2

Review of Energy Harvesting Technologies for Sustainable Wireless Sensor Network

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1. Introduction

The rapid growth in demands for computing everywhere has made computer a pivotal component of human mankind daily lives. Whether we use the computers to gather information from the Web, to utilize them for entertainment purposes or to use them for running businesses, computers are noticeably becoming more widespread, mobile and smaller in size. What we often overlook and did not notice is the presence of those billions of small pervasive computing devices around us which provide the intelligence being integrated into the real world. These pervasive computing devices can help to solve some crucial problems in the activities of our daily lives. Take for examples, in the military application, a large quantity of the pervasive computing devices could be deployed over a battlefield to detect enemy intrusion instead of manually deploying the landmines for battlefield surveillance and intrusion detection Chong et al. (2003). Additionally, in structural health monitoring, these pervasive computing devices are also used to detect for any damage in buildings, bridges, ships and aircraft Kurata et al. (2006).

To achieve this vision of *pervasive computing*, also known as *ubiquitous computing*, many computational devices are integrated in everyday objects and activities to enable better human-computer interaction. These computational devices are generally equipped with sensing, processing and communicating abilities and these devices are known as *wireless sensor nodes*. When several wireless sensor nodes are meshed together, they form a network called the *Wireless Sensor Network (WSN)*. Sensor nodes arranged in network form will definitely exhibit more and better characteristics than individual sensor nodes. WSN is one of the popular examples of ubiquitous computing as it represents a new generation of real-time embedded system which offers distinctly attractive enabling technologies for pervasive computing environments. Unlike the conventional networked systems like Wireless Local Area Network (WLAN) and Global System for Mobile communications (GSM), WSN promise to couple end users directly to sensor measurements and provide information that is precisely localized in time and/or space, according to the users' needs or demands. In the Massachusetts Institute of Technology (MIT) technology review magazine of innovation published in February 2003 MIT (2003), the editors have identified Wireless Sensor Networks as the first of the top ten emerging technologies that will change the world. This explains why WSN has swiftly become a hot research topic in both academic and industry.

2. Smart Environment with Pervasive Computing

Pervasive computing is the trend towards increasingly ubiquitous and connected computing devices in the environment. These pervasive computing devices are not personal computers as we tend to think of them, but they are very tiny computing devices, either mobile or embedded in almost any type of object imaginable, including cars, tools, appliances, clothing and various consumer goods. According to Dan Russell, director of the User Sciences and Experience Group at IBM's Almaden Research Center, by the near future, computing will have become so naturalized within the environment that people will not even realize that they are using computers Kumar (2005). Russell and other researchers expect that in the future smart devices all around us will maintain current information about their locations, the contexts in which they are being used, and relevant data about the users. The goal of the researchers is to create a system that is pervasively and unobtrusively embedded in the environment, completely connected, intuitive, effortlessly portable and constantly available. *Smart environment* is among the emerging technologies expected to prevail in the pervasive computing environment of the future.

The notion of smart environment is becoming a reality with pervasive computing as well as advancements of various related technologies such as wireless networking, micro-fabrication and integration using micro-electromechanical system (MEMS) technology and embedded intelligent with microprocessors. Smart environments represent the next evolutionary development step in various application areas such as building, utilities, industrial, home, marine, animal habitat, traffic, etc. Like any sentient organism, the smart environment relies first and foremost on sensory data from the real world. Sensory data comes from multiple sensors of different modalities in distributed locations. Similarly for the smart environment, information about its surroundings is also needed just like what is captured by the receptors in the biological systems. The information needed by the smart environments is provided by the distributed WSN which has its pervasive sensor nodes for sensing, processing and communicating the information to the base station. To facilitate smart environments in various application areas, a general architecture of the data acquisition and distribution network is provided in Figure.1. The data acquisition network is designed to gather real-world information as well as to monitor the condition of the targeted application. Data are collected at the base station in a wireless manner, preprocessed and then distributed to the end users via different communicating devices.

Referring to Figure.1, it can be seen that the entire data network is a very large and complex system that is made up of many different subsystems i.e. sensor nodes, base station, management center, wireland and wireless communication systems. The sensor nodes and the base station are part of the data acquisition network and the wireland and wireless communication systems belongs to the data distribution network. Once the sensor nodes are deployed in the application areas, the nodes would sense and collect data from the environment and the collected data are then sent to the base station in a wireless manner. The base station consolidates the collected data and preprocesses the data so that it can be delivered quickly and safely over the data distribution network to the end users. Most importantly, the end users must be able to access the information at anywhere and at any time. In between the data acquisition network and the data distribution network, a management center is incorporated so as to better coordinate, monitor and control the data flow between the two networks. When data is transferred within the entire network, there are two important factors that need to be well considered namely data integrity and data security.

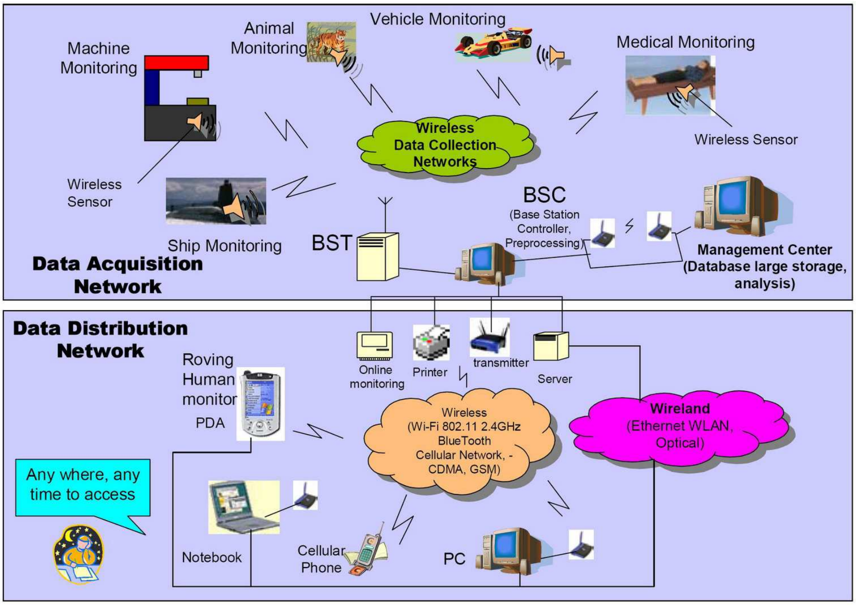


Fig. 1. A general architecture of the data acquisition and distribution network to facilitate smart environments Cook et al. (2004)

The framework of a WSN is similar to the architecture of the general data acquisition and distribution network described in Figure.1. Likewise, the main objective of WSN is to provide the end user with intelligence and a better understanding of the environment so as to facilitate a smart environment. WSN is considerably a new research field and it has a widespread of research problems for both academic scholars and industrial researchers to resolve. WSN itself has also several attractive advantages as discussed in Kuorilehto et al. (2005) Callaway (2003) that make it suitable for many potential implementation areas. These implementation areas include environmental monitoring, health monitoring, miliary surveillance and many others listed in Table.1. The challenging part of the WSN research work is that WSN requires an enormous breadth of knowledge from a vast variety of disciplines such as embedded microprocessor, networking, power, wireless communication and microelectronic to be able to optimize WSN for specific application.

3. Overview of Wireless Sensor Networks

The original motivation of WSN can be traced back to the design of military applications such as battlefield surveillance and intrusion detection mentioned by Chong et al. in Chong et al. (2003). Based on the previous endeavors to build efficient military sensor networks as well as the fast developments in microelectronic design and wireless communication, WSN are gradually introduced to many civil application areas. With the continuous dedications of academic scholars and industrial researchers, people are getting closer and closer to the essential points to understand WSN technology. The unique characteristics of WSN make it advantageous over the former networks on one hand, but on the other hand, many challenges are inevitable. Hence further research and thorough reflections on WSN are greatly needed.

3.1 Architecture of WSN

The architecture of a WSN typically consists of multiple pervasive sensor nodes, sink, public networks, manager nodes and end user Akyildiz et al. (2002). Many tiny, smart and inexpensive sensor nodes are scattered in the target sensor field to collect data and route the useful information back to the end user. These sensor nodes cooperate with each other via wireless connection to form a network and collect, disseminate and analyze data coming from the environment. As illustrated in Figure.2, the data collected by node A is routed within the sensor field by other nodes. The data will reach the boundary node E and then be transferred to the sink. The sink serves as a gateway with higher processing capacity to communicate with the task manager node. The connection between sink and task manager node is the public networks in the form of Internet or satellite. The end user will receive the data from the task manager node and perform some processing on these received data.

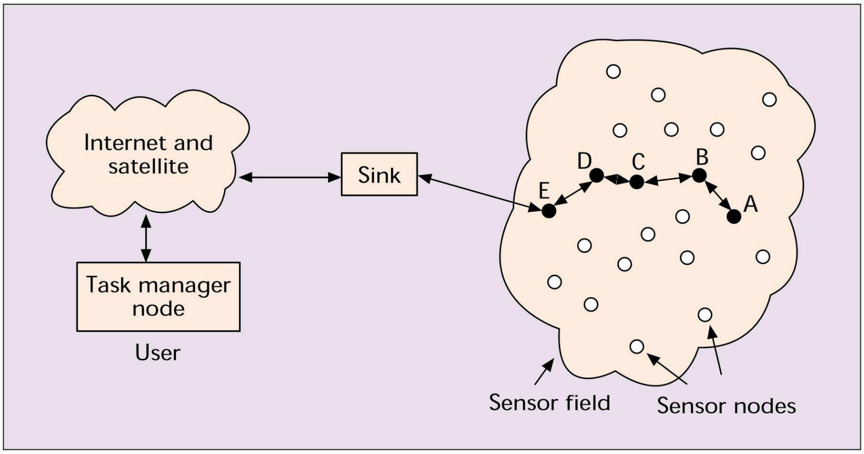


Fig. 2. Architecture of WSN to facilitate smart environments Akyildiz et al. (2002)

In Figure.2, the sink is essentially a coordinator between the deployed sensor nodes and the end user and it can be treated like a gateway node. The need of a sink in WSN architecture is due to limited power and computing capacity of the wireless sensor nodes. The gateway node is equipped with better processor and sufficient memory space because the node can provide the need for extra information processing before data is transferred to the final destination. The gateway node can therefore share the loadings posed on the wireless sensor nodes and hence prolong their working lifetime. The communication means amongst the sensor nodes is through wireless media because in most application scenarios, the physical contacts among the sensor nodes for configuration, maintenance and replacement are rather difficult or even impossible. The design of the wireless sensor network as described by Figure.2 is influenced by many factors, including fault tolerance, scalability, production costs, operating environment, sensor network topology, hardware constraints, transmission media and power consumption. These design factors are important because they serve as a guideline to design a protocol or an algorithm for sensor networks Akyildiz et al. (2002). In addition, these influencing factors can be used to design the WSN to meet the specific requirement of various real-life applications.

