Research Study of Energy Harvesting in Wireless Sensor Networks

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Abstract- A wireless sensor network (WSNs) exploits the sustainability technological requirement and research solution to alternate energy source of power. To power WSNs is by harvesting ambient energy from the environment is a promising challenge as there is no such efficient protocol that can continuously support the requirements. We provide a survey study of applying WSN to real application of habitat monitoring. A system architecture design of sensor nodes to address the requirement of habitat monitoring is analyzed. Consequently, substantial research efforts have been carried in designing sensor nodes that exploit sporadic energy needs to transmit data to maximize the lifetime of WSNs. This paper surveys related recent research development and challenges in protocol design in the harvesting energy in WSN architecture and provide scope for open research issues.

Keywords- Energy harvesting, Energy management, Protocol design, Wireless Sensor Networks

1. Introduction

Wireless sensor networks (WSNs) may be considered as the third age of a revolution in wireless technology that has a great impact on human uprising. The biggest constraint of WSNs is energy limitation since it is difficult to maintain its battery before it drains out. Most of the research on WSNs use limited battery power source to extend the lifetime of the network by minimizing energy usages. Consequently, substantial research efforts have been carried on designing energy-efficient networking protocols by the harvesting concept which is an alternative to power WSNs by converting the ambient renewable energy (e.g., solar, electromagnetic, thermal and mechanical) from the environment into electricity to power the sensor nodes.

Habitat and environmental monitoring represent a class of sensor network applications that provides tremendous scope for the research communities. A sensor's connected to the physical environment to provide information through traditional instrumentation for habitat monitoring using the concept of localization [12], tracking [13], data aggregation [14], and, of course, energy-efficient multihop routing [15]. So sensor design is important factor on WSN applications to operate for longer durations in lieu of battery capacity in environmental/habitat monitoring where, batteries are hard to replace/recharge.

Many research groups have proposed using WSNs for habitat and environmental monitoring applications. Subsequently power-management design is essential for maximizing lifetime of the network. Two basic design considerations are apparent:

1. Energy Distribution: The system multiple sensor distribute harvesting energy that is used to deliver network-wide performance.

2. Maximum Performance: The network performance improvement support depends on the harvested energy at multiple distributed components [1].

In the areas of habitat and environmental monitoring WSNs represent an enormous potential benefits for scientific communities and society as a whole. So Energy harvesting research even incline towards hardware that can sufficiently affordable, reliable and longer lived for various number of applications [2].

Energy Harvesting is defined as the process of capture, accumulate, condition and storage of wasted energy from surrounding environmental sources energy such as that include light, temperature, motion and electromagnetic wave. The Energy Harvesting is the method of efficiently and effectively captures, accumulate, store, and manage the energy and supply it in a form that can be stored for sensor nodes use. Similarly, an Energy Harvesting Module is an electronic device that performs the functions to power a variety of sensor. Wireless sensor applications installations depend on technology as per the demand on number of applications [3].

Much of the research on wireless sensor networks has assumed the use of a portable and limited energy source, namely batteries, to power sensors and focused on extending the lifetime of the network by minimizing energy usage. A wireless sensor network that is not dependent on a limited power source essentially has infinite lifetime. Failure due to structural hardware damage can be overcome by self organization and network re-configuration. This has motivated the search for an alternative source of energy to power WSNs.

Several solution techniques have been proposed to maximize the lifetime of battery-powered sensor nodes. Some of these include energy-aware MAC protocols SMAC, BMAC, XMAC, EXMAC power aware storage, routing and data dissemination protocols, duty-cycling strategies, adaptive sensing rate, tiered system architectures and redundant placement of nodes to ensure coverage guarantees. The above techniques help optimize and adapt energy usage to maximize the lifetime of a sensor node, to prolong the application lifetime and to overcome the requirement of battery replacements by proper power management.

This paper explains a specific harvesting in WSN, is representative of habitat and environmental monitoring applications. Paper provide a brief survey of research on energy harvesting wireless sensor networks along with the details energy harvesting techniques such as architectures, energy sources, storage technologies. Further, describes the core components of the sensor network domain – the hardware and sensor platforms [4]. This paper explains a specific design and implementation of the essential network services, including power management by means of harvesting, communications, routing and node management, can be evaluated in context.

