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Wireless Sensor Networks

First European Workshop, EWSN 2004
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Preface

With great pleasure we welcomed the attendees to EWSN 2004, the 1st European Workshop on Wireless Sensor Networks, held in the exciting and lively city of Berlin.

Wireless sensor networks are a key technology for new ways of interaction between computers and the physical environment which surrounds us. Compared to traditional networking technologies, wireless sensor networks are faced with a rather unique mix of challenges: scalability, energy efficiency, self-configuration, constrained computation and memory resources in individual nodes, data-centricity, and interaction with the physical environment, to name but a few. The goal of this workshop is to create a forum for presenting new results in the flourishing field of wireless sensor networks. By bringing together academia and industry we hope to stimulate new opportunities for collaborations.

In compiling the scientific program we have been quite selective. Thanks to the efforts of 90 reviewers who delivered 252 reviews for the 76 papers originally submitted from all over the world, a strong selection of the 24 best contributions was made possible. The Technical Program Committee created an outstanding program covering the broad scope of this highly interdisciplinary field: from distributed signal processing through networking and middleware issues to application experience.

Running such a workshop requires dedication and much work from many people. We want to thank in particular Petra Hutt, Irene Ostertag and Heike Klemz for their valuable and esteemed help in the local organization of this workshop.

We hope that you enjoy this volume, and if you were lucky enough to attend we hope that you enjoyed the discussions with colleagues working in this fascinating area.

Adam Wolisz
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Table of Contents

Power Sources for Wireless Sensor Networks

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Abstract. Wireless sensor networks are poised to become a very significant enabling technology in many sectors. Already a few very low power wireless sensor platforms have entered the marketplace. Almost all of these platforms are designed to run on batteries that have a very limited lifetime. In order for wireless sensor networks to become a ubiquitous part of our environment, alternative power sources must be employed. This paper reviews many potential power sources for wireless sensor nodes. Well established power sources, such as batteries, are reviewed along with emerging technologies and currently untapped sources. Power sources are classified as energy reservoirs, power distribution methods, or power scavenging methods, which enable wireless nodes to be completely self-sustaining. Several sources capable of providing power on the order of 100 $\mu W/cm^3$ for very long lifetimes are feasible. It is the authors' opinion that no single power source will suffice for all applications, and that the choice of a power source needs to be considered on an application-by-application basis.

1 Introduction

The vast reduction in size and power consumption of CMOS circuitry has led to a large research effort based around the vision of ubiquitous networks of wireless sensor and communication nodes [1-3]. As the size and cost of such wireless sensor nodes continues to decrease, the likelihood of their use becoming widespread in buildings, industrial environments, automobiles, aircraft, etc. increases. However, as their size and cost decrease, and as their prevalence increases, effective power supplies become a larger problem.

The issue is that the scaling down in size and cost of CMOS electronics has far outpaced the scaling of energy density in batteries, which are by far the most prevalent power sources currently used. Therefore, the power supply is usually the largest and most expensive component of the emerging wireless sensor nodes being proposed and designed. Furthermore, the power supply (usually a battery) is also the limiting

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factor on the lifetime of a sensor node. If wireless sensor networks are to truly become ubiquitous, replacing batteries in every device every year or two is simply cost prohibitive.

The purpose of this paper, then, is to review existing and potential power sources for wireless sensor networks. Current state of the art, ongoing research, and theoretical limits for many potential power sources will be discussed. One may classify possible methods of providing power for wireless nodes into three groups: store energy on the node (i.e. a battery), distribute power to the node (i.e. a wire), scavenge available ambient power at the node (i.e. a solar cell). Power sources that fall into each of these three categories will be reviewed.

A direct comparison of vastly different types of power source technologies is difficult. For example, comparing the efficiency of a solar cell to that of a battery is not very useful. However, in an effort to provide general understanding of a wide variety of power sources, the following metrics will be used for comparison: power density, energy density (where applicable), and power density per year of use. Additional considerations are the complexity of the power electronics needed and whether secondary energy storage is needed.

