‘Powerstone’ for Mcore which is a collection 15 embedded applications. Also, EEMBC scores per Watt may be better but the big question is how energy metrics should be standardised?

The metrics discussed so far do not directly address the energy/performance tradeoffs. It is possible that improving energy consumption is being achieved at the expense of performance. Capturing this trade-off is the justification for a single, combined metric such as energy*delay (usually specified without units). The advantage of this metric is that it imposes a penalty for either high energy consumption or high latency. While it is not the most intuitive metric, it serves a purpose by producing a single value that can be compared across many alternative design points.

Another approach to capturing the performance trade-off is to consider the energy metric, subject to quality of Service (QoS) constraints. Example includes efforts to reduce energy such that no deadlines will be missed in a real time system or so the latency of an operation will be bounded.

There are additional metrics that capture the global energy use of an ad-hoc network of mobile devices or a sensor network. For such environments, the battery lifetime of individual nodes is important not just for local performance but also in how they contribute to the overall life of the network. If just one node’s battery dies, but it happens to be only node that can forward message to maintain connectivity between other nodes, then the network fails regardless of the average remaining battery capacity throughout the network. So, the metrics such as time to network partition and variance in power consumption among the nodes are important in these applications.

The Embedded Microprocessor Benchmark Consortium (EEMBC) has established and taken steps to standardise energy metrics.

**Issue 8 – Power consumption and node density**

*How can one minimise the average power consumption while largely maintaining the node density?*

This assumes that the average power consumption of the network is the main parameter of interest, rather than the average power consumption of individual nodes. For energy harvesting systems, as the node density increases, the power available also does (directly proportional - you have more energy generators). Therefore, the question is actually surrounding the average power consumption per node. By increasing the node density, one increases the flexibility over the length of each hop, and so actually has more flexibility over the power consumption. There are no scalability problems by doing this. However, the number of hops is not necessarily linked to the node density. A good solution comes down to clever network, communication and management algorithms. These rely on high accuracy clocks and clock distribution.

One way to perform power management in wireless sensor networks is the sentry-based approach. To minimize average power consumption while maintaining sufficient node density for coarse sensing, nodes are partitioned dynamically into two sets: sentries and non-sentries. Sentry nodes provide sufficient coverage for continuous monitoring and basic communication services. Non-sentry nodes sleep for designated periods of time to conserve power, and switch to full power only when needed to provide more refined services.

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26 Carla S. Elias; Controlling energy demands in mobile computing Systems; 2007.

sensing for tracking. Non-sentry nodes check for beacons from sentry nodes to determine when they should remain on. It should allow as many nodes to turn off at any time, while leaving enough nodes on to maintain a multi-hop path between any two nodes. This implies that a coarse network of nodes must remain on to form a connected backbone.

**Issue 9 – Condition of a battery system**

Unreliable state of charge readings has various consequences. How can the condition of a battery system be accurately determined?

Knowledge of the state of charge (SoC) is particularly important for batteries. Knowing the amount of energy left in a battery compared with the energy it had when it was full, is used to give the user an indication of how much longer a battery will continue to perform before it needs recharging. However, this is highly dependent on the battery chemistry; primary lithium cells are notoriously difficult to monitor due to their flat discharge characteristic (end-of-life can only be detected, with active monitoring, when they are >85% depleted; passive monitoring will only detect this 3% before cut-off). This is a problem as primary lithium cells are the most common cell used in “deploy and forget” sensing applications without energy harvesting. The state-of-charge of alkaline cells can be assessed by looking at the closed-circuit voltage (i.e. under a pulsed load). In a similar way, many rechargeable batteries have a predictable discharge curve, which is dependent on temperature and the discharge current. A further problem is that rechargeable cells will degrade with age and discharge cycles. Recent developments in thin-film lithium secondary cells promise very long life (20 years+, thousands of cycles).

It is also important to note that for some types of battery, the lifetime is critically dependent on the values of peak and average current and the duty cycle. Many wireless sensor nodes draw significant peaks of current (up to 100mA) for a few ms, but this peak demand is at a low duty cycle so that the average current may be only a few mA. High (in this context) peak currents can either damage the battery chemically or waste a large proportion of its capacity (due to $I^2R$ losses in the battery internal impedance). It is therefore important to “smooth out” the peak demand by using, for example, a conventional capacitor or alternatively a supercapacitor to act as an energy reservoir for these brief peak currents. Supercapacitors are easier to monitor the state-of-charge of; however the voltage approximately follows the $E=\frac{1}{2}CV^2$ relationship, so it is normally necessary to boost this voltage to make use of the energy stored below the operating voltage of the microcontroller. Some of the most prominent ways to determine charge of battery are:

**Voltage Based SoC Estimation**

This uses the voltage of the battery cell as the basis for calculating SoC or the remaining capacity. Results can vary widely depending on actual voltage level, temperature, discharge rate and the age of the cell and compensation for these factors must be provided to achieve a reasonable accuracy. Problems can occur with some cell chemistries however, particularly Lithium which exhibits only a very small change in voltage over most of the charge/discharge cycle. The discharge curve for a high capacity Lithium-ion cell is ideal for the battery application in that the cell voltage does not fall appreciably as the cell is discharged, but for the same reason, the actual cell voltage is not a good measure of the SoC of the cell.

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28 For example batteries by Infinite Power Solutions [http://www.infinitepowersolutions.com/]
The rapid fall in cell voltage at the end of the cycle could be used as an indication of imminent, complete discharge of the battery, but for many applications an earlier warning is required. Fully discharging Lithium cells will dramatically shorten the cycle life and most applications will impose a limit on the DOD to which the cell is submitted in order to prolong the cycle life. While the cell voltage can be used to determine the desired cut off point, a more accurate measure is preferred for critical applications.