Section II discusses the research on energy harvesting. Section III gives the research scope in the energy harvesting. Section IV discusses on harvesting research challenges. Section V presents a sensor network architecture that includes the core system components and interfaces. Section VI discusses the study of energy conservation devices in harvesting. Section VII presents the merits in energy harvesting. Section VIII describes the challenges of energy harvesting and finally Section IX makes concluding remarks.

2. Research on energy harvesting

The Energy harvesting is defined as the conversion of ambient energy into usable electrical energy. Energy harvesting technology allows capturing ambient energy (such as vibration, strain, and temperature gradients, energy of gas and liquid flows) and converting into electrical energy which is stored and used for performing sensing or actuation. The environment represents a relatively inexhaustible source of energy when compared with the energy stored in common storage elements, like batteries. The incorporated energy harvesters are packed devices as compared to the conventional solutions. Therefore, WSN opting for energy harvesters minimize maintenance costs and increase network life time. Energy harvesting is a perfect match for wireless devices and wireless sensor networks that otherwise relies on battery power. Consequently, energy harvesting must be characterized by their power density, rather than energy density [5].

Table 1 compares the estimated power and challenges of some important ambient energy sources. Photon, for instance, can be a significant source of energy, is highly dependent on the application and subject to the device where it is exposed [6].

Table 1: Comparison between different ambient energy sources

Energy Source	Power density (µW/cm2)[21]	Network size	Efficiency	Estimated Power
Light (Photon)	3700	40 sq meter	10-25%	10µW-15mW (Outdoors: 0.15mW-15mW) (Indoors: <10µW)
Vibrations	500	40 sq meter	25-50%	1µW-200µW (Piezoelectric: ~ 200µW) (Electrostatic: 50µW-100µW) (Electromagnetic: <1µW)
Thermal	60	40 sq meter	-0.1-3%	15µW (10°C gradient)
Electromagnetic	4.0	40 sq meter	50%	10µW-100µW (2.4 GHz)

On the other hand, Thermal energy because of the temperature differentials across a chip is typically high at particular point. Vibration energy is a moderate source, but again dependent on the particular application and the Electromagnetic wave result in RF energy which is present everywhere can be accessed in remote location also.

The research perspective challenges are based on its application and further development of the network architecture. The multi-disciplinary application need to full fill the requirement of the prototype systems and its architecture [7]. A review of the various range of application is discussed for the proposal of design model.

A. Animal tracking and control

The research in the application of the animal movement is tracked and controlled by sensor nodes. Application like birds breeding as per the climatic condition is also studied. To carry out such analysis the sensor nodes are distributed in cluster formed network. Various sensor nodes are connected to wild animals depending upon the habitat study and observed their behaviour by allowing the mobile or stationed base station to collect the respective data's. Such network sends the information to the remote location to analyze the different behavioural study. Such deployment enables the nodes the measure the temperature, humidity, pressure, ambient conditions etc.

B. Environmental monitoring

The environmental monitoring is the wider areas of WSN application. In this application measurement of the characteristics such as location identification, pressure, temperature and the glaciers condition over periods. Various researches in the environmental field measure the parameters by deploying various sensors in self organize ad-hoc wireless network mode. In the areas of agriculture application the product condition and the condition of soil moisture, humidity, and temperature can able to observe by sensor node such as in the grape field. The agro project is another such example [8].

C. Smart home

The smart home system is now a days getting wider application. To monitor the light, fan, heater and other appliance gadgets etc the wired and wireless sensor system is deployed. In WSN the deployed sensor monitor the energy consumption of the house/office and transmit it to the remote location.

D. Security & Military application

The sensor nodes deployed in the dangerous zone can able to support and guide the applications. In the case of defence the unmanned aerial vehicle (UAV) keep tracks of military vehicle. Another application such as anti-tank land mines, nuclear station process controls, etc.