Let us examine how the design factors can be used as a guideline to design a suitable protocol for the WSN in the military surveillance and intrusion detection application mentioned earlier. During each deployment of the sensor nodes either by dropping from a plane or delivering in an artillery shell or rocket or missile, hundreds to several thousands of sensor nodes are deployed throughout the battlefield for sensing. Since the WSN consists of a large number of sensor nodes, the cost of a single node is very important to justify the overall cost of the network. If the cost of the network is more expensive than deploying traditional sensors, the sensor network is not cost-justified. Next, to achieve good coverage of the whole deployment ground, the sensor nodes in the WSN are desired to be deployed closely to each other. However, deploying a high number of nodes densely requires careful handling of the WSN topology. The topology of the WSN is first considered during the predeployment phases when the sensor nodes are deployed into the battlefield by a plane or an artillery shell. After deployment which is the post-deployment phase, the topology of the WSN may need to be changed due to change in sensor nodesŠ position, reachability (due to issues like jamming and moving obstacles), available energy, malfunctioning and task details. In some cases, redeployment of additional sensor nodes are carried out at any time to replace malfunctioning nodes or to cater for changes in the task dynamics in the WSN. In the mist of the sensing operations, some sensor nodes in the WSN may fail due to the lack of power or experiencing some physical damage or encountering environmental interference. This would interrupt the WSN functionalities. As such, the fault tolerance level of the WSN must be high enough to ensure that the failure of sensor nodes should not affect the overall task of the sensor network. Despite that the fault tolerance of the WSN can be designed to be as high as possible, there is bound to have some limits to where the fault tolerance level of the WSN can achieve. Hence to sustain the WSN functionalities without any interruption, many researchers have been focusing on power conservation and power management for the sensor nodes Sinha et al. (2001) Merrett et al. (2005) and design of energy-aware protocols and algorithms for the WSNs Sohrabi et al. (2000) Lattanzi et al. (2007) in order to reduce the power consumption of the overall wireless sensor network. By doing so, the lifetime of the WSN can be extended.

To understand how data are communicated within the sensor nodes in a WSN, the protocol stack model of a WSN as shown in Figure.3 is investigated. With this understanding, the energy hungry portions of the WSN can be identified and then the WSN redesigned accordingly for lower power consumption. To start with the basic communication process, it consists of sending data from the source to the destination. Primarily, it is the case of two wireless sensor nodes wanting to communicate with each other. Hence, the sensor node at source generates information, which is encoded and transmitted to destination, and the destination sensor node decodes the information for the user. This entire process is logically partitioned into a definite sequence of events or actions, and individual entities then form layers of a communication stack. Traditionally, the process of communication is formally organized as the ISO-OSI reference model stack which consists of seven layers with application layer as the highest layer and physical layer as the lowest layer of the OSI model. However, the protocol stack model adopted by WSN is different from the conventional OSI model. As illustrated in Figure.3, the protocol stack of WSN introduces extra features such as power awareness, mobility control and task management. It offers flexibility for WSN applications which are built on the stack and promotes the cooperativeness among sensor nodes.

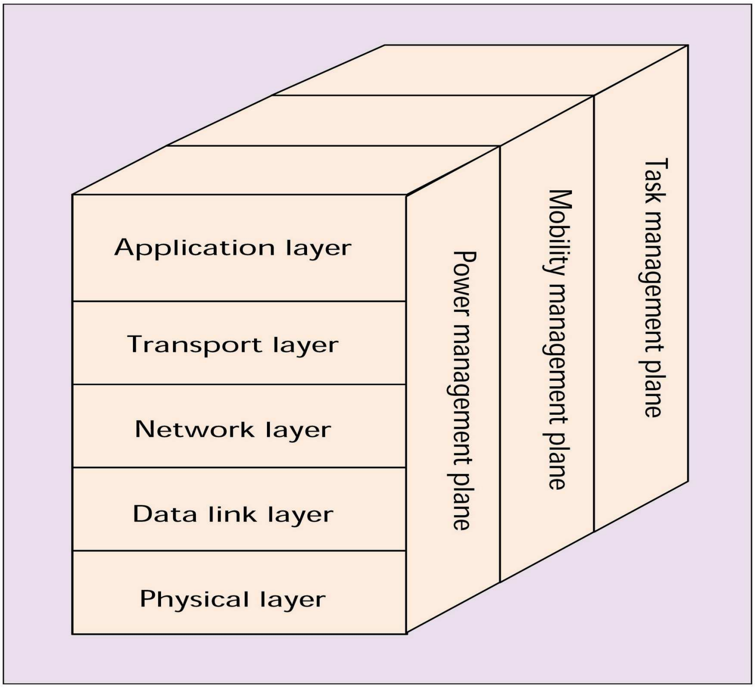


Fig. 3. Sensor networks protocol stack Akyildiz et al. (2002)

The WSN protocol stack shown in Figure.3 consists of five network layers namely physical (lowest), data link, network, transport and application (highest) layers and three new elements: power management plane, mobility management plane and task management plane Akyildiz et al. (2002). Starting from the lowest level, the physical layer is to meet the needs of receiving and transferring data collected from the hardware. It is well known that long distance wireless communication can be expensive, in terms of both energy and implementation complexity. While designing the physical layer for WSNs, energy minimization is considered significantly more important over and above the other factors like propagation and fading effects. Energy-efficient physical layer solutions are currently being pursued by researchers to design for tiny, low-power, low-cost transceiver, sensing and processing units. The next higher layer is the data link layer which ensures reliable point-to-point and point-to-multipoint connections for the multiplexing of data streams, data frame detection, medium access and error control in the WSN. The data link layer should be power-aware and at the same time to minimize the collisions between neighbors' signals because the environment is noisy and sensor nodes themselves are highly mobile. This is also one of the layers in the WSN whereby power saving modes of operation can be implemented. The most obvious means of power conservation is to turn the transceiver off when it is not required. By using a random wake-up schedule during the connection phase and by turning the radio off during idle time slots, power conservation can be achieved. A dynamic power management scheme for WSNs has been discussed in Sinha et al. (2001) where five power-saving modes are proposed and intermode transition policies are investigated. The network layer takes care of routing the data supplied by the transport layer. In WSN deployment, the routing protocols in the network layer are important because an efficient routing protocol can help to serve various applications and save energy. By setting appropriate energy and time delay thresholds for data relay, the protocol can help prolong the lifetime of sensor nodes. Hence the network layer is another layer in the WSN to reduce power consumption. The transport layer helps to maintain the flow of data if the sensor networks application requires it. Depending on the sensing tasks, different types of application software can be built and used on the application layer.

The three special planes in the stack help the sensor nodes to coordinate tasks and keep the power consumption low Akyildiz et al. (2002). The power management plane is designed to control the power usage of each node. For example, when the power level is low, the sensor node will broadcast to the neighbors telling that its remaining power is low and can only be reserved for sensing rather than participating in routing. The mobility management plane will detect and record the movement of sensor nodes to keep track of the route as well as the neighbors. By having the knowledge of neighbors, each sensor node in the network can balance power usage and task processing. The task management plane will schedule the sensing tasks and balance the work loads. As a result, sensor nodes can perform the task depending on current power level and situation of their neighbors. In summary, the three management planes help the sensor nodes to work together in a power efficient way and share resources more wisely.

3.2 WSNs Applications

WSNs can be used in virtually any environment, even where wired connections are not possible or the terrain inhospitable or physical placement of the sensors are difficult. Besides that, WSNs also enable unattended monitoring of physical quantities over large areas on a scale that would be prohibitively expensive to accomplish with human beings. These attractive features promote the potential of WSNs for more application areas. To ensure full connectivity, fault tolerance and long operational life, wireless sensor networks are deployed in ad hoc manner and the networks use multi-hop networking protocols to make real-world information and control ubiquitously available Sohrabi et al. (2000). There have been many applications suggested for WSNs and they are listed in Table.1.

These wide range of applications described in Table.1 for WSNs can be roughly classified into three categories suggested in Culler et al. (2004):

- monitoring space
- monitoring things
- monitoring the interactions of things with each other and the encompassing space

The first classification includes environmental monitoring, indoor climate control, military and space surveillance. The second classification includes structural monitoring, condition-based equipment maintenance, medical health diagnostics, vehicle safety and urban terrain mapping. The most dramatic applications fall under the third classification which involve monitoring complex interactions, including wildlife habitats, disaster management, emergency response, asset tracking and manufacturing process flow. Based on the collaborative efforts of a large number of sensor nodes, WSNs have become proven by many researchers as good candidates to provide economically viable solutions for a wide range of applications such as environmental monitoring, scientific data collection, health monitoring and military operations as tabulated in Table.1. These sensor nodes are coordinated based on some network topologies to cooperate with one another within the WSNs to satisfy the applications

Application	Type	Requirements	Scale and density
Great Duck Island Mainwaring et al. (2002)	Environmental monitoring	Data archiving, Internet access, long lifetime	32 nodes in 1 km^2
Flood detection Boulis et al. (2003)	Disaster management	Current condition evaluation	200 nodes 50m apart
SSIM (artificial retina) Schwiebert et al. (2001)	Health	Image identification, realtime, complex processing	100 sensors per retina
Human monitoring Thomas (2006)	Health	Quality of data, security, alerts	Several nodes per human
WINS for military Marcy et al. (1999)	Military	Target identification, realtime, security, quality of data	Several distant nodes
Object tracking Romer (2004)	Military	Collaborative processing, realtime, location-awareness	7 nodes in proximity
WINS condition monitoring Marcy et al. (1999)	Machinery monitoring	Data aggregation, machinery lifetime projection	Few nodes per machinery
Smart kindergarten Srivastava et al. (2001)	Space surveillance	Video streaming, identification, location-awareness	Tens of sensors, indoor
Pressure in automobile tires Roundy (2003)	Vehicle safety	Real time data, improve the safety and performance of the vehicle	Volume constraint of 1 cm^3

Table 1. Examples of prototyped applications for WSNs Kuorilehto et al. (2005)

requirement stated in Table.1. Because of the great potential in WSN, many groups around the world have invested lots of research efforts and time in the design of sensor nodes for their specific applications. These include Berkeley's Mica motes Hill et al. (2002), PicoRadio projects Rabaey et al. (2000), MIT's μAmps MIT (2008) as well as many others. In addition, the TinyOS project TinyOS (2008) provides a framework for designing flexible distributed applications for data collection and processing across the sensor network. All of these sensor nodes have similar goals which are small physical size, low power consumption and rich sensing capabilities.

