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A Review on Solar Energy Harvesting Wireless Sensor Network

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Abstract— The finite energy of batteries associated with wireless sensor networks is a major constraint which limits its lifetime. One of the methods to overcome this major limitation is energy harvesting systems. Thither are many energy sources available nowadays, but solar energy is flexible, mature and external power source so it is broadly used for energy harvesting in WSN to enhance the life of the network used. This paper presented an overview of solar energy harvesting system and the impact of solar energy harvesting on Wireless Sensor Network. We have also propounded the various energy harvesting sources that are used for WSNs and energy harvesting process. This paper also describes the supercapacitor and various recharging batteries.

Keywords— Wireless sensor network (WSN), Energy Harvesting (EH), Solar energy harvesting (SEH)

I. INTRODUCTION

Wireless sensor network (WSN) is a network, in which there is a random or a symmetric deployment of nodes depending upon the application, to sense the data to execute numerous operations. Due to the miniature size of the WSN, it is employed within a vast diversity of applications comprising defense, medical, industrial applications, environmental and ocean monitoring. WSN is one of the biggest and furthermost used networks in the world. The life cycle and performance of the wireless sensor node and communication paths play a key role in these applications of WSNs. A sensor node comprises of four primary components a sensing unit, a transceiver unit, a processing unit, power unit and it might have secondary application-dependent constituents such as mobilizer, position detection system and power generator [1]. The power unit is one of the prime components of sensor nodes. Solar cells and other subunits used as a scavenging unit to back up power units of sensor network depending upon the application [1]. Mostly power can be supplied to WSN through energy storage devices such as batteries or supercapacitors but now a day some renewable sources are applied to supply power to the network.

Since most of the WSN applications are situated in an inhospitable area consequently replacement of the batteries would be inconvenient. Hence, it is strenuous to enlarge the lifespan of WSNs under a finite power of device [2]. Therefore, energy harvesting technologies could be utilized to prolong the life span of the wireless sensor network and the supreme familiar sources that are used for energy harvesting are solar, wind, vibration, RF (Radio frequency), thermal.

One of the novel techniques to extend the WSN lifetime is solar energy harvesting (SEH) system which can transform the solar power into electrical power and stowed it in the sensor batteries for upcoming purposes. The advantages of solar energy are given as follows [3]**:**

- Solar energy is the eternal power source and eco-friendly.
- Highest achieved power density of the solar energy is 10–15 mW/cm² as a contrast to other renewable energy sources.
- Solar energy is flexible, complimentary of cost and doesn't pollute the surroundings.
- Solar energy systems require compact preservation and last up to a number of years.

The main applications of SEH-WSNs are Temperature monitoring, light intensity measurement, Humidity measurement, pressure monitoring, environment monitoring, Burning Mountains monitoring, Construction monitoring, Transportation monitoring, air quality monitoring, and Forest monitoring [3].

The rest of the paper is organized as follows. Section 2 Renewable energy resources for WSN. Section 3 Energy harvesting in WSN, Section 4 presents Energy storage devices in WSN, Solar energy harvesting WSN (SEH-WSN) is described in Section 5, whereas Section 6 describes the impact of solar energy harvesting on WSN. Finally, Section 6 draws the conclusions.

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II. RENEWABLE SOURCES FOR WSN

A. Solar

Solar energy is most widely used as an ambient source of energy because of its willing availability and constant energy scavenging abilities in day times with a demerit of its inaccessibility during the night- times or bad climate circumstances [4]. Harvested energy can even last throughout the night-time if energy is extracted efficiently. Solar energy is one of the utmost matured, familiar, propitious too amongst various renewable energy sources [5].

B. Wind

Another natural harvestable source for generating the electricity for WSN is wind. Wind can be harvested by utilizing the linear motion of the airflow by the wind turbine to generate electricity [5]. The inconsistent and unpredictable behavior of the wind is a major inadequacy which makes it unreliable. Due to this adequacy, it is difficult to harvest all the times an equivalent volume of energy. Furthermore, it may experience an electrical noise from the movement of the turbine's mechanical parts [4].

C. Heat

One of the methods for harvesting the heat energy is a thermoelectric system. In thermoelectric harvesting system, the generation of electricity is due to the differences in potential or gradients of temperature amid two poles of similar material or dissimilar material [4-5].

D. Vibration

Our surrounding is loaded with vibrations, created either by pressure, rotary motion, kinetic energy or bio-motion. By employing specific equipment these vibrations can be transformed into feasible electrical energy [5]. Mechanical vibrations can be harvested to provide power to electronic devices, such as independent WSNs, ultra-low-power microelectronic devices and portable gadgets in bio-medical applications [6].