E. Medical application

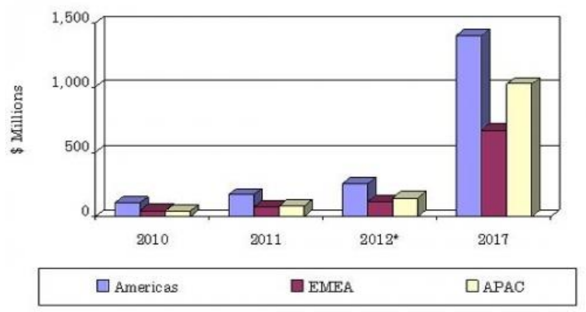
The WSN support the heal application such as patient monitoring, old age people health, drug administration, and personal in hospital. Even the sensor is applied to human bodies. The IEEE802.15.4 wireless standard is applied to the animal body sensor using the ZigBee application layer concept. This enable the doctors sitting in different location can investigate and operate their patients.

3. Research scope in energy harvesting

Energy harvesting is having a wide range of research scope. While the scientific study of energy conversion principles are indisputable for decades, still their application remained restricted to limited domains in industry and heavy engineering. The nature is surrounded by Energy in the form of thermal energy, wave energy, light (solar) energy, wind energy, and mechanical energy. The development of technical devices transforms the environmental energy into electrical energy. Energy harvesting (EH) is the methods by means of which the remote application can runs for a longer period without getting the energy source inexhaustible. This free energy source device is designed for maintenance-free and supports the application for the lifetime. Besides, energy harvesting is used as an alternative energy source to supplement a primary power source to enhance the reliability of the overall system without getting power interruptions.

Now a days the Renewable energy that is being harvested to generate electricity that includes thermal, light, solar, wind, water, electromagnetic energy and thermal energy. Harvesting energy is a low-power devices like wireless sensors presents a new challenge as the energy harvesting device in the present power constraint scenarios for small scale battery operate sensor device. There are certain complex tradeoffs to be considered while designing energy harvesting circuits for WSNs arising due to various factors like the energy sources, energy storage device, power management functionality of the nodes and protocols, and the applications' requirements. In the following subsections, the survey report of BCC (Business Communications Company, Inc.) research is shown in Figure 1. This report summaries figure of global market demand for energy harvesters by geographical region, 2010-2017($ millions).

- The global energy harvesting market was valued at $323 million in 2011 and should reach $514 million in 2012. Total market value is expected to reach nearly $3.1 billion in 2017 after increasing at a five-year compound annual growth rate (CAGR) of 43.2%.
- The Americas are expected to have a value of $253 million in 2012 and $1.4 billion in 2017, a CAGR of 40.8%.
- As a segment, EMEA (Europe, the Middle East and Africa) should total $113 million in 2012 and $670 million in 2017, a CAGR of 42.8%.



Source: BCC Research

Fig 1. Summary figure of global market for energy harvesters

The above report presents the forecasts for energy harvesters for 2012 through 2017 on a volume and value basis. The statistics shows the sales values are presented in U.S. dollars, while shipment volumes are presented in thousand units. The energy harvesting use the power wireless sensor nodes experience tremendous growth as well. This shows that there is tremendous scope for the research in the following energy sources:

- Solar and photovoltaic.
- Thermal.
- Vibration, displacement and mechanical
- Biomechanical and electrostatic
- Radiation and electromagnetic.
- Chemical.

4. Research challenges in harvesting

The Energy harvesting is defined

The research of habitat application is based on the development of harvesting sensor network architecture and study of its related protocol issues. The application requirement shows the identification of research scope and its requirements.

4.1. Research platforms

The two well known research location for the habitat monitoring is Great Duck Island (GDI), Mt Desert Island, Maine and James San Jacinto Mountains Reserve (JMR), Idyllwild, California. The GDI research focuses on basic ecology distribution and abundance of plants and animals. This study is based on climate and habitat movement, Leech's Storm Petrels and other sea birds habitat condition. Researchers found that on Kent Island, Nova Scotia, nesting Leach's Storm Petrels abandon their burrows if disturbed during their first 2 weeks of incubation. This reduces the hatching success of petrel eggs by 56% due to investigator disturbance compared to a control group that for the duration of their breeding cycle [17].