3.3 Challenges on WSNs

The unique features of the WSNs pose challenging requirements to the design of the underlying algorithms and protocols. Several ongoing research projects in academia as well as in industry aim at designing protocols that satisfy these requirements for sensor networks Chong et al. (2003), Kuorilehto et al. (2005), Akyildiz et al. (2002) and Tubaishat et al. (2003). Some of the important challenges are presented as shown below.

- *Sensor nodes are limited in energy, computational capacities and memory:*

  Sensor nodes are small-scale devices with volumes approaching a cubic millimeter in the near future. Such small volumetric devices are very limited in the amount of energy that the storage element such as batteries can store. Hence the batteries with finite energy supply must be optimally used for both processing and communication tasks. The communication task tends to dominate over the processing task in terms of energy consumption. Thus, in order to make optimal use of energy, the amount of communication task should be minimized as much as possible. In practical real-life applications, the wireless sensor nodes are usually deployed in hostile or unreachable terrains, they cannot be easily retrieved for the purpose of replacing or recharging the batteries, therefore the lifetime of the network is usually limited. There must be some kind of compromise between the communication and processing tasks in order to balance the duration of the WSN lifetime and the *energy density* of the storage element. In summary, limitation in the device size and energy supply typically means restricted amount of resources i.e. CPU performance, memory, wireless communication bandwidth used for data forwarding and range allowed.

- *Sensor nodes in the WSN are ad hoc deployed and distributed for processing and sensing:*

  Sensor nodes are either placed one by one in the vicinity of the phenomenon or deployed in an ad hoc fashion by air or by some other means. Once the sensor nodes are deployed, the WSNs would not have any human intervention to interrupt their operations. The sensor nodes must be able to configure themselves to form connections to set up the network to meet the application requirement. In case of any changes in the operating conditions or environmental stress on the sensor nodes that causes them to fail leading to connectivity changes, this requires reconfiguration of the network and re-computation of routing paths. Another point to take note is that using a WSN, many more data can be collected as compared to just one sensor. Even deploying a sensor with great line of sight, it could still have obstructions. Thus, distributed sensing provides robustness to environmental obstacles. Because there are many sensor nodes densely deployed, neighbor nodes may be very close to each other. Hence, multihop communication in WSNs is expected to consume less power than the traditional single hop broadcast communication because the transmission power levels can be kept low. Additionally, multihop communication can also effectively overcome some of the signal propagation effects experienced in long-distance wireless communication.

- *Network and communication topology of a WSN changes frequently:*

  When the sensor nodes are deployed, the position of sensor nodes is not predetermined. This means that the sensor nodes must be able to configure themselves after deployment. They must possess some means to identify their location either globally or with respect to some locally determined position. Once the network is set up, it is required that the WSN be adaptable to the changing connectivity (for e.g., due to addition of more nodes, failure of nodes, etc.) as well as the changing environmental conditions.

Unlike traditional networks, where the focus is on maximizing channel throughput or minimizing node deployment, the major consideration in a sensor network is to extend the system lifetime as well as the system robustness.

In contrast to the traditional networks which focus mainly on how to achieve high quality of service (QoS) provisions, WSN protocols tend to focus primarily on power conservation and power management. However, there must be some embedded trade-off mechanisms that give the end user the option of prolonging the WSN lifetime but at the cost of lower throughput or higher transmission delay. Conversely, the power consumption of the WSN can be reduced by sacrificing the QoS provisions i.e. lowering the data throughput or having higher transmission delay. Among the several challenging requirements posed on the design of the underlying algorithms and protocols of the WSNs, it is well-known among the academia as well as industry that energy constraint is one of the most significant challenges in the WSN research field Callaway (2003). The functionalities of the WSN are highly dependent on the amount of energy that is available to be expended by each of the sensor node in the network. That is why the energy constraint challenge is substantial enough to be chosen for further investigations and discussions in my research work.

4. Wireless Sensor Nodes in WSN

A wireless sensor network consists of many energy-hungry wireless sensor nodes distributed throughout an area of interest. Each sensor node monitors its local environment, locally processing and storing the collected data so that other sensor nodes in the network can use it. Network nodes share these information via a wireless communication link. The block diagram of an energy-hungry wireless sensor node residing in the WSN is shown in Figure.4. The sensor node typically consists of four sub-units namely the sensor itself, data acquisition system, local microcontroller and radio communication block. The sensor, data acquisition, microprocessor and radio communications are all power sink modules because they need to consume electrical energy from the power source in order to operate. These sub-units of the sensor node are all energy hungry. Since the power source is driven by batteries, the energy-hungry sub-units would use up all the energy in the batteries after some times and the sensor node would then go into an idle state.

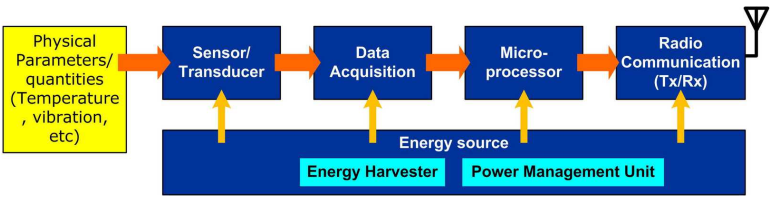


Fig. 4. Block diagram of energy-hungry wireless sensor node

The sensor/transducer converts an environmental sensing parameter such as temperature, vibration, humidity, etc to an electrical signal. A data acquisition unit is incorporated in the sensor node to realize amplification and pre-processing of the output signals from sensors, for example conversion from analog to digital form and filtering. To encompass some level of intelligences like data processing and time scheduling in the sensor node, a microprocessor has been incorporated in the sensor node. A radio communication block is included in the sensor node to enable the node to communicate with its neighbor node or the base station in a wireless manner. If one of the sensor nodes fails, the other sensor nodes in the network would take over the responsibility of the failed node. This provides redundancy and therefore reliability of the wireless sensor network. However, in order to optimize the WSN in practical situations, there must be some considerations to be taken into account i.e. how many sensor nodes to be deployed; should all of them be active at all times; or the nodes communicate with each other and collectively gather and transmit data such that energy consumption of the sensor is minimized at the same time the reliability is not sacrificed. All these requirements are application specific and need to be addressed appropriately.

Other than the above mentioned considerations for optimizing the WSN in practical situations, the information about how much electrical power a sensor node consume during operation also plays an important part. Hence the power consumed by each individual components i.e. processor, radio, logger memory and sensor board in a sensor node has been tabulated in Table.2. It can been observed that all the components in the sensor node consume mW level of power during the active mode of operation and then drop to μW of power when in sleep or idle mode.

In most sensor nodes applications, the processor and radio need to run only for a brief period of time, followed by a sleep cycle. During sleep, current consumption is in the μA range as opposed to mA range. This results in the sensor node drawing very little amount of current for the majority of the time and short duration of current spikes while processing, receiving and transmitting data. This method is known as *duty cycling* which helps to extend the lifetime of the battery. However, due to the current surges during the active mode of operation, the power density of the battery must be high enough to support the current surge. Based on the high energy capacity battery i.e. 3000 mAh, the life of the battery powering the sensor node can last at most 1.5 years as shown in Table.2. After which, without battery replacement, the sensor node can be considered as an idle node. The higher the battery capacity, the bigger will be the size of the battery. Take for an example an AA alkaline battery of 2850 mAh, the size of the battery is 14.5 mm x 23 mm x 50.5 mm but the size of a coin type of alkaline battery of 290mAh is 24.5 mm x 24.5 mm x 3mm. So for the case of 250 mAh battery which is smaller in size, the battery can only sustain the operation of the sensor node for at most 2 months. This time duration is really too short for the WSN to be useful in the practical situations.

5. Problems in Powering the Sensor Nodes

As the network becomes dense with many wireless sensor nodes, the problem of powering the nodes becomes critical, even worst when one considers the prohibitive cost of providing power through wired cables to them or replacing batteries. In order for the sensor nodes to be conveniently placed and used, these nodes must be extremely small, as tiny as several cubic centimeter. When the sensor nodes are small, there would be severe limits imposed on the nodes' lifetime if powered by a battery that is meant to last the entire life of the device.

5.1 High Power consumption of Sensor Nodes

Compared with conventional computers, the low-cost and battery-powered miniaturize sensor nodes have limited energy supply from very small batteries as well as stringent processing and communications capabilities plus memory is scarce. State of the art, non-rechargeable lithium batteries can provide energy up to 800 WH/L (watt hours per liter) or 2880 J/cm^3 Doherty et al. (2001). If an electronic device with a 1 cm^3 coin-size battery is to consume 200 μW of power on average (this is a challenging average power consumption by the load), the device could last for 4000 hours or 167 days which is equivalent to half a year. In fact, the

SYSTEM SPECIFICATIONS		
Currents **Processor**		**Example Duty Cycle**
Current (full operation)	8 **mA**	1
Current sleep	8 µA	99
Radio		
Current in receive	8 mA	0.75
Current transmit	12 mA	0.25
Current sleep	2 µA	99
Logger Memory		
Write	15 mA	0
Read	4 mA	0
Sleep	2 µA	100
Sensor Board		
Current (full operation)	5 mA	1
Current sleep	5 µA	99
Computed mA-hr used each hour		
Processor		0.0879
Radio		0.0920
Logger Memory		0.0020
Sensor Board		0.0550
Total current (mA-hr) used		**0.2369**
Computed battery life vs. battery size		
Battery Capacity (mA-hr)		Battery Life (months)
250		1.45
1000		5.78
3000		17.35

Table 2. Battery life estimation for a senor node operating at 1% duty cycle Crossbow (2007)

calculation is a very optimistic estimate as the entire capacity of the battery usually cannot be completely used up depending on the voltage drop. Additionally, it is also worth mentioning that the sensors and electronics of a wireless sensor node could be far smaller than 1 cm^3.