**Current Based SoC Estimation - (Coulomb Counting)**

The energy contained in an electric charge is measured in Coulombs and is equal to the integral over time of the current which delivered the charge. The remaining capacity in a cell can be calculated by measuring the current entering (charging) or leaving (discharging) the cells and integrating (accumulating) this over time. In other words the charge transferred in or out of the cell is obtained by accumulating the current drain over time. The calibration reference point is a fully charged cell, not an empty cell, and the SoC is obtained by subtracting the net charge flow from the charge in a fully charged cell. This method, known as Coulomb counting, provides higher accuracy than most other SoC measurements since it measures the charge flow directly. However it still needs compensation to allow for the operating conditions as with the voltage based method.

Three current sensing methods may be used:

- **Current Shunt** is the simplest method of determining the current is by measuring the voltage drop across a low ohmic value, high precision, series, sense resistor between the battery and the load known as a current shunt. This method of measuring current causes a slight power loss in the current path and also heats up the battery and is inaccurate for low currents.

- **Hall Effect transducers** avoid this problem but they are more expensive.

- **GMR magneto resistive sensors** are even more expensive but they have higher sensitivity and provide a higher signal level. They also have better high temperature stability than Hall effect devices.

Coulomb counting depends on the current flowing from the battery into external circuits and does not take account of self discharge currents or the Coulombic efficiency of the battery.
Case Study: Spectro - A new way of battery testing

The Spectro CA-12 is a hand-held battery tester that reads reserve capacity (RC), CCA, and state-of-charge (SoC) in a single, non-invasive 15-seconds test. The instrument is based on multi-model electrochemical impedance spectroscopy (Spectro™). The instrument injects 24 excitation frequencies ranging from 20-2000 Hertz. The sinusoidal signals are regulated at 10mV/cell to remain within the thermal battery voltage of lead acid. This allows consistent readings for small and large batteries.

![Image of Spectro CA-12]

**Figure 16** The Spectro CA-12 shows the results in numeric and graphic format. In vehicle mode one can read the capacity and SoC of individual batteries.

With multi-frequency impedance Spectroscopy, all three resistance values of the Randle’s model can be established. Randle’s model states that battery may be viewed as a set of electrical elements in terms of resistors and capacitors. The inductive reactance is commonly omitted because it plays a negligible role in a battery at low frequency. A process evaluates the fine nuances between each frequency to enable an in-depth battery analysis. The instrument is capable of reading to a very low micro-ohms level. With stored matrices as reference, Spectro™ is capable of providing battery capacity in Ah, conductivity (CCA) and state-of-charge.

*Source: Cadex*
Centres of Expertise

A-Z list of Organisations

Table 4 lists organisations active in either carrying out research on power management technologies or in developing power management products and/or integrating power management into sensing systems. Although the list is not exhaustive, the intention is that this examination of the centres of expertise will be useful to those wishing to know where they can go to collaborate and which organisations actually have products that they could buy or at least evaluate. As this report cannot hope to capture all of the detail of each organisation’s research or development programme or keep up with the rapidly evolving field the approach taken has been to highlight the particular techniques used by each organisation and any notable areas they are working on.

Table 4 Organisations active in Power Management technologies.