E. RF

RF energy can be harvested from Communicating and transmitting devices like television broadcasting, cell-phones, radio towers, and Wi-Fi routers [4]. Unlike solar or wind energy, the RF energy is usable all the time for the indoor and outdoor environment, but RF radiations are reliant upon the position of the RF transmitter.

The available power, harvested power, and efficiency of some renewable resources are presented in table 1.

TABLE 1. Renewable sources of energy for WSNs [3]

Renewable sources		**Available power**	**Harvested power**	**Efficiency (%)**
Solar energy	Indoor	10mW/cm^2	10 µW/cm^2	5%–30%
	Outdoor	~100 mW/cm^2	10–15 mW/cm^2	
Vibration (Kinetic energy)	Human	0.5m at 1 Hz, 1 m/s^2 at 50 Hz	4 µW/cm^2	1%–10%
	Industrial machines	~1 m at 5Hz ~10 m/s^2 at 1 kHz	100 µW/cm^2	
Thermal energy	Human,	20 mW/cm^2	30 µW/cm^2	0.15%
	Industrial machines	100 mW/cm^2	1–10mW/cm^2	1%–10%
Radio frequency (RF energy)	Mobile phone @GSM 900MHz	~0.3 µW/cm^2	0.1 µW/cm^2	50%
	Wi-Fi	0.03 µW/cm^2	0.01 µW/cm^2	

III. ENERGY HARVESTING IN WSN

The energy from the sources is converted into electrical form by using appropriate hardware. Due to the expansion and diminutiveness of the technology, it is practicable to coordinate the energy harvesting module in pint-sized and dense sensor nodes and such types of nodes frequently alluded as Energy harvesting (EH) sensor nodes [5]. EH sensor nodes comprise of every fundamental constituent that is needed for executing the tasks, operations with a summation of energy harvesting unit which can transform the surrounding's energy into electrical form [5]. The scavenging process is shown in Figure 1.

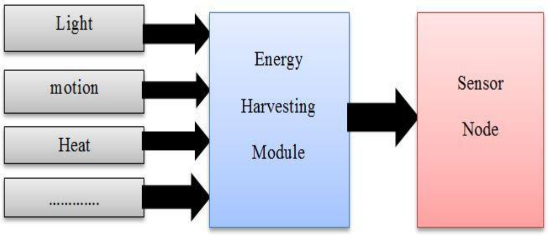

Figure 1. Energy harvesting process [5].

The transformation method applied into the energy harvesting unit relies on the kind of energy source i.e., solar for light energy, thermoelectric for heat, acoustic for sound, piezoelectric for pressure. These methods will not only surge the lifetime of the network but also lessen the need for battery replacement. The harvested energy can be used directly in a network, i.e. power unit directly utilizes the harvested energy to run the network or it can accumulate harvested energy in batteries for current and later use [5].

Figure 2 demonstrates the EH module used with the power unit and figure 3 illustrates the storage of harvested energy.

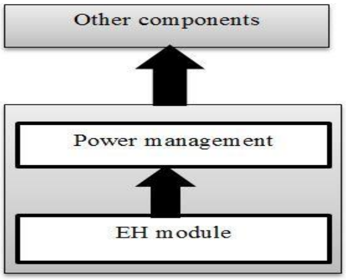

Figure 2. Harvested energy used directly [5]

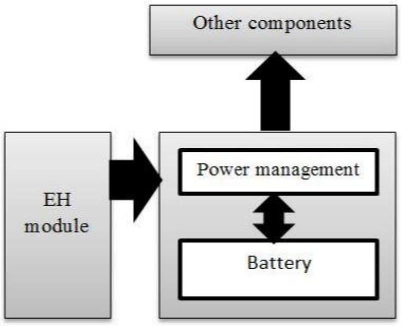

Figure 3. Harvested energy storing in battery [5]

IV. ENERGY STORAGE TECHNIQUES IN WSN

Primarily there are two types of energy storage devices in WSNs and those are batteries and supercapacitors. Generally, rechargeable batteries are utilized in SEH-WSNs.