Hence in this case, the battery would dominate the system space usage. Clearly, a lifetime of half a year for the electronic device to operate is far from sufficient because the duration of the device's operation could last for several years. This implies that the battery supply of the electronic device has to be regularly maintained. The need to develop alternative method for powering the wireless sensor and actuator nodes is acute. Hence the research direction is targeted to resolve the energy supply problems faced by the energy hungry wireless sensor nodes.

5.2 Limitation of Power Sources for Sensor Nodes

Like any other electronic devices, the sensor nodes in the WSN need to be powered by energy sources in order to operate. If a wired power cable is used, many of the advantages such as self-autonomous and mobility of the sensor nodes enabled by the wireless communications are sacrificed. In many applications, a power cable is not a preferable option to power the sensor nodes knowing the advantages of wireless option. Instead, there are many types of portable energy systems listed in Figure.5 that are suitable for powering sensor nodes in the wireless sensor networks. Among these energy systems or sources, the rechargeable/alkaline battery is one of the most popular method so far. Although batteries have been widely used in powering sensor nodes in WSN presently, the problem is that the energy density of batteries are limited and they may not be able to sustain the operation of the sensor nodes for a long period of time. In many application scenarios, the lifetime of the sensor node typically ranges from two to ten years depending on the requirement of the specific application. Take for the case of deploying sensor nodes on the ice mountain to detect the thickness level of the ice on the mountain, it will take years for the melting process to be measurable. Hence the lifetime of the sensor nodes must be to last for several years before they go into idle state. If that is the case, the lifetime of one or several sensor nodes, depending on the size of the WSN, would affect the performance of the WSN.

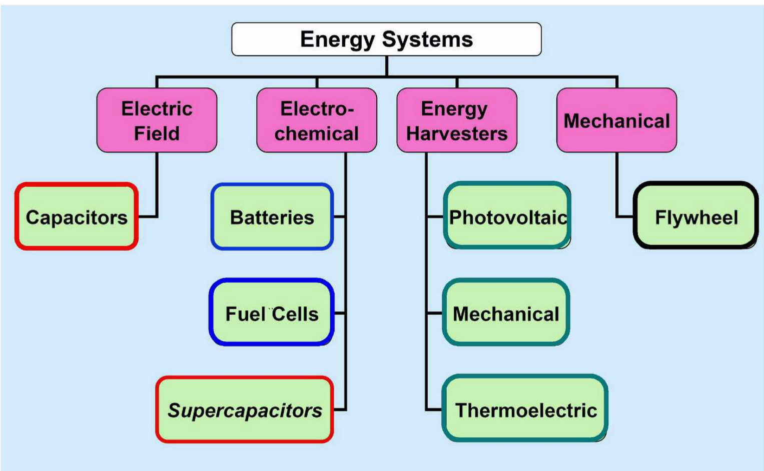


Fig. 5. General types of portable energy systems

Supercapacitor, in short supercap, is another electrochemical energy system other than batteries that has been gaining its presence in powering the wireless sensor nodes. There are

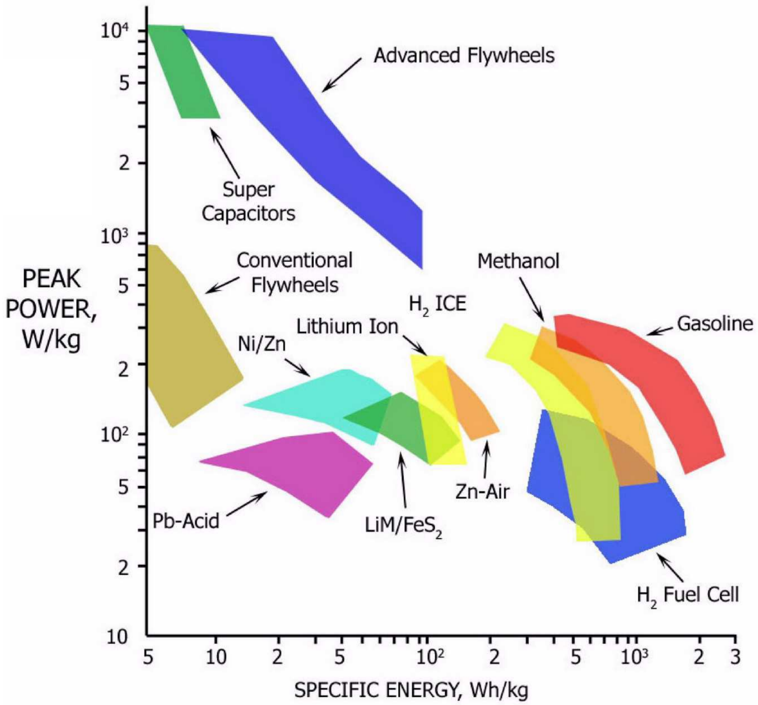


Fig. 6. Ragone plot for comparing the energy storage technologies and their power density versus energy density characteristics Tester (2005)

several reasons for this phenomenon to occur. One reason is that supercapacitor is very scalable and its performance scales well with its size and weight. Another reason is that supercap has many desirable characteristics that favour the operations of the sensor nodes such as high power density, rapid charging times, high cycling stability, temperature stability, low equivalent series resistance (ESR) and very low leakage current. Referring to the Ragone plot Tester (2005) shown in Figure.6 which consolidates various energy storage technologies and compare their power density and energy density characteristics, it can be identified that supercapacitor has much higher peak power density than the other energy storage devices like batteries and fuel cells. This means that supercap can deliver more electrical power than batteries and fuel cells within a short time. As shown in Figure.6, the peak power densities of supercapacitors are well above 1000 W/kg level whereas the power densities of all types of batteries are in the range of 60 W/kg to 200 W/kg and fuel cells are well below 100 W/kg. Hence for burst power operation, supercapacitors are better choice than batteries and fuel cells. The only major drawback of supercap is that it has very low energy density as compared to the rest of the energy storage devices. Batteries and fuel cells have much higher energy storage capacities than the supercapacitors, therefore they are more suitable for those energy-hungry sensor nodes that need to operate for a long time.
The electrical characteristics of a battery define how it would perform in the circuit and the physical properties of the battery have a large impact on the overall size and weight

of the sensor node. Batteries convert stored chemical energy directly into electrical energy. They are generally classified into two groups namely 1) single-use/primary and 2) rechargeable/secondary batteries. The distinction between the two groups is based on the nature of the chemical reactions. Primary batteries are discarded when sufficient electrical energy can no longer be obtained from them. Secondary batteries, on the other hand, convert chemical energy into electrical energy by chemical reactions that are essentially reversible. Thus, by passing the electrical current in the reverse direction to that during discharge, the chemicals are restored to their original state and the batteries are restored to full charge again. Some important parameters of the batteries that help to determine the performances of the battery are listed as follows: -

- Energy density by weight (Wh/kg) and volume (Wh/cm^3) determines how much energy a battery contains in comparison to its weight and volume respectively
- Power density by weight (W/kg) determines the specific power available per use
- Self-charge rate determines the shelf life of a battery
- Cost of battery

The performances of the wireless sensor nodes meshed together in a network form are largely constrained by some limitations in the electrochemical type of energy system. One significant limitation is the limited energy storage capabilities of the batteries or supercapacitors. The energy stored in the storage elements would definitely be drained off by the connected loads after some time. If this is the case, the distance range and data transmission frequency of the communication device in the sensor nodes are highly dependent upon the available electrical power supply and the electrical energy stored in the storage elements. Usually, the wireless sensor networks are preferred to be left unattended once deployed in inaccessible environments where maintenance would be inconvenient or impossible, therefore replacement of the batteries in the wireless sensor nodes is out of the question. The lifetime of the wireless sensor network is therefore determined by the characteristics of the batteries used. In order to overcome the energy constraint of the WSN due to the energy hungry sensor nodes and the limited energy density of the storage elements, some solutions have been proposed in the next section. The proposed solutions are suggested to extend and sustain the operation of the WSNs.

6. Proposed Solutions for WSN problems

Often WSNs are deployed in regions that are difficult to access and so the sensor nodes should not require any maintenance at all under ideal condition. They must be energetically autonomous and independent. This implies that once the batteries/supercapacitors are installed for the sensor nodes, they do not need to be replaced or recharged for a long period of time and really operate in an autonomous manner for life-long operation. In many application scenarios, the lifetime of the sensor node typically ranges from two to ten years depending on the requirement of the specific application. For that, the stringent condition imposes drastic constraints on the power consumption of the sensor node. Take for an example, a single 1.5 V good AA alkaline battery is used to power a wireless sensor node for two to ten years, it can be roughly estimated that the average power consumption of the sensor node ranges from 250 μW to 50 μW. Given that today's commercially available low power radio transceivers typically consume several tens of milliwatts, keeping the transceiver constantly active is clearly impossible. Several possible solutions to address these problems related to powering the emerging wireless technologies have been suggested in the below list and these solutions will be further elaborated in the following sections.

- Improve the performance of the finite power sources for e.g. by increasing the energy density of the power sources
- Reduce the power consumption at different levels of the sensor nodes hierarchy i.e. signal processing algorithms, operating system, network protocols and integrated circuits
- Develop energy harvesting techniques that enable a sensor node to generate its own power by harvesting energy from the ambient

6.1 Improvements on Finite Power Sources

Research to increase the energy storage density of both rechargeable and primary batteries has been conducted for many years and continues to receive substantial focus Blomgren (2002). The past few years have also seen many efforts to miniaturize fuel cells which promise several times the energy density of batteries. While these technologies promise to extend the lifetime of wireless sensor nodes, they cannot extend their lifetime indefinitely. Other than that, there are many disadvantages such as risk of fire, short shelf life of typically 2-3 years, limited energy density, low power density, etc in the existing rechargeable or alkaline batteries that are not only impacting on the operation of the sensor nodes but also causing problems to the environmental conditions.