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Country</th>
<th>Web</th>
<th>Main expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agilent Technologies</td>
<td>USA</td>
<td><a href="http://www.agilent.com">www.agilent.com</a></td>
<td>Battery drain analysis and current drain measurement devices.</td>
</tr>
<tr>
<td>ARM</td>
<td>UK</td>
<td><a href="http://www.arm.com">www.arm.com</a></td>
<td>ARM Cortex-M processors (reduced power mP)</td>
</tr>
<tr>
<td>Cadex</td>
<td>Canada</td>
<td><a href="http://www.cadex.com">www.cadex.com</a></td>
<td>Battery State of Charge (SoC) testing devices and techniques.</td>
</tr>
<tr>
<td>Cap-XX</td>
<td>Australia</td>
<td><a href="http://www.cap-xx.com">www.cap-xx.com</a></td>
<td>High power, high energy super capacitors for PM</td>
</tr>
<tr>
<td>Center for Embedded Networked Sensing (CENS), UCLA</td>
<td>USA</td>
<td>research.cens.ucla.edu/</td>
<td>Urban sensing mobile applications</td>
</tr>
<tr>
<td>Centre Suisse d’Electronique et de Microtechnique</td>
<td>Switzerland</td>
<td><a href="http://www.csem.ch">www.csem.ch</a></td>
<td>Ultra low power DSP RISC cores for portable applications</td>
</tr>
<tr>
<td>Eaton Corporation</td>
<td>USA</td>
<td><a href="http://www.eaton.com">www.eaton.com</a></td>
<td>Metering Devices, Protective Relays &amp; Communications</td>
</tr>
<tr>
<td>EECS Dept., Univ. of California, Berkeley</td>
<td>USA</td>
<td><a href="http://www.eecs.berkeley.edu">www.eecs.berkeley.edu</a></td>
<td>Signal-Based Power Management for Digital Signal Processing Systems</td>
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<tr>
<td>Embedded Microprocessor Benchmark Consortium</td>
<td>USA</td>
<td><a href="http://eembc.org">http://eembc.org</a></td>
<td>Standardisation of Energy/Power metrics in batteries</td>
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<tr>
<td>EnOcean GmbH</td>
<td>Germany</td>
<td><a href="http://www.enocean.com">www.enocean.com</a></td>
<td>Wireless sensor solutions, ultra-low-power electronic circuitry</td>
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<tr>
<td>Fac. of Electron. Eng., Univ. of Nis, Nis, Serbia</td>
<td>Serbia</td>
<td><a href="http://www.ni.ac.rs/en">http://www.ni.ac.rs/en</a></td>
<td>Energy harvesting techniques for wireless sensor nodes</td>
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<td>Fairchild Semiconductor International</td>
<td>USA</td>
<td><a href="http://www.fairchildsemi.com">www.fairchildsemi.com</a></td>
<td>Charge Pump Regulators for Power Management ICs</td>
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<tr>
<td>Fraunhofer IIS</td>
<td>Germany</td>
<td><a href="http://www.iis.fraunhofer.de">www.iis.fraunhofer.de</a></td>
<td>Intelligent image sensors</td>
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<tr>
<td>Hewlett-Packard Labs., Palo Alto, CA</td>
<td>USA</td>
<td><a href="http://www.hpl.hp.com/palo_alto/">www.hpl.hp.com/palo_alto/</a></td>
<td>Chip to Chip optical interconnection</td>
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<td>Infineon Technologies</td>
<td>USA</td>
<td><a href="http://www.infineon.com">www.infineon.com</a></td>
<td>Wireless sensors and MOSFETs for automotive applications</td>
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<td>Infinite Power Solutions</td>
<td>USA</td>
<td><a href="http://www.infinitepowersolutions.com">www.infinitepowersolutions.com</a></td>
<td>Rechargeable thin-film micro-energy storage devices</td>
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<td>Inst. of Microelectronics., Tsinghua Univ., Beijing</td>
<td>China</td>
<td>dns.ime.tsinghua.edu.cn/english</td>
<td>Energy efficient ASIC for wireless sensor network</td>
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<td>International Rectifier</td>
<td>USA</td>
<td><a href="http://www.irf.com">www.irf.com</a></td>
<td>PWM control and high speed</td>
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<td>Intersil</td>
<td>USA</td>
<td><a href="http://www.intersil.com">www.intersil.com</a></td>
<td>Single Cell Li+/Polymer Battery Chargers</td>
</tr>
<tr>
<td>Linear Technology Corporation</td>
<td>UK</td>
<td><a href="http://www.linear.com">http://www.linear.com</a></td>
<td>Integration of high and low power devices.</td>
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<tr>
<td>Luna Innovations Inc</td>
<td>USA</td>
<td><a href="http://www.lunainnovations.com">www.lunainnovations.com</a></td>
<td>Distributed Sensing System</td>
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<td>Maxim Integrated Products</td>
<td>USA</td>
<td><a href="http://www.maxim-ic.com">www.maxim-ic.com</a></td>
<td>Fuel gauges for Battery Management</td>
</tr>
<tr>
<td>Micro Power Electronics</td>
<td>USA</td>
<td><a href="http://www.micro-power.com">www.micro-power.com</a></td>
<td>Custom power systems, battery packs and power supply subassemblies</td>
</tr>
<tr>
<td>National Chiao Tung University</td>
<td>Taiwan</td>
<td><a href="http://www.nctu.edu.tw/english">www.nctu.edu.tw/english</a></td>
<td>Characterization power consumption in radio devices</td>
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<tr>
<td>National Physical Laboratory</td>
<td>UK</td>
<td><a href="http://www.npl.co.uk">www.npl.co.uk</a></td>
<td>Small and Smart antenna efficiency measurement; Piezo Energy Harvesting materials</td>
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<tr>
<td>National Semiconductor</td>
<td>USA</td>
<td><a href="http://www.national.com">www.national.com</a></td>
<td>Network Power Management and Protection IC</td>
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<tr>
<td>NXP Semiconductors</td>
<td>USA</td>
<td><a href="http://www.nxp.com">www.nxp.com</a></td>
<td>Monolithic microwave integrated circuit</td>
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<tr>
<td>ON Semiconductor</td>
<td>USA</td>
<td><a href="http://www.onsemi.com">www.onsemi.com</a></td>
<td>Thermal Monitors for Power management applications</td>
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<tr>
<td>Perpetuum</td>
<td>UK</td>
<td><a href="http://www.perpetuum.com">www.perpetuum.com</a></td>
<td>Magnetic resonator for vibration energy-harvester technology</td>
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<tr>
<td>PPM Power</td>
<td>UK</td>
<td>Ppmpower.co.uk</td>
<td>Power management in High voltage and high current circuit</td>
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<td>ROHM Semiconductor</td>
<td>Japan</td>
<td><a href="http://www.rohm.com">www.rohm.com</a></td>
<td>Power management ICs designed for automotive body applications</td>
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<td>Samtec</td>
<td>USA</td>
<td><a href="http://www.samtec.com">www.samtec.com</a></td>
<td>Combination Signal / Power Systems for Wireless applications</td>
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<td>STMicroelectronics</td>
<td>Switzerland</td>
<td><a href="http://www.st.com">www.st.com</a></td>
<td>Linear Regulators, DC-DC Conversion, Voltage and Current Controllers for Battery Management, AC-DC Conversion for PM applications</td>
</tr>
<tr>
<td>Synopsys</td>
<td>USA</td>
<td><a href="http://www.synopsys.com">www.synopsys.com</a></td>
<td>Low power implementation and verification techniques</td>
</tr>
<tr>
<td>Taiwan Semiconductor Manufacturing Company Ltd.</td>
<td>Taiwan</td>
<td><a href="http://www.tsmc.com">http://www.tsmc.com</a></td>
<td>Power management in microprocessors</td>
</tr>
<tr>
<td>Tektronix</td>
<td>USA</td>
<td><a href="http://www.tek.com">www.tek.com</a></td>
<td>Power Supply Measurement and Analysis</td>
</tr>
<tr>
<td>Texas Instruments</td>
<td>USA</td>
<td><a href="http://www.ti.com">www.ti.com</a></td>
<td>AC/DC and DC/DC Power Supplies, Linear Regulators, MOSFETs and integrated power modules.</td>
</tr>
<tr>
<td>Texas MicroPower</td>
<td>USA</td>
<td><a href="http://www.texasmicropower.com">www.texasmicropower.com</a></td>
<td>Power Management evaluation modules for wireless sensor systems</td>
</tr>
<tr>
<td>University of Bristol</td>
<td>UK</td>
<td><a href="http://www.bris.ac.uk/eeng/">http://www.bris.ac.uk/eeng/</a></td>
<td>Power and Energy Management, and Non-linear energy harvesting</td>
</tr>
<tr>
<td>University of Southampton</td>
<td>UK</td>
<td>ecs.soton.ac.uk</td>
<td>Electromagnetic energy harvesting; multi-source energy harvesting</td>
</tr>
<tr>
<td>Universität Karlsruhe (TH), System Architecture Group</td>
<td>Germany</td>
<td><a href="http://i30www.ira.uka.de/pm">http://i30www.ira.uka.de/pm</a></td>
<td>Process Cruise Control-Event-Driven Clock Scaling for Dynamic Power Management</td>
</tr>
<tr>
<td>Vishay Intertechnology</td>
<td>USA</td>
<td><a href="http://www.vishay.com">www.vishay.com</a></td>
<td>Power MOSFET package</td>
</tr>
<tr>
<td>Organisation</td>
<td>Country</td>
<td>Website</td>
<td>Technology Description</td>
</tr>
<tr>
<td>-----------------------</td>
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<td>--------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Waterfall Solutions</td>
<td>UK</td>
<td><a href="http://www.waterfallsolutions.co.uk">www.waterfallsolutions.co.uk</a></td>
<td>Generic sensor model producing performance metrics</td>
</tr>
<tr>
<td>Wolfson Microelectronics</td>
<td>UK</td>
<td><a href="http://www.wolfsonmicro.com">www.wolfsonmicro.com</a></td>
<td>Power management IC integration (WM8352) and Ultra low power circuits</td>
</tr>
<tr>
<td>Xilinx</td>
<td>USA</td>
<td><a href="http://www.xilinx.com">www.xilinx.com</a></td>
<td>Power-Optimized Designs for FPGAs and CPLDs</td>
</tr>
</tbody>
</table>