A. Supercapacitors

Supercapacitors or ultracapacitors are electrical modules which are capable of storing and accommodating definite volumes of energy**.** Supercapacitors are utilized in the applications, where it is the necessity to reserve or release vast amounts of energy in a little period [7]. As compared to batteries supercapacitors emerged as a strong storage device for network lifetime enhancement because of large no. of charge and discharge cycles and also the storage efficiency of super-capacitor is higher than the battery. Supercapacitor has a high charging efficiency, extensive voltage, temperature evaluations, a simple charging circuit and remarkable lifetime [5]. Supercapacitors also experience excessive discharge rate as compared to batteries which is a bottleneck for WSN lifetime and the two imperfections of supercapacitor are self-discharge and charge redistribution [8].

B. Rechargeable batteries

An alternative technology for storage of energy is rechargeable batteries in WSN. This method is more matured and has high gain densities as compared to a supercapacitor. Recharging batteries are also used with solar harvesting system for the storage of energy. Some rechargeable batteries are a lead-acid battery, a nickel-cadmium battery, a nickel-hydrogen battery, lithium-ion battery, and lithium-polymer battery and comparison of these batteries are given in table 2.

Table 2. Comparison of rechargeable batteries [9].

Rechargeable batteries	Voltage (V)	Volumetric energy density (Wh/L)	The number of cycles	Self-discharge rate (%M-1)	Memory effect	Environmental protection
Lead-acid battery	2.0	60~75	250~300	5~15	No	Poisonous
Nickel-cadmium battery	1.2	110~130	300~700	15~30	Yes	Poisonous
Nickel-hydrogen battery	1.2	140~300	400~1000	25~35	Little	Harmful
Lithium-ion battery	3.7	250~360	500~1000	5~10	No	Harmful
Lithium-polymer battery	3.7	300~460	500~1000	2~5	No	Non-poisonous

V. SOLAR ENERGY HARVESTING WSN

In recent times, though, environs energy comes as an attainable addition to the network's battery in WSN where manual restoring and recharging of batteries is not pragmatic and the sun is the most reliable source of energy for the wireless sensor networks [10]. Solar energy is broadly used for harvesting energy because of its high power density, which is about $15mW/cm^3$. Solar energy is a renewable, flexible, mature and unlimited source of power. Generalized solar energy harvesting system is shown in figure 4. Nowadays solar-powered nodes are used along with WSN for harvesting purposes. Maximum power point tracking (MPPT) can also be utilized by SEH-WSN nodes to maximize the power under solar conditions.

A. REAL LIFE SEH-WSN

Some SEH-WSN nodes are:

1. *Solar Biscuit:* Solar Biscuit [12] is a dense solar powered based battery-less wireless sensor network system and it consists of a 5cm × 5cm solar panel and a 5V 1F super-capacitor, alongside with further application dependent units. Below the usual weather situations, the solar cell supplies about 20mA.

2. *Everlast:* It [13] is a supercapacitor operated, solar-powered wireless sensor node. It utilizes PFM (pulse frequency modulated) converter and open-circuit solar voltage method for MPPT, enabling the solar cell to efficiently charge the supercapacitor and power the node.

3. *Heliomote:* Heliomote [14] is a solar based battery recharging system and it is plug-and-play solar energy harvesting module for the Berkeley/Crossbow motes. Heliomote independently performs energy harvesting, storage, and power routing, and permits harvesting aware operation by providing instantaneous solar and battery-state information through a simple one wire interface [3].

Several other real life, but non-commercial SEH-WSN nodes are hydroWatch, fleck1, Sunflower, Promtheus, and Ambimax are some examples of real-life SEH-WSNs [3].

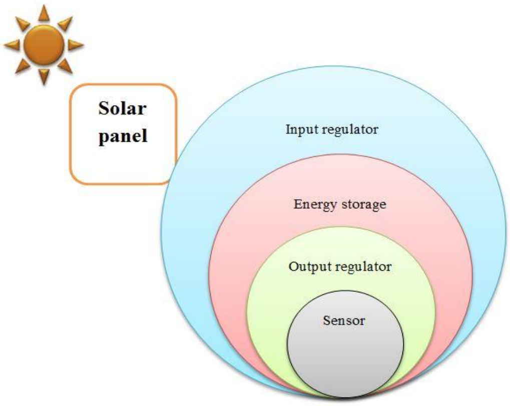

Figure 4. Generalized solar harvesting system [11]

VI. IMPACT OF SOLAR ENERGY HARVESTING ON WSN

In many uses of WSN, harvested energy can be utilized to prolong the network's lifespan, peculiarly when the necessities of a network's life make the batteries unrealistic. Solar oriented energy is an accessible, reasonable source of power to elongate the life of the network [15]. The solar energy holds the two exceptional properties given as [16]:

- **Periodicity**: Every day the sun rises and sets and this is the continuance of the harvesting cycle or charging. A fresh provision of solar energy could be anticipated through each harvesting cycle.
- **Dynamics**: Sunlight based energy changes all through the day. For the most part, it increases toward the beginning of the day and diminishes toward the evening and is missing amid the night. To boot, it fluctuates from every day, relying upon the climate and season.