2 Energy Reservoirs

Energy storage, in the form of electrochemical energy stored in a battery, is the predominant means of providing power to wireless devices today. However, several other forms of energy storage may be useful for wireless sensor nodes. Regardless of the form of the energy storage, the lifetime of the node will be determined by the fixed amount of energy stored on the device. The primary metric of interest for all forms of energy storage will be usable energy per unit volume (J/cm^3). An additional issue is that the instantaneous power that an energy reservoir can supply is usually dependent on its size. Therefore, in some cases, such as micro-batteries, the maximum power density (μW/cm^3) is also an issue for energy reservoirs.

2.1 Macro-Scale Batteries

Primary batteries are perhaps the most versatile of all small power sources. Table 1 shows the energy density for a few common primary battery chemistries. Note that while zinc-air batteries have the highest energy density, their lifetime is very short, and so are most useful for applications that have constant, relatively high, power demands.

Table 1. Energy density of three primary battery chemistries.

Chemistry	Zinc-air	Lithium	Alkaline
Energy (J/cm^3)	3780	2880	1200

Because batteries have a fairly stable voltage, electronic devices can often be run directly from the battery without any intervening power electronics. While this may not be the most robust method of powering the electronics, it is often used and is advantageous in that it avoids the extra power consumed by power electronics.

Macro-scale secondary (rechargeable) batteries are commonly used in consumer electronic products such as cell phones, PDA's, and laptop computers. Table 2 gives the energy density of a few common rechargeable battery chemistries. It should be remembered that rechargeable batteries are a *secondary* power source. Therefore, in the context of wireless sensor networks, another primary power source must be used to charge them.

Table 2. Energy density of three secondary battery chemistries.

Chemistry	Lithium	NiMHd	NiCd
Energy (J/cm^3)	1080	860	650

2.2 Micro-Scale Batteries

The size of batteries has only decreased mildly when compared to electronic circuits that have decreased in size by orders of magnitude. One of the main stumbling blocks to reducing the size of micro-batteries is power output due to surface area limitations of micro-scale devices. The maximum current output of a battery depends on the surface area of the electrodes. Because micro-batteries are so small, the electrodes have a small surface area, and their maximum current output is also very small.

The challenge of maintaining (or increasing) performance while decreasing size is being addressed on multiple fronts. Bates *et al* at Oak Ridge National Laboratory have created a process by which a primary thin film lithium battery can be deposited onto a chip [4]. The thickness of the entire battery is on the order of 10's of µm, but the areas studied are in the cm^2 range. This battery is in the form of a traditional Volta pile, with alternating layers of Lithium Manganese Oxide (or Lithium Cobalt Oxide), Lithium Phosphate Oxynitride and Lithium metal. Maximum potential is rated at 4.2 V with Continuous/Max current output on the order of 1 mA/cm^2 and 5 mA/cm^2 for the $LiCoO_2$ – Li based cell.

Work is being done on thick film batteries with a smaller surface area by Harb *et al* [5], who have developed micro-batteries of Ni/Zn with an aqueous NaOH electrolyte. Thick films are on the order of 0.1 mm, but overall thicknesses are minimized by use of three-dimensional structures. While each cell is only rated at 1.5 V, geometries have been duty-cycle optimized to give acceptable power outputs at small overall theoretical volumes (4 mm by 1.5 mm by 0.2 mm) with good durability demonstrated by the electrochemical components of the battery. The main challenges lie in maintaining a microfabricated structure that can contain an aqueous electrolyte.

Radical three dimensional structures are also being investigated to maximize power output. Hart *et al* [6] have theorized a three dimensional battery made of series alternating cathode and anode rods suspended in a solid electrolyte matrix. Theoretical power outputs for a three dimensional microbattery are shown to be many times larger than a two dimensional battery of equal size because of higher electrode surface area to volume ratios and lower ohmic losses due to lower ionic transport distances. However, it should be noted that the increased power density comes at a lower energy density because of the lower volume percentage of electrolyte.