**Intellectual Property Landscape**

In order to collect and analyse the patent data, we used the EPO Worldwide Patent Statistical Database also known as PATSTAT, accessed via the Matheo Patent software tool. This database contains patent bibliographic data from more than 80 patent offices. The patent datasets used in this study were defined through:

- Consultation with experts, identifying key “technology descriptors” used;
- Developing and optimising patent search queries;
- Identification of patent datasets;
- Analysis of patent data using the Matheo Patent analysis platform.

**Patents granted per year**

According to our analysis, during the period 1991 to 2009, 6744 patents, organized in 1505 families, were granted in the field of power management. These patents were filed by 2123 applicants and listed 5801 individual inventors. As depicted in Figure 17, there was a jump in patents granted in 2001 and a steady increase every year since then.

![Figure 17 Patents published over the last 20 years in the power management field.](image)

**Top patent applicants**

The organisations holding the highest numbers of patents are shown in ...
Country of applicants

As can be seen in Figure 19 the applicant country with the largest number of family patents granted in the field is the USA (37.8%) followed by China (25.0%) and S. Korea (7.3%).

Patent Classes

The International Patent Classification most frequently used in patenting AUV technologies is as follows:

G06F ELECTRIC DIGITAL DATA PROCESSING (computers in which a part of the computation is effected hydraulically or pneumatically G06D, optically G06E; self-contained input or output peripheral equipment G06K; computer systems based on specific computational models G06N; impedance networks using digital techniques H03H)
G08C  TRANSMISSION SYSTEMS FOR MEASURED VALUES, CONTROL OR SIMILAR SIGNALS (fluid pressure transmission systems F15B; sensing members for specific physical variables, see the relevant subclasses, e.g. of G01, of H01; indicators or recorders, see the relevant subclasses, e.g. G01D, G09F; mechanical means for transferring the output of a sensing member into a different variable G01D 5/00; self-balancing bridges G01R; position control in general G05D 3/00; mechanical control systems G05G; systems for transmitting "on/off" signals only, systems for transmitting alarm conditions G08B; order telegraph systems G08B 9/00; generating electric pulses H03K; coding, decoding or code conversion, in general H03M; transmission of digital information H04L; selective calling from one station to another H04Q 9/00)

H02J  CIRCUIT ARRANGEMENTS OR SYSTEMS FOR SUPPLYING OR DISTRIBUTING ELECTRIC POWER; SYSTEMS FOR STORING ELECTRIC ENERGY (power supply circuits for apparatus for measuring X-radiation, gamma radiation, corpuscular radiation or cosmic radiation G01T 1/175; electric power supply circuits specially adapted for use in electronic time-pieces with no moving parts G04G 19/00; for digital computers G06F 1/18; for discharge tubes H01J 37/248; circuits or apparatus for the conversion of electric power, arrangements for control or regulation of such circuits or apparatus H02M; interrelated control of several motors, control of a prime-mover/generator combination H02P; control of high-frequency power H03L; additional use of power line or power network for transmission of information H04B)

H04B  TRANSMISSION (transmission systems for measured values, control or similar signals G08C; speech analysis or synthesis G10L; coding, decoding or code conversion, in general H03M; broadcast communication H04H; multiplex systems H04J; secret communication H04K; transmission of digital information H04L)