The JMR study the range of habitats from streambeds to forest to desert landscape. For example, nest boxes and bat caves. Further it monitors the ecosystem overtime and response of vegetation to climate changes.

For the measurement of the parameters the sensor network is formed to capture the data and send to the sink station. In certain case the infrared sensor is used to capture the movement information's.

4.2. System platforms

1. Sensor network: For the longevity of the network operation the sensor nodes life need to prolongate. Normally sensor runs for 10 months, when based on optimum network conditions.
2. Hierarchical network: The multiple sensor nodes are deployed in the areas of interest either in static or dynamic mode based on cluster distribution. The network is connected by means of sensor over internet.
3. Uninterrupted operation: The network operation should be uninterrupted during the process of study. Any system failure will cause variation in the data collection and its appropriate distribution.
4. Sampling: Sensor should capable of sampling the measuring data's based on application such as temperature, pressure, humidity, and light.

4.3. Data aggregation

The deployed large numbers of sensors in various fields is connected to corresponding base station and then linked to sink. The data's read by sensors are processed and analyzed since the network needs to be energy efficient. The data redundancy and its error need to analyzed and rectified in the real-time environment.

As the wireless sensor network growth is rising in tremendous pace the challenge, the ad hoc wireless network is soaring. The routing protocol that is harvesting-aware is higher in cost, or whose nodes have depleted batteries. While there has been extensive research on wireless sensor networks, those specific to energy harvesting WSNs are just emerging. Some of such issues are in the areas [18] such as:

- Topology control
- Deployment issue
- MAC issue
- Power Management
- Network & protocol issue
- Reliable data release

- Data Delivery Schemes
- Routing algorithm
- Design factors
- Energy Storage Technology
- Energy harvesting for infinite life time sensor nodes
- Security

The distributed processing capability in sensor network is life time of battery related big issue. Because each sensor node is operated by battery with finite energy storage and the lifetime of nodes depends on the available energy in the battery. Wireless sensor network architecture interconnects the core system components ranging from much localized collections of sensor nodes to the wide-area for data analysis.

5. Architecture of energy harvesting in WSN

The Wireless networked sensors and actuators [9] deeply embedded in the physical environment application in areas of human society, engineering, arts, entertainment, education, the military and day-to-day life. But in all these area the battery constraint is the biggest issue. Normally in tradition way researchers address this by developing energy-efficient circuits and software so as to make the batteries last longer, thus increasing node life before batteries need to be replaces. Though, a wireless sensor network depends on their reliable operation for extensive times using harvesting technology without human intervention for energy supply.

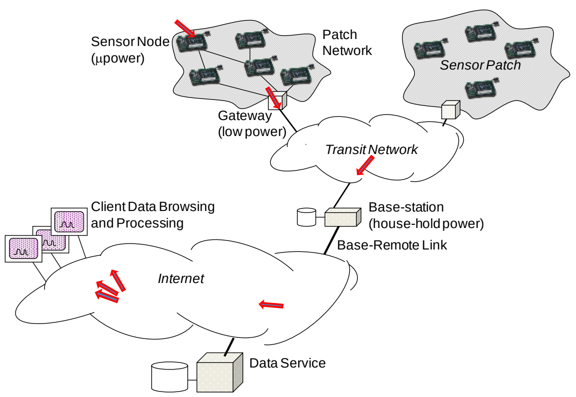


Fig 2. Architecture of Harvesting wireless sensor network

The Figure 2 shows the energy harvesting using wireless sensor network consist of sensor motes [10] placed at various location as per the application and it is energized by the various harvesting sources. Each sensor nodes collect the information and process through the gateway to the internet network. The sensors will typically form a multi-hop network by forwarding each other's messages, in a connective mesh network. To provide the data to remote end-users location, the base station includes a WAN connectivity and transfer the data through various sensor nodes. The architecture of the wireless sensor network management addresses the data management using the sensor nodes, gateways, base stations.