2.3 Micro-Fuel Cells

Hydrocarbon based fuels have very high energy densities compared to batteries. For example, methanol has an energy density of 17.6 kJ/cm^3, which is about 6 times that of a lithium battery. Like batteries, fuel cells produce electrical power from a chemical reaction. A standard fuel cell uses hydrogen atoms as fuel. A catalyst promotes the separation of the electron in the hydrogen atom from the proton. The proton diffuses through an electrolyte (often a solid membrane) while the electron is available for use by an external circuit. The protons and electrons recombine with oxygen atoms on the other side (the oxidant side) of the electrolyte to produce water molecules. This process is illustrated in Figure 1. While pure hydrogen can be used as a fuel, other hydrocarbon fuels are often used. For example, in Direct Methanol Fuel Cells (DFMC) the anode catalyst draws the hydrogen atoms out from the methanol.

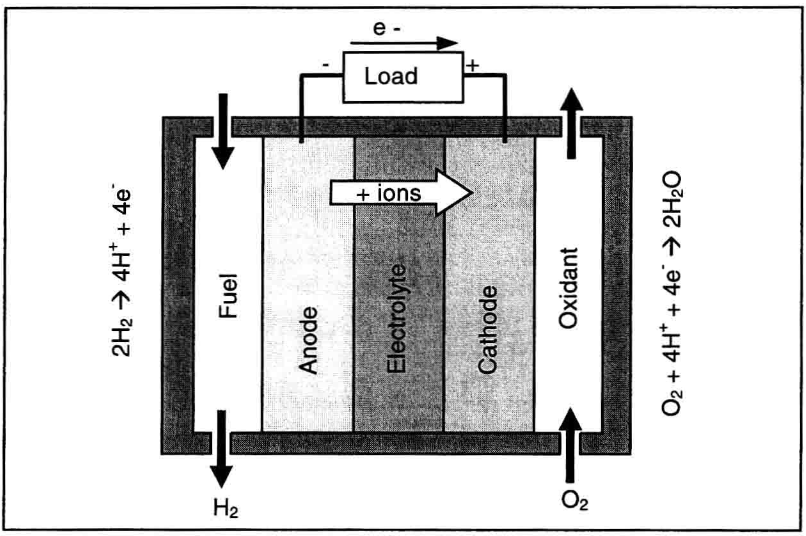

Fig. 1. Illustration of how a standard hydrogen fuel cell works.

Most single fuel cells tend to output open circuit voltages around 1.0 – 1.5 volts. Of course, like batteries, the cells can be placed in series for higher voltages. The voltage is quite stable over the operating lifetime of the cell, but it does fall off with increasing current draw. Because the voltage drops with current, it is likely that some additional power electronics will be necessary if replacing a battery with a fuel cell.

Large scale fuel cells have been used as power supplies for decades. Recently fuel cells have gained favor as a replacement for consumer batteries [7]. Small, but still macro-scale, fuel cells are likely to soon appear in the market as battery rechargers and battery replacements [8].

The research trend is toward micro-fuel cells that could possibly be closely integrated with wireless sensor nodes. Like micro-batteries, a primary metric of comparison in micro-fuel cells is power density in addition to energy density. As with micro-batteries, the maximum continuous current output is dependent on the electrode surface area. Efficiencies of large scale fuel cells have reached approximately 45%

electrical conversion efficiency and nearly 90% if cogeneration is employed [9]. Efficiencies for micro-scale fuel cells will certainly be lower. The maximum obtainable efficiency for a micro-fuel cell is still uncertain. Demonstrated efficiencies are generally below 1% [10].