H04L  TRANSMISSION OF DIGITAL INFORMATION, e.g. TELEGRAPHIC COMMUNICATION (typewriters B41J; order telegraphs, fire or police telegraphs G08B; visual telegraphy G08B, G08C; teleautographic systems G08C; ciphering or deciphering apparatus per se G09C; coding, decoding or code conversion, in general H03M; arrangements common to telegraphic and telephonic communication H04M; selecting H04Q)

H04M  TELEPHONIC COMMUNICATION (counting mechanisms G06M; circuits for controlling other apparatus via a telephone cable and not involving telephone switching apparatus G08; reels or other take-up devices for cords H02G 11/00; multiplex transmission between switching centres H04J; selecting arrangements H04Q; loudspeakers, microphones, gramophone pick-ups or like electromechanical transducers H04R). Figure 20 shows the patent classes used by the top applicants. The numbers of patents are shown.
Figure 20 Top applicants and the IP classes they patent into.

**Patent description keywords**

Figure 21 shows the most frequently used keywords to describe the patents by the top applicants. These include power, system, method, device, plurality, data, power management, communication, apparatus, response, and user, circuit (in descending order).

Figure 21 Most frequently used keywords by the top applicants
Conclusions and Recommendations

Power Management has become the key aspect to enable remote and wireless sensing in applications of interest to industry. Although this report has been structured in three levels, power management has to be considered with holistic approach. It has to be implemented right from the conception of the design. By concentrating on influencing all steps in a development process and all levels in the design hierarchy, we’re able to make major breakthroughs that in some instances can lead to orders-of-magnitude savings in the power consumption of a system.

System designers, system integrators and system planners have to prioritize the need of power management to consider efficient designs which ultimately will have long term gains. The successful system designer will take a systems approach, involve technical and business representatives from all functions, and advocate site-wide ownership of the system.

Some of the study remarks are:

- Power consumption can be as important design criterion as computational performance. Power management is a systems issue that requires circuit, software architecture and network interaction. Although the techniques described in this report are generic to many types of wireless sensing systems, an optimal solution and trade-offs will be very application-specific. This has parallels with energy harvesting where solutions are also very application-specific.

- It is important to understand the way in which a system will use its power - regular low-level usage (e.g. continuous monitoring) vs. sporadic (e.g. alarm or reactive system) as this affects the type of storage/harvesting options. Recent experience with mobile phones, RFID, sensor networks etc is that you need to understand the execution profile of the application to be able to save power. So, first you need hardware that supports such functionality and then software to drive the process. There is huge variability in how efficient are the different platforms. Most of the recent work in WSN is about algorithms that minimise power consumption (for the whole network) through software and protocol design. So, to be able to capitalize on the capabilities of the hardware you also need appropriate software hooks.

- It is of vital importance to properly specify the measurement that the WSN must carry out to fulfill the user requirements. Factors such as sample rates, precision, synchronisation accuracy etc. all have a significant impact upon power consumption. Users often over-specify the system (e.g. sample more often than needed) if they have not properly defined the measurement. System designers must then set a power budget at the start of the design process and measure it as they go. Tools are becoming available to help but the industry needs to be encouraged to develop more such tools.

- One of the major issues which are prominent the existence of significant synergies between various components. If power management is being considered at the microprocessor level then overall costs and complexity increases and the same happens for network level management. These synergies have to be identified by bringing the whole design under simpler optimization criteria and tools. However this is easier said than done. Today’s engineering

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29 For example, some evidence from mobile phones shows that Symbian is significantly more efficient than Android on the same hardware.
skills where every engineer has his own area of expertise and knows only vaguely the alternatives and what is connected to his part of the system are very far from the multidisciplinary skill-sets needed for adjusting today’s and tomorrow’s demanding products. Networking engineers at different levels of the supply chain is an essential task and KTNs have a key role to play in it.

- Antenna design and connection is an area for quick power savings as it is known that many systems (particularly development kits) have extremely lossy antennas. Directional antennas for static deployments offers good potential for saving on transmit power usage.

- Batteries play an important role and there are no standardised ways to know the accurate measurements of their power density. Better devices and battery calibration tools are needed for evaluating the conditions of battery. Also, there is a need to standardise the energy metrics to bridge the information gap between vendors and systems integrators. This will help to overcome mismatches between user-supplied specifications and actual requirements of the task.

- For systems with energy harvesting, accurately estimating the incoming power can be problematic; there are several ways of doing this but each have their own drawbacks.

- There is definitely a need for more R&D to investigate power management issues for real-world applications of WSNs. As other aspects of the technology reach maturity, lack of power or shorter than expected lifetime could seriously damage the commercial viability of systems.

- As devices become networked, interdependent, and smarter, the number of factors affecting power management will only increase, so their control will likely become more complex. Controls that are highly configurable, e.g. adaptive to user behaviour or environmental conditions also add to the complexity. Delaying the development of standard power management techniques and common interfaces will make it even more difficult to gain convergence in the future.
### Appendix 1: Selected Collaborative R&D Projects