6.2 Reduce Power Consumption of Sensor Nodes

Low power consumption by each individual sensor node is paramount to enable a long operating lifetime for a wireless sensor network. A long sensor node lifetime under diverse operating conditions demands power-aware system design. In a power-aware design, the energy consumption of the sensor node at different levels of the system hierarchy, including the signal processing algorithms, operating system, network protocols and even the integrated circuits themselves have to be considered. Computation and communication are partitioned and balanced for minimum energy consumption. This is facilitated by low duty cycle operation typically of the order of 0.1 % to 1 % (most of the time the sensor nodes are sleeping), local signal processing, multi-hop networking among sensor nodes can also be introduced to reduce the communication link range for each node in the sensor network. Since the loss in the communication path increases with the communication range, this reduction in the nodes linkage range would result in massive reductions in power requirements. Compared with characteristics of conventional long-range wireless systems, the reduced link range and data bandwidth yield a significant link budget advantage for typical wireless sensor applications. However, the severely limited energy sources (compact battery systems) for wireless sensor nodes create profound design challenges.

6.3 Proposed Sustainable Power Source for WSN

The wireless sensor node harvests its own power to sustain its operation instead of relying on finite energy sources such as alkaline/rechargeable batteries. This is an alternative energy system for the WSN. The idea is that a node would convert *renewable energy* abundantly available in the environment into *electrical energy* using various conversion schemes and materials for use by the sensor nodes. This method is also known as "*energy harvesting*" because the node is harvesting or scavenging unused freely available ambient energy. Energy harvesting is a very attractive option for powering the sensor nodes because the lifetime of the nodes would only be limited by failure of theirs own components. However, it is potentially the most difficult method to exploit because the renewable energy sources are made up of different forms of ambient energy and therefore there is no one solution that would fit all of applications. However, this option would be able to extend the lifetime of the sensor node to a larger extent compared to the other two possibilities i.e. improvements on the existing finite energy sources and reduce the power consumption of sensor nodes.

7. Overview of Energy Harvesting

Energy harvesting is a technique that capture, harvest or scavenge unused ambient energy (such as vibrational, thermal, wind, solar, etc.) and convert the harvested energy into usable electrical energy which is stored and used for performing sensing or actuation. The harvested energy is generally very small (of the order of mJ) as compared to those large-scale energy harvesting using renewable energy sources such as solar farms and wind farms. Unlike the large-scale power stations which are fixed at a given location, the small-scale energy sources are portable and readily available for usage. Energy harvested from the ambient are used to power small autonomous sensors that are deployed in remote locations for sensing or even to endure long-term exposure to hostile environments. The operations of these small autonomous sensors are often restricted by the reliance on battery energy. Hence the driving force behind the search for energy harvesting technique is the desire to power wireless sensor networks and mobile devices for extended operation with the supplement of the energy storage elements if not completely eliminating the storage elements such as batteries.

7.1 Concept of Energy Harvesting

Energy harvesting systems generally consist of: energy collection elements, conversion hardware and power conditioning and storage devices as shown in Figure.7. Power output per unit mass or volume i.e. power/energy density is a key performance unit for the collection elements. The harvested power must be converted to electricity and conditioned to an appropriate form for either charging the system batteries or powering the connected load directly. Load impedance matching between the energy collectors/energy sources and storage elements/connected to the load is necessary to maximize the usage of the scavenged energy. Appropriate electronic circuitry for power conditioning and load impedance matching may be available commercially or may require custom design and fabrication.

Various scavengable energy sources, excluding the biological type, that can be converted into electrical energy for use by low power electronic devices are shown in Figure.7. Our environment is full of waste and unused ambient energy and these energy sources like solar, wind, vibration, ocean wave, ambient radio frequency waves, etc are ample and readily available in the environment. Since these renewable energy sources are already available, it is not necessary to deliberately expend efforts to create these energy sources like the example of burning the non-renewable fossil fuels to create steam which in turn would cause the steam turbine to rotate to create electrical energy. Unlike fossil fuels which are exhaustible, the environmental energies are renewable and sustainable for almost infinite long period. The energy harvesting process can be easily accomplished. As long as the conversion hardware are chosen correctly in relation to the energy sources, the environmental energy can then be harvested and converted into electrical energy. The energy conversion hardware are designed in different forms to harvest various types of renewable energies. Take for an example, the material of the photovoltaic cell in the solar panel is doped in such a way that when the solar radiation is absorbed by the cell, the solar energy from the sun would be harvested and converted into electrical

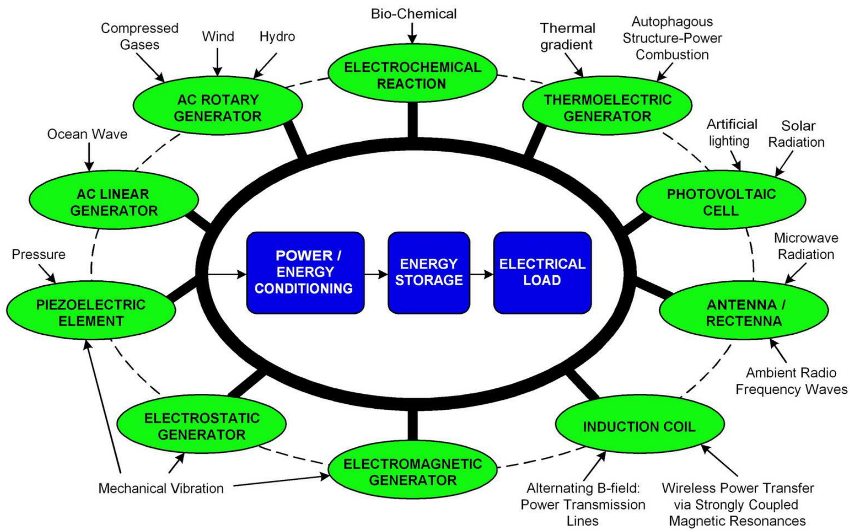


Fig. 7. Energy sources and respective transducers to power autonomous sensor nodes. Adapted from Thomas (2006) with additional power sources.

energy. The whole energy harvesting process involves energy conversion hardware that converts the environmental energy into electrical energy, electrical energy conditioning by the power management circuit and then store in energy storage elements and finally supply to the electrical load.

7.2 Benefits of Energy Harvesting

Energy harvesting provides numerous benefits to the end user and some of the major benefits about EH suitable for WSN are stated and elaborated in the following list. Energy harvesting solutions can:

1. Reduce the dependency on battery power. With the advancement of microelectronics technology, the power consumption of the sensor nodes are getting lesser and lesser, hence harvested ambient/environmental energy may be sufficient to eliminate battery completely.
2. Reduce installation cost. Self-powered wireless sensor nodes do not require power cables wiring and conduits, hence they are very easy to install and they also reduce the heavy installation cost.
3. Reduce maintenance cost. Energy harvesting allows for the sensor nodes to function unattended once deployed and eliminates service visits to replace batteries.
4. Provide sensing and actuation capabilities in hard-to-access hazardous environments on a continuous basis.
5. Provide long-term solutions. A reliable self-powered sensor node will remain functional virtually as long as the ambient energy is available. Self-powered sensor nodes are perfectly suited for long-term applications looking at decades of monitoring.

6. Reduce environmental impact. Energy harvesting can eliminate the need for millions on batteries and energy costs of battery replacements.

7.3 Various Energy Harvesting Techniques

In both academic research works and industry applications, there are many research and development works being carried out on harnessing large-scale energy from various renewable energy sources such as solar, wind and water/hydro NREL (2010). Little attention has been paid to small-scale energy harvesting methods and devices in the past as there are hardly any need. Having said that, it does not mean that there is no research activity being conducted on small-scale energy harvesting. In fact, there are quite a significant amount of research works recorded in the literature that discuss about scavenging or harvesting small-scale environmental energy for low powered mobile electronic devices especially wireless sensor nodes. Figure.8 shows various types of ambient energy forms suitable for energy harvesting along with examples of the energy sources. The energy types are thermal energy, radiant energy and mechanical energy.

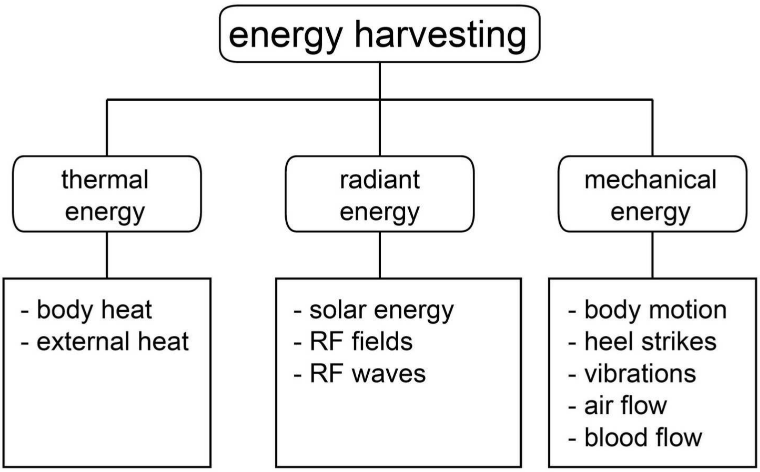


Fig. 8. Types of ambient energy sources suitable for energy harvesting

Some energy harvesting research prototypes for harvesting various energy sources have been discussed. A substantial piece of the research work done by Roundy et al. in Roundy et al. (2004) describes the extraction of energy from kinetic motion. Roundy gave a comprehensive examination on vibration energy scavenging for wireless sensor network. There are other vibration based energy harvesting research works being reported for instances piezoelectric generators in shoes Schenck et al. (2001), wearable electronic textiles Emdison et al. (2002) and electromagnetic vibration-based microgenerator devices for intelligent sensor systems Glynne et al. (2004). In the research area of thermal energy harvesting, both Stevens Stevens (1999) and Lawrence et al. Lawrence et al. (2002) consider the system design aspects for thermal energy scavenging via thermoelectric conversion that exploits the natural temperature difference between the ground and air. Similarly, Leonov et al. Leonov et al. (2007) have considered thermal energy harvesting through thermoelectric power generation from body heat to power wireless sensor nodes. Research on small-scale wind energy harvesting have also been performed by several group of researchers like Weimer et al. Weimer et al. (2006), Myers et al. Myers et al. (2007) and the author himself Tan et al. (2007) and Ang et al. (2007). Heliomote is a sensor node prototype developed by Aman Kansal et al. Raghunathan et al. (2005) that utilizes solar energy harvesting to supplement batteries to power the wireless embedded systems.