Many research groups are working on microfabricated partial systems that typically include an electrolyte membrane, electrodes, and channels for fuel and oxidant flow. Recent examples include the hydrogen based fuel cells developed by Hahn *et al* [11] and Lee *et al* [12]. Both systems implement microfabricated electrodes and channels for fuel and oxidant flow. The system by Hahn *et al* produces power on the order of 100 mW/cm^2 from a device 0.54 cm^2 in size. The system by Lee *et al* produces 40 mW/cm^2. It should be noted that the fundamental characteristic here is power per unit area rather than power per unit volume because the devices are fundamentally planar. Complete fuel storage systems are not part of their studies, and therefore an energy or power per unit volume metric is not appropriate. Fuel conversion efficiencies are not reported.

Hydrogen storage at small scales is a difficult problem that has not yet been solved. Primarily for this reason, methanol based micro-fuel cells are also being investigated by numerous groups. For example, Holloday *et al* [10] have demonstrated a methanol fuel processor with a total size on the order of several mm^3. This fuel processor has been combined with a thin fuel cell, 2 cm^2 in area, to produce roughly 25 mA at 1 volt with 0.5% overall efficiency. They are targeting a 5% efficient cell.

Given the energy density of fuels such as methanol, fuel cells need to reach efficiencies of at least 20% in order to be more attractive than primary batteries. Nevertheless, at the micro scale, where battery energy densities are also lower, a lower efficiency fuel cell may still be attractive. Finally, providing for sufficient fuel and oxidant flows is a very difficult task in micro-fuel cell development. The ability to microfabricate electrodes and electrolytes does not guarantee the ability to realize a micro-fuel cell. To the authors' knowledge, a self-contained, on-chip fuel cell has yet to be demonstrated.

2.4 Micro Heat Engines

At large scales, fossil fuels are the dominant source of energy used for electric power generation, mostly due to the low cost per joule, high energy density (gasoline has an energy density of 12.7 kJ/cm^3), abundant availability, storability and ease of transport. To date, the complexity and multitude of components involved have hindered the miniaturization of heat engines and power generation approaches based on combustion of hydrocarbon fuels. As the scale of a mechanical system is reduced, the tolerances must reduce accordingly and the assembly process becomes increasingly challenging. This results in increasing costs per unit power and/or deteriorated performance.

The extension of silicon microfabrication technology from microelectronics to micro-electromechanical systems (or MEMS) is changing this paradigm. In the mid-1990's, Epstein *et al* proposed that microengines, i.e. dime-size heat engines, for portable power generation and propulsion could be fabricated using MEMS technology [13]. The initial concept consisted of using silicon deep reactive ion etching, fusion wafer bonding, and thin film processes to microfabricate and integrate high speed turbomachinery, with bearings, a generator, and a combustor within a cubic centimeter volume. An application-ready power supply would also require auxiliary components, such as a fuel tank, engine and fuel controller, electrical power conditioning with short term storage, thermal management and packaging. Expected performance is 10-20 Watt of electrical power output at thermal efficiencies on the order of 5-20%. Figure 2 shows a microturbine test device used for turbomachinery and air bearing development.

Multiple research groups across the globe have also undertaken the development of various micro heat engine-based power generators. Approaches ranging from micro gas turbine engines to thermal-expansion-actuated piezoelectric generators and micro-thermophotovoltaic systems are being investigated [13–20].

Most of these and similar efforts are at initial stages of development and performance has not been demonstrated. However, predictions range from 0.1-10W of electrical power output, with typical masses ~1-5 g and volumes ~1 cm^3. Given the relatively large power level, a single microengine would only need to operate at low duty-cycles (less than 1% of the time) to periodically recharge a battery. Microengines are not expected to reduce further in size due to manufacturing and efficiency constraints. At small scales, viscous drag on moving parts and heat transfer to the ambient and between components increase, which adversely impacts efficiency.