<table>
<thead>
<tr>
<th>Title</th>
<th>Participant(s)</th>
<th>Dates</th>
<th>Funding body</th>
<th>Abstract</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis and Management of Wireless Networks with Selfish Users (WNET-GT)</td>
<td>Technion - Israel Institute Of Technology, Massachusetts institute of technology,</td>
<td>25-03-2008 to 24-03-2011</td>
<td>EC FP7 (International Outgoing Fellowships)</td>
<td>The emerging use of wireless technologies for data communication has brought to focus novel system characteristics, such as power control, time variation in the channel quality and mobility of the network users. In addition to diversity in these physical parameters, mobile users are heterogeneous with regard to their Quality of Service (QoS) criteria, differently evaluating delay, throughput and power. Distributed mechanisms for wireless medium-sharing, branching from the celebrated Aloha protocol, have gained prominence due to their relative simplicity. Accordingly, this research will employ (non-cooperative) game-theoretic tools for the analysis of multiple access wireless networks. Based on the analysis, we shall design distributed protocols, which allow users to obtain their required QoS, and still preserve network-wide objectives such as fairness. At a higher level, we shall develop efficient management schemes, with the objective of bringing network interference to a minimum. Finally, the designed protocols and management schemes will be evaluated under current network standards.</td>
</tr>
<tr>
<td>Next Generation Energy-Harvesting Electronics: Holistic Approach</td>
<td>University of Southampton, Newcastle University, Imperial College, University of Bristol, QinetiQ, Diodes Incorporated, ARM, NXP and Mentor Graphics.</td>
<td>01-10-2009 to 30-09-2012</td>
<td>EPSRC</td>
<td>Future self-powered applications will require electronic systems that are more complex and compact but also intelligent, adaptive and able to perform more computation with less energy. This project recognises the high level of interaction in an energy harvesting system, from the design and properties of the micro-generator and power conversion electronics, to the design and architecture of the load and the algorithms and applications that operate on it. This approach aims to maximise the available harvested energy and the efficiency with which it is used, and is fundamental to ultra energy-efficient design and to the miniaturisation of next-generation wireless electronics. These developments are needed in emerging application areas, including pervasive healthcare and autonomous environmental and industrial monitoring. The three themes of the project are: a) Adaptive, High-Efficiency Micro Generators; b) Energy Harvesting-Aware Computation Circuits and c) Integrated Modelling &amp; Performance Optimisation for Energy Harvesting Systems. The project will deliver a range of...</td>
</tr>
</tbody>
</table>
research outputs, and includes the creation of demonstrators for the concepts in each theme and also of the project as a whole, highlighting the importance of ‘holistic’ design in this field. The three research themes are key areas that require interdisciplinary and inter-institutional collaboration. The key differentiator of this project is that, due to the strong interaction between themes, they cannot be achieved in isolation (instead requiring a multi-disciplinary consortium taking a holistic design approach). This design approach is fundamental to ultra energy-efficient design and to the miniaturisation of next-generation wireless electronics.

<table>
<thead>
<tr>
<th>PI</th>
<th>Bashir Al-Hashimi</th>
</tr>
</thead>
<tbody>
<tr>
<td>url</td>
<td><a href="http://www.holistic.ecs.soton.ac.uk/">http://www.holistic.ecs.soton.ac.uk/</a></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Title</th>
<th>Efficient smart systems with enhanced energy storage (E-STARS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participant(s)</td>
<td>Commissariat a l’ energie atomique Liten</td>
</tr>
<tr>
<td>Dates</td>
<td>01-06-2008 to 31-05-2011</td>
</tr>
<tr>
<td>Funding body</td>
<td>European Commission FP7</td>
</tr>
<tr>
<td>Abstract</td>
<td>E-STARS project aims at developing enhanced sensing and communication capability on an autonomous smart micro system powered by a new 3D high capacity integrated micro battery. According to the experts, the market of wireless smart sensors should generate revenues more than 5 billion euro in 2011 (source: <a href="http://www.rfidjournal.com">http://www.rfidjournal.com</a>). Faced with such future strong technical and economical impact, it is of strategic importance to maintain the Europe’s leadership in these domains. Considered as an RandD topic of high relevance in such domain (EpoSS Strategic Research Agenda), the energy-management, scavenging and storing techniques aspects will be particularly investigated by the E-STARS project. As a STREP project, E-STARS addresses clearly the objective 6 of challenge 3 of the ICT call 2 : Micro/nanosystems. The targeted applications within the project are: wearable intelligent micro sensors, wireless networked sensors associated to an intelligent data to internet platform and innovative nanogravimetric sensors and biosensors. More globally, thanks to an optimized dissemination of the result, the project will provide the EU industry with new highly autonomous wireless sensors to face the strong competition in this field.</td>
</tr>
<tr>
<td>PI</td>
<td>Yves Hussenot</td>
</tr>
<tr>
<td>url</td>
<td><a href="http://www.thermonano.org">www.thermonano.org</a></td>
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<thead>
<tr>
<th>Title</th>
<th>Feedback design for wireless networked systems (FEEDNETBACK)</th>
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<tr>
<td>Participant(s)</td>
<td>INRIA, ETH, U. Sevilla, KTH, U. Padova, Ifremer, Vodera, Vitamib, Videotec, OMG</td>
</tr>
<tr>
<td>Dates</td>
<td>01 Sept 2008 to 31 Aug 2011</td>
</tr>
<tr>
<td>Funding body</td>
<td>FP7</td>
</tr>
<tr>
<td>Abstract</td>
<td>The project addresses issues on complexity, temporal and spatial uncertainties, such as delays and bandwidth in communications and node availability. The goal is to enable the development of more efficient, robust and affordable networked control systems that scale and adapt with changing application demands. To further refine and validate the co-design framework FeedNetback applies it to two test cases: [] underwater inspection systems based on fleets of Autonomous Underwater Vehicles (AUVs), and surveillance systems using</td>
</tr>
</tbody>
</table>
a network of smart Cameras. The two case studies have been selected to demonstrate the wide spectrum of possible applications of our methodology: from systems with relatively few, highly mobile nodes, communicating over a low bandwidth, unreliable network (underwater inspection systems); to systems with a very high number of immobile nodes, with high available bandwidth but also high communication requirements (smart camera network).