7.4 Comparison of Energy Harvesting Sources

To make the sensor node truly autonomous and self-sustainable in the WSN, the energy consumption of the sensor node must be entirely scavenged from the environment. The choice of the energy harvesting technique is crucial. Numerous studies and experiments have been conducted to investigate the levels of energy that could be harnessed from the ambient environment. A compilation of various power densities derived from various energy harvesting sources has been listed in Table.3.

Energy Source	**Performance (Power Density)**	**Notes**
Solar (direct sunlight)	100 mW/cm^3	Common polycrystalline solar cells are 16 %-17 % efficient, while standard mono-crystalline cells approach 20 %
Solar (illuminated office)	100 $\mu W/cm^3$	
Thermoelectric	$^{a)}60\mu W/cm^2$ at 5^oC gradient $^{b)}135$ $\mu W/cm^2$ at 10^oC gradient	Typical efficiency of thermoelectric generators are $\leq 1\%$ for $\Delta T < 40^oC$ $^{a)}$Seiko Thermic wristwatch at 5^oC body heat, $^{b)}$Quoted for a Thermo Life generator at $\Delta T = 10\ ^oC$
Blood Pressure	0.93W at 100mmHg	When coupled with piezoelectric generators, the power that can be generated is order of μW when loaded continuously and mW when loaded intermittently
Proposed Ambient airflow Harvester	177 $\mu W/cm^3$	Typical average wind speed of 3 m/s in the ambient.
Vibrational Micro-Generators	4 $\mu W/cm^3$ (human motion-Hz) $800\mu W/cm^3$ (machines-kHz)	Predictions for 1 cm^3 generators. Highly dependent on excitation (power tends to be proportional to ω, the driving frequency and y_o, the input displacement
Piezoelectric Push Buttons	50 $\mu J/N$	Quoted at 3 V DC for the MIT Media Lab Device

Table 3. Power density comparison on various energy harvesting sources

From Table.3, it can be clearly seen that the solar energy source which is abundant outdoors during the daytime provides the best performance in terms of power density, measuring up to 100 mW/cm^3. The power density of the solar radiation on the earth's surface indicates that in a small volume of 1 cm^3, 100 mW of power can be harvested from the sun by using the solar panel. To achieve this high power density, the solar panel has to be exposed in outdoor condition which has direct bright sunlight. When the solar panel is brought into indoor conditions such as illuminated office, the light intensity is reduced tremendously and the power density of the solar energy source drops to almost 100 μW/cm^3. This shows that the available solar power in indoors is drastically lower than that available in outdoors. For design of embedded wireless sensor nodes to be deployed indoors or overcast areas such as buildings and installations, and forestry terrains, where access to direct sunlight is often not available, solar energy source may not be a suitable choice. Hence there is a need to search for alternative energy sources either to replace the solar energy source as a whole or to supplement the solar energy source when the intensity of the light is low. Thermal energy is an example of the alternative energy sources. To harvest the thermal energy, the *thermoelectric generator (TEG)* has been developed and it harvests the heat energy based on Seebeck effect. One commercial application example of TEG is illustrated by the Seiko Thermic wristwatch. The thermoelectric module in the wristwatch is recorded to yield 60 μW/cm^2 at 5^{o}C temperature gradient with 10 thermoelectric generators coupled together Kanesaka (1999). However typical efficiency for thermoelectric generators is less than 1% for temperature gradient less than 40^{o}C and it is hard to find such temperature gradient in the normal ambient environment. Hence thermal energy harvesting is more suitable for low power applications that consume power less than a few mW or hundreds of μW.

Other than solar and thermal energy sources, there is another type of energy source that is available in human blood pressure. Assuming an average blood pressure of 100 mmHg (normal desired blood pressure is 120/80 above atmospheric pressure), a resting heart rate of 60 beats per minute and a heart stroke volume of 70 milliliters (ml) passing through the aorta per beat Braunwald (1980), then the power generated is about 0.93 W. Ramsay and Clark Ramsay et al. (2001) found that when the blood pressure is exposed to a piezoelectric generator, the generator can generate power of the order of μW when the load applied changes continuously and mW as the load applied changes intermittently. However harnessing power from blood pressure would only limit the application domains to wearable micro-sensors. Taking an interesting turn, Shenck and Paradiso Schenck et al. (2001) have built shoe inserts capable of generating 8.4 mW of power under normal walking conditions. This shows that mechanical vibration is another promising energy source worth investing effort to investigate. Chandrakasan and Amirtharajah Meninger et al. (2001) have demonstrated an electromagnetic vibration-to-electricity converter that produces 2.5 $\mu W/cm^3$. Similarly, another piece of research work discussed by Mitcheson et. al in Mitcheson et al. (2004) has made an analysis indicated that up to 4 μW/cm^3 can be achieved from vibrational microgenerators (of order 1 cm^3 in volume) that typical human motion (5 mm motion at 1 Hz) stimulates and up to 800 μW/cm^3 from machine-induced stimuli (2 nm motion at 2.5 kHz). Additionally, Joe Paradiso and Mark Feldmeir in Paradiso et al. (2002) have successfully demonstrated a piezoelectric element with a resonantly matched transformer and conditioning electronics that, when struck by a button, generate 1 mJ at 3V per 15N push, enough power to run a digital encoder and a radio that can transmit over 50 feet. The mechanical vibration energy harvesting is restricted to specific applications where vibration energy source is available.

In summary, the comparison table has shown the performance of each energy harvesting source in terms of the power density factor. Although the table shows that the solar energy source yields the highest power density, this may not be always the case. Under illuminated indoor condition, the solar energy harvested by the solar panel drops tremendously. The other energy harvesting sources would provide higher power density. Depending on the renewable energy sources available at the specific application areas like outdoor bright sunny day with rich amount of solar energy, along coastal area with a lot of wind energy, bridge structure with vehicles travelling has strong vibrations, etc, a suitable energy harvesting source should be selected to power the load for the specific application. Additionally, there is also a possibility that two or more energy sources are available for harvesting, so hybrid energy harvesting could also be an interesting option for energy-hunger load.

8. Energy Harvesting for Wireless Sensor Network

The concept of energy harvesting in relation to wireless sensor network (WSN) entails the idea of scavenging energy from mechanical, vibrational, rotational, solar or thermal means rather than relying on mains power or alkaline/rechargeable batteries to power the sensor nodes in the WSN. For instance, power can be harvested from the mechanical force of a conventional mechanical ON and OFF switch being turned on or off. Alternately, power can be derived from the difference in temperature between the human body and the surrounding ambient environment. Energy harvesting is increasingly gaining notice in the WSN research as well as industry market because it is a very potential solution to extend the lifetime of the sensor node's operation.

8.1 Architecture of Self-Powered Wireless Sensor Nodes

Figure.9 shows an overview functional diagram of a self-powered wireless sensor node in a WSN which contains the four key units namely

- Energy harvesting unit i.e. power supply, power management/conditioning and energy storage
- Microcontroller unit i.e. signal processing, data manipulation and networking
- Sensor unit for parameters such as temperature, humidity, light and speed sensing
- Wireless communication i.e. transmitter and receiver pair or transceiver unit

The energy harvesting system consists of three main components namely energy harvester, power management/conditioning and energy storage. Figure.10 shows the general block diagram representation of a typical energy harvesting unit. The function of the energy harvester is to convert energy harnessed from ambient energy sources into electrical energy. For examples, the Lead Zirconate Titanate (PZT) ceramic material converts mechanical (strain or stress) energy into electrical energy due to the piezoelectric effect, the photovoltaic cell converts solar energy into electrical energy, the thermoelectric generator output electrical voltage when there is a thermal gradient across it and the wind turbine converts kinetic energy from wind flow into electrical energy. The generated electrical energy from the energy harvester needs to be conditioned by the power management unit before supplying to the load. The main objective of the power electronics technology in the power management unit is to process and control the flow of electrical energy from the source to the load in such a way that energy is used efficiently. This matching process is a crucial step in ensuring that maximum power is transferred from the source to the load. Another function of the power conditioning unit involves the conversion and control of electrical voltage at higher levels into suitable levels for the loads.

