Journal of Wireless Sensor Networks and IoT, ISSN: 3048-8729 Vol. 2, No. 1, 2025 (pp. 50-61)
REVIEW ARTICLE
ECEJOURNALS.IN

Wireless Sensor Network Energy Harvesting for IoT Applications: Emerging Trends

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Keywords:
IoT Device Interoperability; Intelligent Transportation Systems; Smart Energy Systems; Cognitive Radio Networks; IoT Cloud Integration

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DOI: 10.31838/WSNIOT/02.01.06

Received : 14.09.2024
Revised : 20.11.2024
Accepted : 25.12.2024

Abstract

Thanks to the Internet of Things (IoT), we now live in an era of connectivity and interaction between a growing set of devices to the internet, other devices and ourselves. Wireless sensor networks (WSNs) are the core of most IoT applications and they constitute the very heart of the IoT technology revolution. Yet as these networks intensify use and become more sophisticated, they leave the one challenge behind: the question of how to power them efficiently and sustainably. Energy harvesting techniques for WSNs were born out as a game-changer of sorts, a solution that can increase the lifespan and scope of IoT devices, while leaving a light footprint on the environment. This extensive exploration covers the cutting edge of energy harvesting for the wireless sensor network, taking a look at how these innovations are set to reshape IoT applications. We will find out about a huge variety of technique, including solar and thermal energy capture, and kinetic and electromagnetic harvesting. In addition, we discuss the challenges this field presents as well as the promise of some energy storage solution and the interesting future trends for WSN energy harvesting. As the conversation unfolds, you'll hear that energy harvesting is not only a technological requirement, but a fuel that feeds innovation in the IoT landscape. These techniques are enabling longer lasting, more autonomous devices, while enabling new applications in environmental monitoring, smart cities, industrial automation, and beyond. Let's take a peek into the worlds of wireless sensor network energy harvesting, and what it could mean for IoT in the future.

How to cite this article: Weiwei L, Xiu W, Yifan JZ (2025). Wireless Sensor Network Energy Harvesting for IoT Applications: Emerging Trends. Journal of Wireless Sensor Networks and IoT, Vol. 2, No. 1, 2025, 50-61

With IoT, it's easy to understand Wireless Sensor Networks

Wireless Sensor Networks (WSNs) are the backbone for many Internet of Things (IoT) applications, as the sensory system responsible for collecting and transmitting data from the real world to the digitized world. The components of these networks are spatially distributed, autonomous sensors which can monitor different environmental or physical conditions including temperature, sound, pressure or motion. These sensors collect data and send it over wireless links to one or a few central nodes or gateways, which process, and if necessary, retransmit the information to end users or other systems. In the IoT scenario, WSNs bridge the dichotomy between physical and digital world. With real time monitoring and data collection in wide scenarios including smart homes, industrial facilities, agricultural fields and urban infrastructures. Due to its versatility, WSN has been used in more than one sector such as healthcare, transportation, environment monitoring and Smart city initiatives (Figure 1).[1-4]

One of the main benefits of the use of WSNs in IoT applications is their usage in remote or hard to reach locations. Thus these networks can be deployed in areas where it would be either impossible or impractical to deploy traditional wired systems. Because environments that have previously been inaccessible can be opened to research, conservation, and industrial

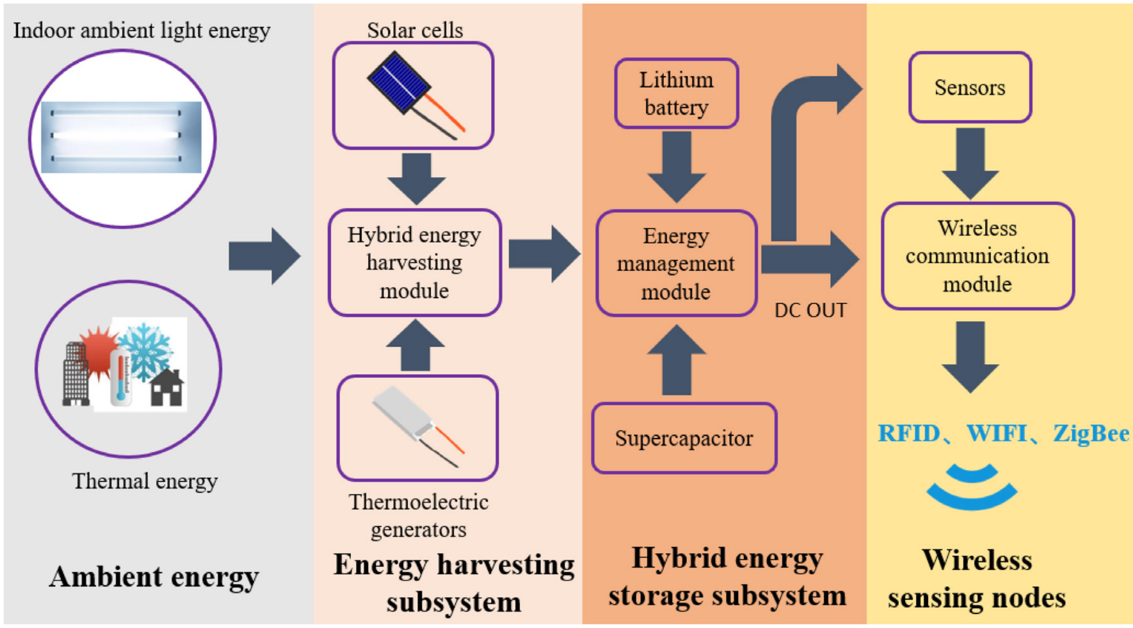

Fig. 1. With IoT, it's easy to understand Wireless Sensor Networks.