**Title**

**EPSRC/VCE Strategic Partnership: Green Radio**

**Participant(s)**

Institute of Advanced Telecommunications, Swansea University

**Dates**

01 January 2009 to 30 June 2012

**Funding body**

EPSRC

**Abstract**

There is a need on environmental grounds to reduce the energy requirements of radio access networks. From an operator perspective, reduced energy consumption translates directly to the bottom line - lower Operating Expenditure (OPEX). These are the key drivers of the Green Radio programme. Both wide area public networks (traditionally "cellular") and local area private networks (traditionally "wireless LAN") will be considered, recognizing that the structure of a Green Radio Network may differ from today's radio networks. Thus in essence, the specific objective of the Green Radio programme is to investigate and create innovative methods for the reduction of the total power needed to operate a radio access network and to identify appropriate radio architectures which enable such power reduction.

**PI**

Professor T O'Farrell

**url**

http://www.swan.ac.uk/engineering/

---

**Title**

**Wireless sensor networks for the protection of critical infrastructures (WSAN4CIP)**

**Participant(s)**

EURESCOM-EUROPEAN INSTITUTE FOR RESEARCH AND STRATEGIC STUDIES IN TELECOMMUNICATIONS GMBH

**Dates**

01/01/2009 to 31/12/2011

**Funding body**

European Commission FP7

**Abstract**

The goal of WSAN4CIP is to substantially advance the technology of Wireless Sensor and Actuator Networks (WSANs) beyond the current state of the art and to apply this technology to the Protection of Critical Infrastructures. In particular, the WSAN4CIP project will apply these advanced wireless and sensor network developments to the management of power generation and distribution infrastructure management systems, which is one of the most demanding applications for wireless infrastructure, to demonstrate the appropriateness and effectiveness of the WSAN4CIP project results.

**PI**

Uwe Herzog

**url**

http://www.wsan4cip.eu/
<table>
<thead>
<tr>
<th>Title</th>
<th>The Reduction of Power Consumption in Battery Powered Products by the Use of Switch-Mode Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participant(s)</td>
<td>University of Bristol and Intersolar Group Plc</td>
</tr>
<tr>
<td>Dates</td>
<td>25 May 2000 to 24 May 2003</td>
</tr>
<tr>
<td>Funding body</td>
<td>EPSRC</td>
</tr>
<tr>
<td>Abstract</td>
<td>The programme is aimed at significantly reducing the world consumption of batteries by applying switched-mode power management technology to all types of battery-powered products. By combining switched-mode amplification with power conversion technology, each section of an electronic circuit can be supplied with the optimum voltage for power consumption minimisation. The programme aims to change fundamentally the way in which batteries are used. Switched mode battery management systems will be developed which promote optimum battery usage and allow high efficiency to be achieved. In addition, we hope to demonstrate that the new technology can be incorporated in application specific integrated circuits and that the non-semiconductor elements of the circuit can be miniaturised thereby demonstrating that the technology is affordable as well as efficient. The programme aims to pioneer the new field of low-power power electronics in which techniques developed for high power circuits are applied beneficially to low power applications. A target of special interest will be the transistor radio (broadcast receiver) in which it is believed that a twenty-fold reduction can be achieved in the power consumed by a typical radio.</td>
</tr>
<tr>
<td>PI</td>
<td>DA Grant</td>
</tr>
<tr>
<td>url</td>
<td><a href="http://gow.epsrc.ac.uk">http://gow.epsrc.ac.uk</a></td>
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<tr>
<th>Title</th>
<th>Smart Antenna Systems for Cooperative Low-Power Wireless Personal and Body Area Networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participant(s)</td>
<td>Queen Mary, University of London</td>
</tr>
<tr>
<td>Dates</td>
<td>15 June 2010 to 14 September 2011</td>
</tr>
<tr>
<td>Funding body</td>
<td>EPSRC</td>
</tr>
<tr>
<td>Abstract</td>
<td>Wireless sensor networks are attractive solutions that can be used in healthcare and sport performance monitoring applications which will enable constant monitoring of health data and constant access to the patient regardless of the current location or activity and with a fraction of cost of the regular face-to-face examination. Such a system is particularly useful in the case of in-home assistance of the elderly and rapid repatriation of recovering patients to their own homes, as well as for smart nursing homes, clinical trials and research augmentation. It was estimated in 2012, that wireless sensor solutions could save $25 billion worldwide in annual healthcare costs by reducing hospitalisations and extending independent living for the elderly. Current wireless sensor solutions are limited in that they do not provide the means to overcome obstacles and shadowing of propagating radio waves and also reduce the effect of interference in congested radio environments. The project will conduct research into new techniques and methods that combine both antenna and radio propagation engineering with networking and smart frequency agile communication systems. It aims to develop underpinning capabilities for an advanced low-power wearable antenna elements coupled with intelligent control algorithm capable of sensing and understanding the dynamic human body and dense indoor radio environment.</td>
</tr>
</tbody>
</table>
Title: Hybrid nano-electro-mechanical / integrated circuit systems for sensing and power management applications (NEMSIC)


Dates: 01/06/2008 to 31/05/2011

Funding body: EC FP7

Abstract: The devices envisaged in this project are some tens of nanometre thick and one micrometre long and will include both the sensors and the electronics necessary for data analysis. At the heart of the "intelligent sensor" is a suspended nanowire which is excited to vibrate at a particular frequency - its resonance frequency. The wire is chemically or biologically functionalised to make it selective for target molecules like carcinogens. Binding of target molecules leads to an increase in the mass of the wire which in turn will change its resonance frequency and vibrate at a lower frequency (think of a violin: the thicker the string the lower the tone). Apart from the resonance frequency, the shape of the resonance curve (its quality factor) is also expected to change.
Appendix 2: Additional Reading Material

This study has focused primarily on addressing practical application of power management technology. The following articles may be of interest to those seeking a deeper technical review of the field.