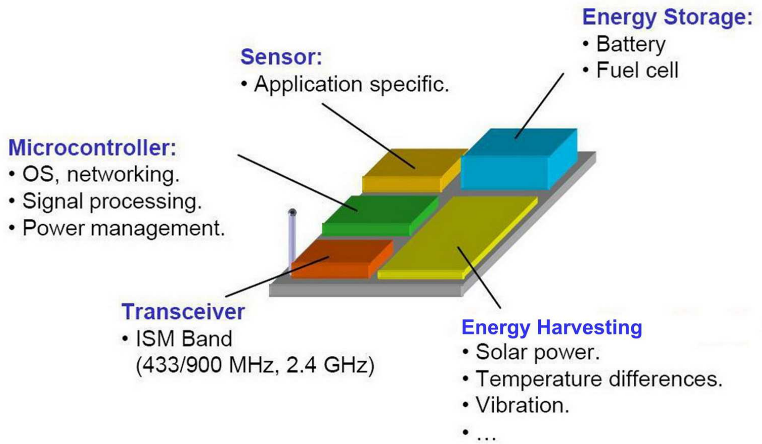


Fig. 9. Key components of a self-powered wireless sensor node

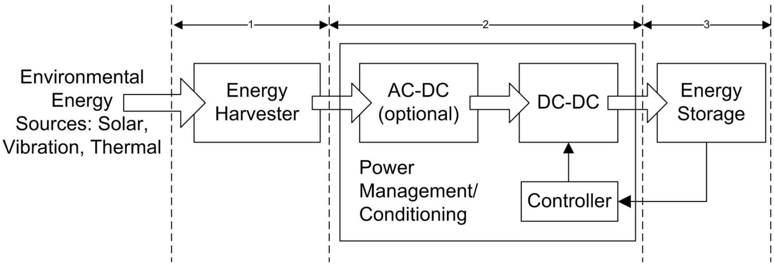


Fig. 10. General block diagram representation of energy harvesting system unit

To ensure continuity in the load operation even when the external power source is temporarily unavailable, the excess energy harnessed has to be stored either in a rechargeable battery or electrochemical double layer capacitors, also known as supercapacitors/ultracapacitors. As mentioned before, batteries have higher energy density (more capacity for a given volume/weight) but lower power density compared to supercapacitors. Recently, such capacitors have been explored for energy storage because they are more efficient and suitable to handle short duration power surges than batteries. Supercapacitors also offer higher lifetime in terms of charge-discharge cycles. However they involve leakage (intrinsic and due to parasitic paths in the external circuitry), which precludes their use for long term energy storage. The overall coverage of this research work involves the investigations on several potential renewable energy harvesting sources and applying these energy sources on some technically feasible application areas to verify that energy harvesting is indeed applicable for real-life applications. The power conditioning electronic circuits in the energy harvesting system are designed based on the energy harvesting input energy sources and the connected output loads, hence different types of power conditioning circuit designs have been proposed to bridge between the source and the load. It is worth noting that the design of the energy harvesting system to power the sensor node in the WSN may differ from one application to another application because of the variations in the load requirements and the differences in

the condition of the deployment area. This would be covered in greater detail in the next few chapters.
The other units of the self-powered wireless sensor node are treated as loads to the energy harvesting system unit. They consume electrical power from the energy sources i.e. energy harvester and/or energy storage to perform their respective operations. Sensors are devices that responds to a physical stimulus (such as thermal energy, electromagnetic energy, acoustic energy, pressure, magnetism or motion) to produce an electrical sensed signal. These sensor devices generally consume relatively low power as compared to the processing and communication units. Hence they are normally not regarded as the major bottleneck in the electronic circuitry. Microcontroller (MCU), which includes an integrated CPU, memory (a small amount of RAM, ROM, or both) and other peripherals such as counters, timer and Analog-Digital Converter (ADC) on the same chip, is a highly integrated single purpose processing unit capable of executing small control programs such as signal processing, power management and networking. The processing power of the MCU is a function of the electrical power consumed i.e. the higher the processing speed, the higher the electrical power consumed by the MCU. Microcontroller is one of the energy hungry units in the wireless sensor node which typically consumes few tens of mW to hundreds of mW during processing and very little power in the order of μW is needed to keep in standby mode. Another energy hunger unit in the sensor node is the communication unit. The function of the communications unit is to transmit or receive data in a wireless manner. A transmitter or receiver has only one function in the communication unit whereas a transceiver has both transmit and receive functions. Some sensor nodes might have only the transmitter to perform uni-directional data transmission whereas others may need to have a transceiver for bi-directional communication.

8.2 Sensor nodes operation with Energy Harvesting Principle

The energy harvester of the energy harvesting system described in Figure.10 converts the environmental energy into electrical energy, at a certain efficiency. The harvested energy is then either stored in the energy storage element or supplied to the load. Energy storage is a very essential element of the energy harvesting system because it acts like a stable bridge between the source and load that provides a constant power flow to the load from a variable environmental source. In short, the power conditioning unit is used to condition the harvested energy so as to properly charge the storage unit and also to provide the appropriate power supply to the load. For a perpetual sensor node operation, it must be such that

$$\overline{P}_g \geq \overline{P}_c \tag{1}$$

where $\overline{P}_g$ and $\overline{P}_c$ are the generated and consumed average/mean powers respectively. As illustrated in Section.4, the power consumed by the sensor node is typically few tens to hundreds of mW and the power generated by the various energy sources of the same area/volume space as the sensor node are much smaller, in the range of units or tens of μW. This is very obvious that energy harvesting is not able to power the operation of the wireless sensor node continuously. One of the possible approach is to reduce the power consumption of the sensor node by duty cycling the node's operation into intermittent form. However, the intermittent mode of operation of the sensor node should not affect the monitoring process of the WSN. In duty cycling type of approach, autonomous sensor nodes are often designed to operate in a very low duty cycle, D, with moderate power consumption in active mode, P_{active} (tens or hundreds of mW), and very low power consumption while idle (sleep mode), P_{sleep} (units or tens of μW), in order to minimize the average power consumed by the sensor node. By doing so, the operation of the sensor node in the WSN can then be sustained by the energy harvesting source. This is one of the methods to sustain the operational lifetime of the wireless sensor node with aid of energy harvesting principle. Let's investigate the amount of power consumed by sensor node when duty-cycling operation is implemented. The consumed average power can be approximated as follows: -

$$\overline{P}_c = P_{sleep} + DP_{active} \tag{2}$$

From Equations (1) and (2), it is observed that when D is large which means the sensor node is active for a long period of time, the average power consumed by the node would be high. Hence the generated power may not be sufficient to power the sensor node's operation. Conversely, if D is small, the sensor node is put to idle state for most of the time and it wakes up to perform sensing and communicating when needed, the average power consumption of the node would be reduced tremendously. If this is the case, there is a higher possibility that the generated power is either able to power the sensor node directly or able to accumulate enough energy in the energy storage and then release to sensor node. Based on the above two equations, it can be worked out that the maximal duty cycle to maintain the operation of the sensor node in continuous mode is given as: -

$$D_{max} = \frac{\overline{P}_g - P_{sleep}}{P_{active}} \tag{3}$$

D_{max} must selected such that it is neither too small until the WSN operation is affected due to the lack in communicating or sensing time nor too large until the average power consumed by the sensor node is much larger than the average power generated by the energy harvesting source. Often, it is hard to have such a situation whereby the generated average power is more than the consumed average power. This is because the power consumed by the sensor node is much more than what the energy harvester of the similar size can provide. Another reason is the variability of environmental energy sources. As the environmental energy sources change their characteristics from time to time, the harvested electrical energy would change accordingly and so there would be times where $P_g < P_c$. To overcome that, a storage unit is needed. This energy reservoir must be able to supply power to the load whenever $P_g < P_c$. For any arbitrary long period of time, T, a long-term storage ($E_{storage}$) unit must be designed to fulfill the condition of: -

$$E_{storage} \geq max \int (P_c - P_g)dt \tag{4}$$

The burst power operation of the sensor node is another condition to be considered for energy harvesting source. Even if generated power, P_g, is constant, for example solar power coming from permanent indoor lights, a short-term storage is still needed to withstand the burst power consumption profile of an autonomous sensor node. Figure.11 illustrates this situation when $P_{active} > P_g$. The capacity of the energy storage should not be selected to be too high because the physical size of the storage would become too large. Depending on the operational requirement of the application, the characteristic of the energy harvesting source and the energy consumption of the sensor node in the WSN, the energy storage and the duty cycle, D, of the sensor node can be determined accordingly.

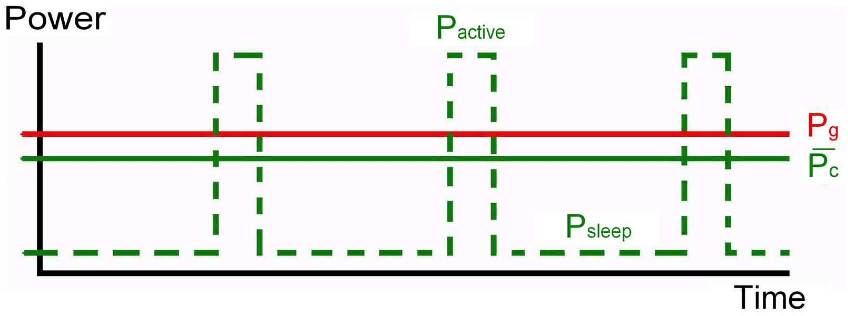


Fig. 11. Burst power consumption by the sensor node when $P_{active} > P_g$

9. Conclusions

The major hindrances of the "deploy and forget" nature of the wireless sensor networks (WSNs) are the limited energy capacity and unpredictable lifetime performance of the battery. In order to overcome these problems, energy harvesting/scavenging, which harvests/ scavenges energy from a variety of ambient energy sources and converts into electrical energy to recharge the batteries, has emerged as a promising technology. With the significant advancement in microelectronics, the energy and therefore the power requirement for sensor nodes continues to decrease from few mWs to few tens of μW level. This paves the way for a paradigm shift from the battery-operated conventional WSN, that solely relies on batteries, towards a truly self-autonomous and sustainable energy harvesting wireless sensor network (EH-WSN).

10. References

Chong C. & Kumar S.P. (2003). Sensor Networks: Evolution, Opportunities, and Challenges, *Proceeding of the IEEE, Sensor Networks and Applications*, vol.91, no.8, pp.1247-1256, 2003.

N. Kurata, S. Saruwatari & H. Morikawa (2006). Ubiquitous Structural Monitoring using Wireless Sensor Networks, *International Symposium on Intelligent Signal Processing and Communications*, pp.99-102, 2006.

Technology Review (2003). 10 Emerging Technologies That Will Change the World, *February 2003 Issue of Technology Review*, >http://www.technologyreview.com/Infotech/13060/?a=f<.

Rakesh Kumar (2005). Shaping Ubiquitous Technology for developing countries, *International Telecommunications Union (ITU) Workshop on Ubiquitous Network Societies*, >itu.int/osg/spu/ni/.../Papers/Paper_Ubiquity_and_developing_world.pdf<.

D.J. Cook & S.K. Das (2004). Wireless Sensor Networks, *Smart Environments: Technologies, Protocols and Applications*, John Wiley, New York, 2004.

M. Kuorilehto, M. Hannikainen & T.D. Hamalainen (2005). A survey of application in wireless sensor networks, *EURASIP Journal on Wireless Communications and Networking*, vol.2005, no.5, pp.774-788, 2005.

Edgar H. Callaway (2003). Wireless sensor networks: architectures and protocols, *Auerbach Publications*, Boca Raton, 2003.