Here the sensor of Mica mote resided on a single sensor board developed by UC Berkeley [19] running the TinyOS operating system [15] chosen for study. In the wireless sensor networks limited energy source, viz. batteries, in the power sensors shows a negative feature in this technology. Without energy, a sensor is essentially useless and cannot contribute to the effectiveness of the network as a whole. A possible solution to this crisis is to harvest the energy from the physical environment at run time. The various sources of energy that is harvested for the sensor nodes are light, thermal, RF and vibration. Every harvesting has unique advantages and disadvantages, and the specific harvesting technology is dependent on the application.

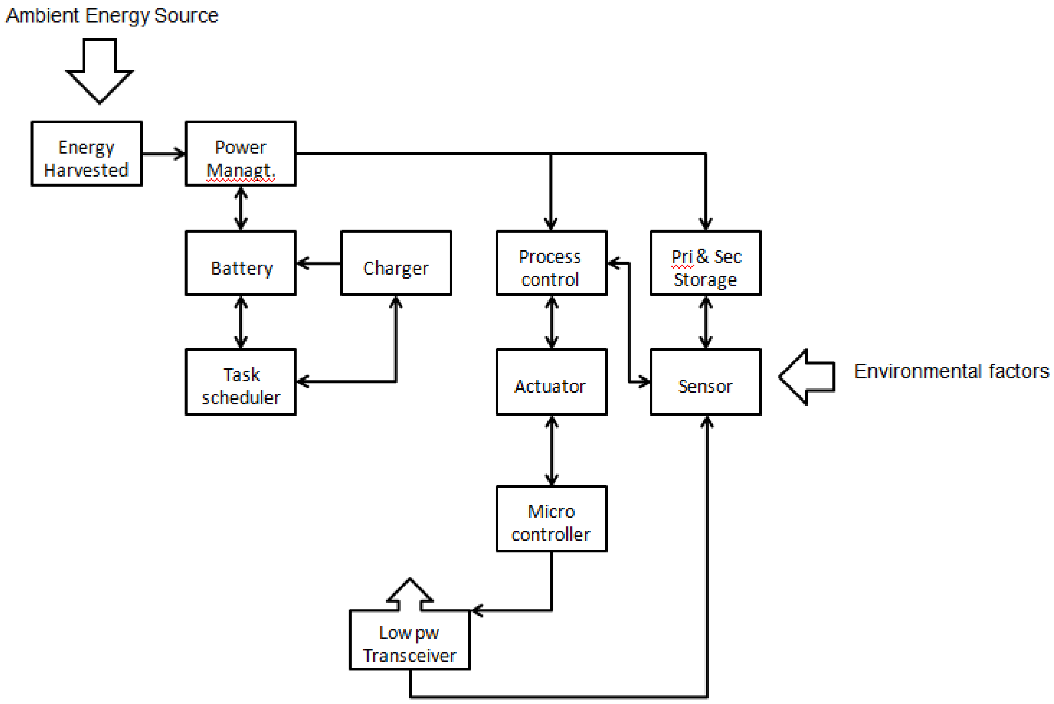


Fig 3. Design of harvesting wireless sensor network architecture

The Figure 3 shows the generic design of sensor network using harvesting device. The energy harvesting device receives the harvesting energy from the ambient environment by converting ambient energy to electrical energy by sensor node. The characteristics that a sensor network to monitor the power management and the battery charging [11] using received harvested energy. The power from this energy harvesting sensor such as solar panel of area 3.75 inches by 2.5 inches which outputs 60mA at a voltage of 3.3V is used to recharge two AA-sized Ni-MH battery of capacity 1800 mAh each. The over-charge and under-charge protection modules use control circuits consisting of comparator with hysteresis, that control analog switches. Radio Frequency Identification (RFID) systems use radio frequency to identify, locate and track people, assets and animals using the RFID reader identification tag.