Due to the battery-operated WSNs, it is impossible to concentrate simply upon the accomplishment of the wide network performance, latency or throughput since this would lessen the lifetime of the network. Suitable amounts of latency or throughput needed to be dealt against the energy in the node's batteries, thus a framework of the battery-powered WSN is designed in a way that it mainly centered on minimizing the energy expenditure to surge the lifespan of the network [10]. In recent times, solar energy has gone forth as a viable addition, to provide energy to the battery of WSNs. The accessibility of restoring the power of solar energy made it viable for nodes to function in such a manner which enriches the performance of a network, alternatively concentrated on reducing the energy utilization. In [10], the authors have designed a SolarTC algorithm which is an adaptive topology control based algorithm for solar-powered nodes. The aim of the authors was to make an effective routing scheme that maintains a balance amongst latency and energy utilization via an energy-rich (EH)-backbone network made by SolarTC and this scheme was termed as an ER-backbone-based geographical routing (ERB-GR). In this paper, the ERB-GR routing scheme was operated with SolarTC topology control scheme (represented as 'SolarTC + ERB-GR') and their results were compared with three other routing schemes given as:

- MPR routing scheme with Max power topology control scheme (max power + MPR).
- LPR routing scheme with LMST (localized minimum spanning tree) topology control scheme (LMST+LPR).
- MPR routing scheme with LMST topology control scheme (LMST + MPR).

The SolarTC scheme exhibits large duty-cycle as well as the finest performance in latency because this scheme executes adaptive energy based operations whereas others did not. The node which presently holds sufficient energy was utilized as relaying nodes and the transmission power, duty-cycle surged and notably, the latency slimmed down. The bigger is the duty-cycle, the larger is the throughput. Performance of basic SolarTC was also compared with advanced SolarTC in terms of latency and duty cycle. The advanced SolarTC showed almost the same performance as basic SolarTC but it delivers much lesser variance of the latency than basic SolarTC. The results of this paper exhibited that by controlling the ER-nodes a comparatively stable backbone network was produced by advanced solarTC, while utilizing the energy as proficiently as basic SolarTC.

[16] elucidate two energy allocation schemes, Simple Solar Energy Allocation (SSEA) scheme and Accurate Solar Energy allocation (ASEA) scheme based on time-slots, which focuses on the lessening the inconsistency in energy allotment and on the optimal employment of the harvested solar energy. The SSEA scheme was proposed for resource-restraint sensors and ASEA approach was proposed for

sensors which have an immense energy budget. Both the schemes utilized a probabilistic model which was based on former observation of harvested solar energy. The node-level energy optimization used in this paper leads to the improvement of the latency and throughput**.** Firstly, the authors checked whether the different allotment schemes worked correctly in outdoors by performing experiments. Then, they performed an indoor experiment by gathering the input values of solar energy for the comparison of different scheme's performance. Next, they selected three energy allocation schemes which were an ideal scheme, naïve scheme and the greedy scheme for the comparison with SSEA and ASEA. Several performance metrics (average duty cycle, variance of duty cycle, the ratio of all-sleeping slots, wasted solar energy) of each allocation scheme were accumulated for 10 days from all nodes. The worst duty-cycle was exhibited by the naïve scheme and because of prediction inaccuracy it squanders most of the solar energy, comparatively the high duty-cycle was exhibited by a greedy scheme. In all the aspects the ASEA scheme attained the outcomes close to the ideal scheme and SSEA comes next. Both the SSEA and ASEA exhibits almost the similar average duty-cycles which mean they enlarged the use of harvested energy even though balancing the energy given to time-slots. A comparison of the SSEA scheme and greedy scheme in terms of average end-to-end latency, the variance of latency and application layer throughput were done and the network which exhibits the better performance in all three traits was SSEA-scheme. The primary advantage of SSEA and ASEA algorithms were that they enriched the network-wide performance.