I.F. Akyildiz, W.L. Su, S. Yogesh & C. Erdal (2002). A Survey on Sensor Networks, *IEEE Communications Magazine*, vol.40, no.8, pp.102-114, 2002.

D. Culler, D. Estrin & M. Srivastava (2004). Overview of sensor networks, *IEEE Computer*, vol.37, no.8, pp.41-49, 2004.

A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler & J. Anderson (2002). Wireless sensor networks for habitat monitoring, *Proceedings of the ACM International Workshop on Wireless Sensor Networks and Applications*, pp.88-97, 2002.

A. Boulis, C.C. Han & M.B. Srivastava (2003). Design and implementation of a framework for efficient and programmable sensor networks, *Proc. 1st International Conference on Mobile Systems, Applications and Services (MobiSys'03)*, San Francisco, Calif, USA, 2003.

L. Schwiebert, S. K. S. Gupta & J. Weinmann (2001). Research challenges in wireless networks of biomedical sensors, *Proc. 7th ACM International Conference on Mobile Computing and Networking (MobiCom '01)*, pp.151-165, Rome, Italy, 2001.

Thomas von Buren (2006). Body-Worn Inertial Electromagnetic Micro-Generators, *Ph.D Thesis*, Swiss Federal Institute of Technology Zurich, 2006.

H.O. Marcy, J.R. Agre, C. Chien, L.P. Clare, N. Romanov & A. Twarowski (1999). Wireless sensor networks for area monitoring and integrated vehicle health management applications, *Proc. AIAA Guidance, Navigation, and Control Conference and Exhibit*, Portland, Ore, USA, 1999.

K. Romer (2004). Tracking real-world phenomena with smart dust, *Proc. 1st European Workshop on Wireless Sensor Networks (EWSN'04)*, pp.28-43, Berlin, Germany, 2004.

M.B. Srivastava, R.R. Muntz & M. Potkonjak (2001). Smart kindergarten: sensor-based wireless networks for smart developmental problem-solving enviroments, *Proc. 7th ACM International Conference on Mobile Computing and Networking (MobiCom'01)*, pp.132-138, Rome, Italy, 2001.

S. Roundy (2003). Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion, *Ph.D Thesis*, University of California, Berkeley, 2003.

TinyOS (2008). The TinyOS Project, *TinyOS Community Forum*, >http://www.tinyos.net<.

M. Tubaishat & S. Madria (2003). Sensor networks: an overview, *IEEE Potentials*, vol.22, pp.20-23, 2003.

A. Sinha & A. Chandrakasan (2001). Dynamic Power Management in Wireless Sensor Networks, *IEEE Design Test Comp.*, 2001.

G.V. Merrett, B.M. Al-Hashimi, N.M. White & N.R. Harris (2005). Resource aware sensor nodes in wireless sensor networks, *Journal of Physics*, vol.15, no.1, pp.137-42, 2005.

K. Sohrabi, J. Gao, V. Ailawadhi & G. Pottie (2000). Protocols for self-organization of a wireless sensor network, *IEEE Personal Communications*, vol.7, no.5, pp.16-27, 2000.

E. Lattanzi, E. Regini, A. Acquaviva & A. Bogliolo (2007). Energetic sustainability of routing algorithms for energy-harvesting wireless sensor networks, *Computer Communications*, vol.30, no.14-15, pp.2976-2986, 2007.

Crossbow Technology Inc.(2007). MPR-MIB Users Manual, *Crossbow Resources*, Revision A, 2007.

L. Doherty, B.A. Warneke, B.E. Boser & K.S.J. Pister (2001). Energy and performance considerations for smart dust", *International Journal of Parallel and Distributed Systems and Networks*, vol.4, no.3, pp.121-133, 2001.

J. L. Hill & D. E. Culler (2002). Mica: A wireless platform for deeply embedded networks, *IEEE Micro*, vol.22, pp.12-24, 2002.

J. M. Rabaey, M. J. Ammer, J. L. da Silva, Jr. D. Patel & S. Roundy (2000). PicoRadio supports ad hoc ultra-low power wireless networking, *IEEE Computer*, vol.33, pp.42-48, 2000.

Massachusetts Institute of Technology (2008). μAmps projects, *Microsystems Technology Laboratories*, >http://www-mtl.mit.edu/researchgroups/icsystems/uamps/<.

J.W.Tester (2005). Energy Transfer and Conversion Methods, *Sustainable Energy Lecture Notes*, Topic on Energy Storage Modes, MIT, 2005.

Crossbow Technology Inc. (2007). MPR-MIB Users Manual, *Crossbow Resources*, Revision A, 2007.

G.E. Blomgren (2002). Perspectives on portable lithium ion batteries liquid and polymer electrolyte types, *Seventeenth Annual Battery Conference on Applications and Advances*, pp.141-144, 2002.

J. P. Thomas, M. A. Qidwai, and J. C. Kellogg (2006). Energy scavenging for small-scale unmanned systems, *Journal of Power Sources*, vol.159, pp.1494-1509, 2006.

Renewable Resource Data Center (RReDC). *National Renewable Energy Laboratory*, >http://www.nrel.gov/rredc/< accessed on 14-06-2010.

S. Roundy, P.K. Wright and J.M. Rabaey (2004). Energy Scavenging for Wireless Sensor Networks with Special Focus on Vibrations, *Kluwer Academic Press*, Boston, MA, 2004.

N.S. Schenck and J.A. Paradiso (2001). Energy Scavenging with Shoe-Mounted Piezoelectrics, *IEEE Micro*, vol.21, pp.30-41, 2001.

J. Edmison, M. Jones, Z. Nakad and T. Martin (2002). Using piezoelectric materials for wearable electronic textiles, *Proceedings of Sixth International Symposium on Wearable Computers (ISWC)*, 2002.

P. Glynne-Jones, M.J. Tudor, S.P. Beeby and N.M. White (2004). An electromagnetic, vibration-powered generator for intelligent sensor systems, *Sensors and Actuators*, vol.110, no.1-3, pp.344-349, 2004.

J.W. Stevens (1999). Heat transfer and thermoelectric design considerations for a ground-source thermo generator, *Proceedings of 18th International Conference on Thermoelectrics*, 1999.

E.E. Lawrence and G.J. Snyder (2002). A study of heat sink performance in air and soil for use in a thermoelectric energy harvesting device, *Proceedings of 21st International Conference on Thermoelectrics (ICT Š02)*, 2002.

V. Leonov, T. Torfs, P. Fiorini, C. Van Hoof (2007). Thermoelectric Converters of Human Warmth for Self-Powered Wireless Sensor Nodes, *IEEE Sensors Journal*, vol.7, issue.5, pp.650-657, 2007.

Michael A. Weimer, Thurein S. Paing, and Regan A. Zane (2006). Remote area wind energy harvesting for low-power autonomous sensors", *37th IEEE Power Electronics Specialists Conference*, pp.2911-2915, 2006.

R. Myers, M. Vickers, Kim Hyeoungwoo and S. Priya (2007). Small scale windmill, *Applied Physics Letters*, vol.90, no.5, p.54106-1-3, 2007.

Y.K. Tan and S.K. Panda (2007). A Novel Piezoelectric Based Wind Energy Harvester for Low-power Autonomous Wind Speed Sensor, *33th Annual IEEE Conference of Industrial Electronics Society (IECON'07)*, pp.2175-2180, 2007.

R.J. Ang, Y.K. Tan and S.K. Panda (2007). Energy harvesting for autonomous wind sensor in remote area, *33th Annual IEEE Conference of Industrial Electronics Society (IECON'07)*, pp.2104-2109, 2007.

V. Raghunathan, A. Kansal, J. Hsu, J. Friedman and M. Srivastava (2005). Design considerations for solar energy harvesting wireless embedded systems, *Fourth International Symposium on Information Processing in Sensor Networks (IPSN 2005)*, pp.457-462, 2005.

T. Kanesaka (1999). Development of a Thermal Energy Watch", *Proc. 64th Conference on Chronometry (Société Suisse de Chronométrie)*, Le Sentier, Switzerland, pp.19-22, 1999.

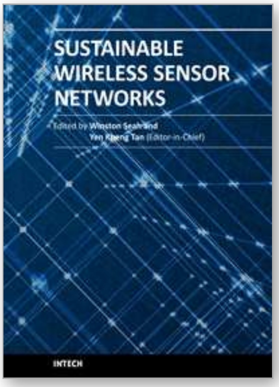
E. Braunwald (1980). Heart Disease: A Textbook of Cardiovascular Medicine, *W. B. Saunders Company*, Philadelphia, 1980.

M. Ramsay and W. Clark (2001). Piezoelectric energy harvesting for bio-MEMs applications, *Proceedings of the SPIE - The International Society for Optical Engineering*, vol.4332, pp.429-439, 2001.

S. Meninger, A.P. Amirtharajan and R.Chandrakasan (2001). Vibration-to-Electric Energy Conversion, *IEEE Transaction on VLSI System*, vol.9, pp.64-71, 2001.

P.D. Mitcheson, T.C. Green, E.M. Yeatman and A.S. Holmes (2004). Architectures for Vibration-Driven Micropower Generators, *Journal of Microelectromechanical Systems*, vol.13, no.3, pp.429-440, 2004.

J. A. Paradiso and Mark Feldmeier (2002). A compact, wireless, self-powered pushbutton controller, *MIT Media Laboratory*, 2002.



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Wireless Sensor Networks came into prominence around the start of this millennium motivated by the omnipresent scenario of small-sized sensors with limited power deployed in large numbers over an area to monitor different phenomenon. The sole motivation of a large portion of research efforts has been to maximize the lifetime of the network, where network lifetime is typically measured from the instant of deployment to the point when one of the nodes has expended its limited power source and becomes in-operational â€“ commonly referred as first node failure. Over the years, research has increasingly adopted ideas from wireless communications as well as embedded systems development in order to move this technology closer to realistic deployment scenarios. In such a rich research area as wireless sensor networks, it is difficult if not impossible to provide a comprehensive coverage of all relevant aspects. In this book, we hope to give the reader with a snapshot of some aspects of wireless sensor networks research that provides both a high level overview as well as detailed discussion on specific areas.

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