The RFID tag is energized by a time-varying electromagnetic radio frequency wave called the carrier signal is transmitted by the reader to the base station. When the RF field passes through an antenna coil on the RF tag, an AC voltage is generated across the coil. A magnetic coupling happens between the RFID reader and the tag due to mutual inductance of their loop antennas. The response is based on amplitude modulating the carrier signal received.

The figure 4 shows the response of Mica node energy with respect to amount of time under battery operation and harvesting operation based on architecture. From the response it is observed that sensor node discharge its battery for duration without rebuilding its energy. The estimate lifetime of the batteries will be able to supply 2.2 Ah at 3 volts is not able to renewable externally.

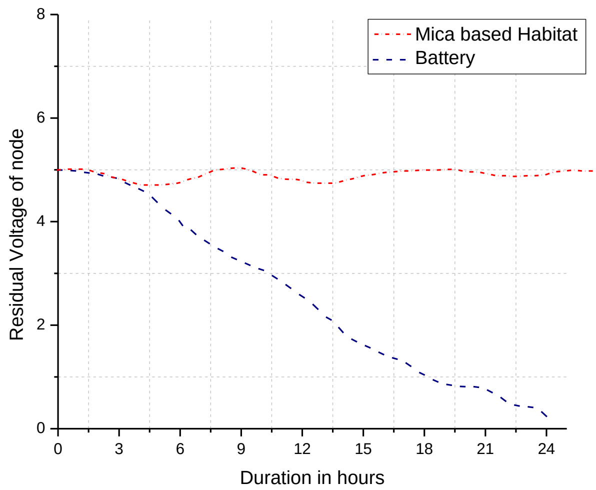


Fig. 4. Habitat based vs Battery-powered WSN

Whereas, during harvesting as compared to battery-operated the one or more energy harvesting devices, stores it energy. The architecture empirical study shows that batteries total lifetime of the nodes improved by 2.7 months.

The processing unit determines the amount of power consumption by the nodes is suitable for data acquisition, scheduling and to support effective communication protocol. The chip level processor offers low cost and low power. The most considered IEEE802.11 wireless standard for WLAN and IEEE802.15.3 for WPANs is widely grouped. Specific communication protocols are also considered for WSN application includes Bluetooth IEEE802.15.1 and ZigBee IEEE802.15.4. Table 2 shows the comparison chart of commercial sensor network nodes which uses the RF energy harvesting.

Table 2. Summary of power consumption of commercial sensor network nodes

	Crossbow MICAz	Intel Mote2
Radio standard	IEEE 802.15.4/ZigBee	IEEE 802.15.4
Typical range	100m outdoor, 30m indoor	30m
Data rate (kbps)	250 kbps	250 kbps
Sleep mode	15 µA	390 µA
Processor only	8 mA	31-53 mA
RX	19.7 mA	44 mA
TX	17.4 mA	44 mA
Supply voltage	2.7 V	3.2 V
Average	2.8 mW	12 mW

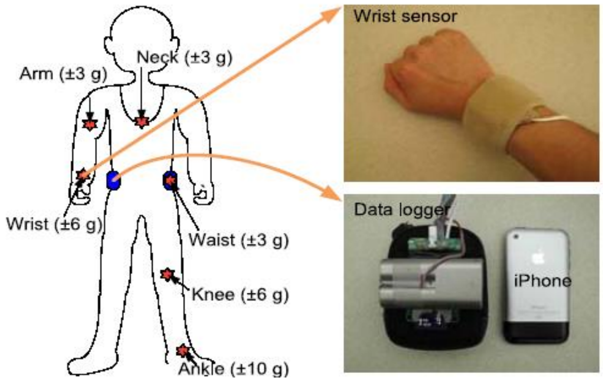
6. Energy conversion devices

The effectiveness of the energy harvesting device depends on both on the available energy and the efficiency of the energy conversation. Following are the some of the energy conversion device.