In [17], the authors have pondered the issue of information transmitted to the sensor nodes (SNs) from the base station (BS) in solar harvested aided WSNs. They propounded a solution termed as ADAPCAST (Adaptive Learning-Enforced Broadcast Policy for Solar Energy Harvesting WSNs) which was based on the analytical models for both the energy harvesting arrivals and energy consumption for each sensor node in a frame. A greedy policy was propounded to computed the optimal set of time-slots for executing the broadcast operation to reduce the minimum covering set issue. Hidden Markov Model plus Baum–Welch Estimation Maximization Algorithm to get utmost alike sequences was used to executing the broadcasting. Next the proposed solution, i.e., ADAPCAST was compared with RMBMEH (Reliable Multicast and Broadcast Mechanisms for Energy Harvesting Devices). ADAPCAST's performance was calculated with regards to ensuing metrics: broadcast count, effective energy, number of the missed node, and the broadcast delay. Afterward, the authors took three scenarios, 1) rainy weather, 2) partially cloudy and 3) and sunny. In the rainy weather, presented energy was scant whereas in sunny there was enough energy. The consequence of this paper expresses the supremacy of ADAPCAST in an amount of missed nodes, i.e., the minor number of missed nodes in entire scenarios and covered nearly all nodes in remained two scenarios. The results also showed significant furtherance in performance in aspects of average effective energy in a network, the number of missed nodes, and latency.

In WSNs, if the sensor network holds ample residual energy, then the sensor network receives a long life. Yet, it is easier to retain a high residual power of the sensor if every sensor expends energy efficiently. With progressively dynamic sensors the power utilization is higher. The power consumption can be reduced by using a scant number of nodes as possible. Thus, [18] represented an efficient node-selection system to raise the proficiency of the saving power and coverage of solar-powered WSNs in a stream environment. They classified sensors into different segments and analyzed the stream environment, including single stream and cross-stream cases. The deployment conditions were also presented, which was relevant for every stream case. This node selection strategy reduced the number of dynamic nodes, transmitted packets to prolong the lifespan of solar-powered WSN in the stream environment. The sensors were affixed along the stream side to gather the information and to send back to sink while monitoring. The results of this scheme showed that while sensors were installed along the stream sides and the finest sensor radius derived was utmost effective with the lowest energy consumption in the maximum monitoring area. Also, the Sun delivered stable energy in this paper using solar modules to the batteries of a sensor to run the entire network steadily.

As the Energy availability in Wireless Sensor Networks is a vital issue and adjusting the utilization of network's energy can be an option to increase the usefulness of the system whereas guaranteeing that not a single node goes out of vitality. Effective algorithms are necessary for calculating the solar power and for handling the energy which is needed for sensing, computing and for performing the communication tasks, to enhance the utility of solar based sensor network. Since most of the WSN tasks depend upon the power predictions therefore, the robustness and accuracy of the forecast are pivotal [15]. There are different estimation schemes which are proposed to forecast the availability of solar power. [15] also proposed a forecast algorithm: Universal Dynamic Weather-Conditioned Moving Average (UD-WCMA) which is applicable to solar-powered WSN. This scheme amalgamated the real-time measured data and a set of stored profiles signifies the energy patterns to update the prediction model. The UD-WCMA approach was based on adaptive weighting parameters which made it flexible in comparison to other existed estimation schemes. For the performance evaluation of UD-WCMA, the authors considered different scenarios for the numerical tests. The forecast accurateness of D-WCMA (Dynamic Weather-

Conditioned Moving Average) and UD-WCMA were compared to the standard methods EWMA (Exponentially Weighted Moving Average), WCMA (Weather Conditioned Moving Average) and Pro-Energy. Energy profiles were taken for different weather conditions and the number of the energy profile might vary. Here reference profiles were equal to 6. First a number of tests were done for the performance evaluation of D-WCMA and UD-WCMA algorithms with regard to the standard estimation methods. In the majority of cases, UD-WCMA performed better than other methods. An experiment was also done to implement the UD-WCMA. In the experiment, the 10 nodes were deployed for 6 months to gather the measured data and concluded that the performance of UD-WCMA was good. Constant outstanding performance and lack of tuning parameters made UD-WCMA appropriate for the applications which are based on energy harvesting alike wireless sensor networks in which the environmental parameters changed radically between the nodes.

VII. CONCLUSION

One of the principal challenges in WSN is limited battery life that limits the performance of the nodes and the network**.** To enhance the lifetime of the network energy harvesting system could be used in WSN and the mature method to harvest energy is solar energy harvesting system. We also proffered overview of renewable sources, energy harvesting system, solar harvesting system, supercapacitor and on the features of the rechargeable batteries.

In the future, the solar energy could be used with other renewable energy to make a hybrid energy harvesting system to augment the life of the WSN.

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