Appendix 3: Acronyms

Below is a list the acronyms used throughout the report. Short definitions have been added for the readers:

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
</table>
| AC      | Alternate Current  
An electrical current whose magnitude and direction vary cyclically, as opposed to direct current, whose direction remains constant. |
| ADC     | Analogue to Digital Converter  
An electronic integrated circuit, which converts continuous signals to discrete digital numbers. |
| API     | Application Programming Interface  
A source code interface that an operating system, library or service provides to support requests made by computer programmes. |
| ATEX    | Appareils destinés à être utilisés en ATmosphères EXplosibles  
A standard/guideline for explosion protection in the industry. |
| CMOS    | Complementary Metal-Oxide. Semiconductor  
A class of integrated circuits used in microprocessors, microcontrollers, static RAM, and other digital logic circuits. CMOS technology is also used for a wide variety of analog circuits such as image sensors, data converters, and highly integrated communication transceivers. |
| DARPA   | Defense Advanced Research Projects Agency, an agency of the US Dept. of Defense responsible for the development of new technology for use by the military. |
| DC      | Direct Current  
The unidirectional flow of electric charge. Direct current is produced by such sources as batteries and solar cells. |
| DPM     | Dynamic power management refers to power management schemes implemented while system/program is still running and executing in a microprocessor or CPU |
| DSP     | Digital signal processing is concerned with the representation of signals by a sequence of numbers or symbols and the processing of these signals. |
| EDLC    | Electrochemical Double Layer Capacitors  
Electrochemical capacitors that have an unusually high energy density when compared to common capacitors. |
<p>| FEC     | Forward error correction is a system of error control for data transmission, whereby the sender adds redundant data to its messages, also known as an error-correction code. |
| FLOPS   | FLoating point Operations Per Second, is a measure of a computer’s performance, especially in fields of scientific calculations that make heavy use of floating point calculations. |
| IEC     | International Electrotechnical Commission is a not-for-profit, non-governmental international standards organisation for electrical, electronic and related technologies. |
| ISO     | International Organisation for Standardisation is an international standard-setting body composed of representatives from various national standards |</p>
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>Line of Sight. The straight line propagation of electromagnetic radiation when the rays of waves are not diffracted, reflected, or absorbed by obstructions.</td>
</tr>
<tr>
<td>LED</td>
<td>Light-emitting diode is a semiconductor light source.</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control is a data communication protocol sub-layer of the Data Link Layer specified in the seven-layer OSI model. It provides addressing and channel access control mechanisms that make it possible for several terminals or network nodes to communicate within a multi-point network.</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro Electro Mechanical System Devices made up of components between 1 to 100 micrometers in size (i.e. 0.001 to 0.1 mm) and overall device size from 20 micrometers (20 millionth of a meter) to a millimeter (thousandth of a meter).</td>
</tr>
<tr>
<td>MIPS</td>
<td>Million Instructions per second, a measure of a computer's processor speed.</td>
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<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracker A high efficiency DC to DC converter which functions as an optimal electrical load for a photovoltaic cell, most commonly for a solar panel or array, and converts the power to a voltage or current level which is more suitable to whatever load the system is designed to drive.</td>
</tr>
<tr>
<td>NPD</td>
<td>Normalised Power Density A measure used to compare the relative performance of machines of differing sizes operating at differing speeds (W/cm² rpm²).</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer The original manufacturer of a component for a product, which may be resold by another company</td>
</tr>
<tr>
<td>PIC</td>
<td>Programmable Interface Controller A PIC microcontroller is a single-chip package that combines a microprocessor, ROM program memory, and RAM variable memory, along with several input and output logic gates. This makes them a one-chip computer, with an operating system supplied by the programmer</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead Zirconate Titanate (piezoelectric ceramic material) A ceramic perovskite material that shows a marked piezoelectric effect.</td>
</tr>
<tr>
<td>RAS</td>
<td>Remote Access Switch A technique used to wake up a receiver only when it has data destined for it.</td>
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<tr>
<td>RF</td>
<td>Radio Frequency A frequency or rate of oscillation within the range of about 3 Hz to 300 GHz.</td>
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<tr>
<td>RFID</td>
<td>Radio Frequency Identification An automatic identification method, relying on storing and remotely retrieving data using devices called RFID tags or transponders.</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square A statistical measure of the magnitude of a varying quantity.</td>
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<tr>
<td>RTG</td>
<td>Radioisotope Thermoelectric Generator An electrical generator which obtains its power from radioactive decay.</td>
</tr>
<tr>
<td><strong>RTOS</strong></td>
<td>Real-time operating system: an operating system intended for real-time applications. Such operating systems serve application requests nearly real-time and offer programmers more control over process priorities.</td>
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<tr>
<td><strong>SoC</strong></td>
<td>State of Charge</td>
</tr>
<tr>
<td><strong>TPV</strong></td>
<td>Thermophotovoltaic, a direct conversion process from heat differentials to electricity via photons.</td>
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<tr>
<td><strong>WSN</strong></td>
<td>Wireless Sensor Network</td>
</tr>
<tr>
<td><strong>UAV</strong></td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td><strong>USB</strong></td>
<td>Universal Serial Bus: a specification for establishing communication between devices and a host controller, that has become commonplace on devices such as PCs, smartphones.</td>
</tr>
<tr>
<td><strong>VLSI</strong></td>
<td>Very Large Scale Integration</td>
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</tbody>
</table>

The process of creating integrated circuits by combining thousands of transistor-based circuits into a single chip.