- Thermal Energy – waste energy from furnaces, heaters, and friction sources. Also from human body.
- Mechanical Energy – from sources such as vibration, mechanical stress and strain.
- Natural Energy – from the environment such as wind, water flow, ocean currents, and solar
- Light Energy – captured from sunlight or room light via photo sensors, photo diodes, or solar panels
- Electromagnetic Energy – from inductors, coils and transformers
- Human Body – a combination of mechanical and thermal energy naturally generated from bio-organisms or through actions such as physical movement walking and sitting.
- Other Energy – from chemical and biological sources

Below mentioned figure 5(a) shows the thermal energy harvesting devices. The thermo probe is being used for the remote application or space research applications.

External Thermo harvester TE-Power PROBE



Human Body Sensor

Fig 5. Energy harvesting devices (a) Thermo probe (b) Human body sensor

In cases where the devices are not actively driven, due to limited power can generally be harvested by recovering energy from body heat, breathing, blood pressure, arm motion, typing, and walking. The human body sensor is implanted inside the body for control and communicating data with the remote devices. Hence a potential power source from various body-cantered actions is provided in Figure 5(b).

7. Advantages of Energy Harvesting

Energy harvesting provides numerous benefits to the end user as per application. Energy harvesting solutions can reduce dependency on battery power and it is sufficient to eliminate battery completely. The harvesting device can be powered only from by the harvester and rely on internal energy storage to smooth out variations as per ambient energy. For example, thermoelectric can produce watts per cubic centimeter, while piezoelectric in actuators and vibration harvesters can exhibit 60% efficiency and it reduces installation costs. The self-powered wireless sensors are wired and are very easy to install.

i. Based on empirical analysis based on Voltage (power), temperature, humidity and light shown the effective energy saving of 38%. The amount of energy consumed in company buildings, shows long life and affordable building controls are focused of the companies.

ii. It reduces maintenance costs and energy harvesting allows for devices not to replace batteries.

iii. It provides sensing and actuation capabilities in hard-to-access in hazardous environments.

iv. The life of energy-harvesting devices without batteries is at least 10 years longer than the normal battery-driven wireless devices life and this gives valuable paybacks.

v. It provides the long-term solutions in the network nodes. A dependable self-powered device will remain functional virtually in the ambient energy. This device perfectly suited for long-term applications.

vi. It reduces the environmental impact and energy harvesting can eliminate the need for new batteries and energy costs of battery replacements.

vii. The next generation of energy-harvesting devices will be smaller, lower in cost and have long life. With the statistics of demand on energy-harvesting devices predicted in EMEA (Europe, the Middle East and Africa) about $670 million in 2017, a CAGR of 42.8% the energy density improvement will provide more research scope and will also expand the market by 48%. Many devices will be announced that work within the human body without need of further intrusive surgery and many other applications. Many others will be embedded in apparel. IDTechEx forecasts huge numbers of energy-harvesting devices to be sold into electronic medical disposables, e-labels, e-packaging and e-posters.

Energy harvesting will power many of the medical disposables needed for self-diagnostics and drug delivery in the future days.

8. Challenges of Energy Harvesting

In the wireless sensor networks the use of the harvesting technologies limitation is on the efficiencies and effectiveness of the harvesting devices. The power requirements of the sensor system supplied by conventional battery source need preservation of energy for industrial applications. There is a need to develop energy harvesting device that can supply sufficient power for autonomous sensor networks in energy efficient ways.

The challenges of energy harvesting are new for the real world application that provides the scope to develop novel techniques. Some of such features are as follows:

- Development of software or hardware tools for power predictions and management.
- Design of hybrid energy harvesting devices combining sources, control and storage items.
- Energy harvesting devices that support the harsh and hazardous applications.
- Efficient low power conversion devices from energy harvesting devices.
- Design of low cost energy harvesting devices.

9. Conclusion

In the wireless sensor networks the use of renewable and non-renewable energy source is a promising technology with harvesting to overcome the limitation of battery source. However the current harvesting technology does not provide sustained energy supply. We have presented the WSN architecture for habitat monitoring and its implementation. With the advancement in the internet technology provides a connectivity of application and information sharing in the Habitat monitoring. The protocol design for energy harvesting is a challenging task. In this paper, we have discussed the various methods and challenges of recent development in the harvesting energy and the research scope.

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