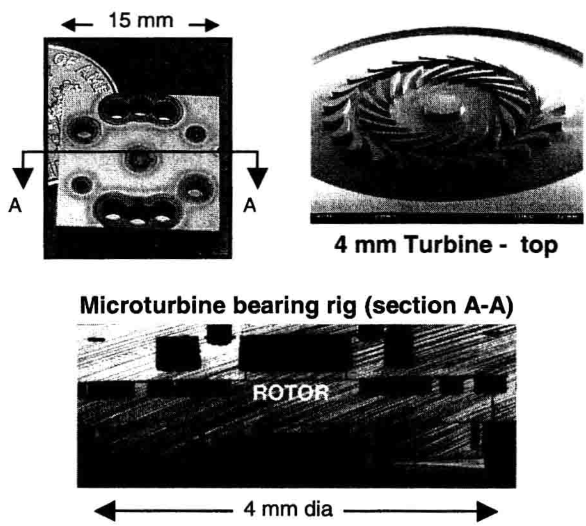

Fig. 2. Micro-turbine development device, which consists of a 4 mm diameter single crystal silicon rotor enclosed in a stack of five bonded wafers used for micro air bearing development.

Overall, the greatest benefits of micro heat engines are their high power density (0.1-2 W/g, without fuel) and their use of fuels allowing high density energy storage for compact, long duration power supplies. For low power applications, the power density is not as important as efficiency. Microengines will therefore require many years of development before reaching the expected efficiencies and being applicable for wireless sensor network applications.

2.5 Radioactive Power Sources

Radioactive materials contain extremely high energy densities. As with hydrocarbon fuels, this energy has been used on a much larger scale for decades. However, it has not been exploited on a small scale as would be necessary to power wireless sensor networks. The use of radioactive materials can pose a serious health hazard, and is a highly political and controversial topic. It should, therefore, be noted that the goal here is neither to promote nor discourage investigation into radioactive power sources, but to present their potential, and the research being done in the area.

The total energy emitted by radioactive decay of a material can be expressed as in equation 1.

$$E_t = A_c E_e T \tag{1}$$

where E_t is the total emitted energy, A_c is the activity, E_e is the average energy of emitted particles, and T is the time period over which power is collected. Table 3 lists several potential radioisotopes, their half-lives, specific activities, energy densities, and power densities based on radioactive decay. The half-life of the material has been used as the time over which power would be collected.

Table 3. Comparison of radio-isotopes.

Material	Half-life (years)	Activity volume density (Ci/cm^3)	Energy density (J/cm^3)	Power density (mW/cm^3)
^{238}U	4.5 X 10^9	6.34 X 10^{-6}	2.23 X 10^{10}	1.6 X 10^{-4}
^{63}Ni	100.2	506	1.6 X 10^8	50.6
^{32}Si	172.1	151	3.3 X 10^8	60.8
^{90}Sr	28.8	350	3.7 X 10^8	407
^{32}P	0.04	5.2 X 10^5	2.7 X 10^9	2.14 X 10^6

While the energy density numbers reported for radioactive materials are extremely attractive, it must be remembered that efficient methods of converting this power to electricity at small scales do not exist. Therefore, efficiencies would likely be extremely low.

Recently, Li and Lal [21] have used the ^{63}Ni isotope to actuate a conductive cantilever. As the beta particles (electrons) emitted from the ^{63}Ni isotope collect on the conductive cantilever, there is an electrostatic attraction. At some point, the cantilever contacts the radioisotope and discharges, causing the cantilever to oscillate. Up to this point the research has only demonstrated the actuation of a cantilever, and not electric power generation. However, electric power could be generated from an oscillating cantilever. The reported power output, defined as the change over time in the combined mechanical and electrostatic energy stored in the cantilever, is 0.4 pW from a 4mm X 4mm thinfilm of ^{63}Ni. This power level is equivalent to 0.52 μW/cm^3. However, it should be noted that using 1 cm^3 of ^{63}Ni is impractical. The reported efficiency of the device is 4 X 10^{-6}.

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