applications, this flexibility allows for complete data collection and monitoring abilities. At the same time, WSNs have the negative characteristic of the distributed nature, which makes power management difficult. Current battery powered sensors, however, have a limited lifespan, which can be problematic for large scale or long term deployments. This also means that the maintenance costs are increased as well as the scalability and sustainability of the IoT solutions are limited by the need of frequent batteries replacements. Energy harvesting techniques fill in this gap and can extend the operation life of WSN nodes and improve the overall efficiency of IoT systems. With the energy harvesting for WSNs getting more and more interesting as a topic, it is vital that we understand the relationship between these networks and the other parts of the IoT ecosystem. These techniques for energy harvesting are not just technical improvements; in fact they represent a paradigm shift in designing and building IoT solutions. Energy harvesting technologies address the power constraints of WSNs to enable more robust, sustainable and pervasive IoT technologies that can actually transform how we interact with the physical world.[5-7]

Energy Harvesting in WSNs: The Need.

The rapid proliferation of Internet of Things (IoT) devices and the expansion of wireless sensor networks (WSNs) have brought to light a critical challenge: the need for inexhaustible and energy efficient power generation devices. Traditional battery powered sensors are great in the short term, but have severe drawbacks when it comes to large scale IoT. The need for energy harvesting solutions in WSNs is explored in this section as well as how such technologies solve long standing power constraints inherent in currently deployed IoT applications. The high maintenance requirements and lack of autonomy in today's WSNs represent one of the primary drivers for energy harvesting in WSNs. However, in many IoT scenarios, sensor nodes are deployed in remote, or hard to reach, locations where frequent battery replacements are unwanted and costly. For example, environmental monitoring systems in forests or the marine environment greatly benefit from sensors which function for extended periods without human intervention. Energy harvesting techniques to provide self sustaining nodes that run on collected energy around them at all time, hence, no energy consumption.

Battery powered devices play another major role in its environmental effects. But as the amount of IoT devices grows exponentially, disposing spent batteries becomes a major ecological issue. By offering more sustainable alternative to energy harvesting technologies, we decrease dependency on disposable power sources and save the electronic waste that IoT deployment creates. That fits squarely within the recent focus on green technologies and sustainable development in the tech world. Energy harvesting solutions are also driven by the scalability of IoT networks. However, as WSNs increase in size from hundreds to thousands, or even millions of nodes, the logistical burden of keeping hundreds of batteries alive begins to spiral out of control. Energy harvesting techniques allow larger, more complex networks to be deployed without the requirement for battery replacement at regular intervals. However, the scalability provided by this technique is essential to these kinds of applications like smart city initiatives where large numbers of sensors need to monitor and control significant urban areas.[6-9]

On the other hand, energy harvesting addresses power constraints usually impeding IoT devices functionality. By operating with a consistent and renewable power source, sensors can be run more frequently, report data more frequently, and even perform more complex algorithms on site. This will enable new possibilities for edge computing and real time data analysis in IoT applications beyond what is allowed. So as we take a deeper look at how various energy harvesting techniques work and what they can do in WSNs, it becomes obvious that these technologies are solving a power problem, but in fact it's enabling a new generation of IoT applications. Harvesting techniques are providing a solution to the fundamental issue of energy supply, opening the door to more resilient, efficient, and innovative IoT ecosystems which are truly capable of driving ubiquitous sensing and connectivity.

Energy Harvesting Techniques: Overview

Energy harvesting for wireless sensor networks (WSNs) spans a wide range of techniques that extract and convert ambient energy of the environment in to useful electrical power. Different methods exist that are efficient, applicable, and exploit different types of energy sources. In this section, we present an exhaustive summary of most exploited and promoted energy harvesting (EH) techniques for WSN applications in the Internet of Things (IoT) environment. One of the most widely adopted solar energy harvesting techniques is in deployments for outdoor IoT. Photovoltaic cells take sunlight and convert it into electrical energy, providing a dependable energy source for sensors in well lit environments. However, recent developments in solar cell efficiency, as well as indoor photovoltaic technologies, have expanded the applicability of this method to more applications such as in low light indoor settings.[10-14]

However, thermal energy harvesting utilizes temperature differentials to produce electricity by thermoelectric effect. This technique is really useful in industrial IoT applications, e.g., where waste heat coming out of machine or process may be converted to useful power for sensor nodes. While thermoelectric materials and designs are continually innovating to improve this harvesting method, it can now even be viable for small temperature gradients. Knowledge of the properties of the harvested energy (kinetic, thermal) and energy sources (kinetic, thermal, chemical) is necessary to enable the connection to the grid. Piezoelectric generators, which generate electricity as a result of mechanical stress, and electromagnetic harvesters that generate power between a magnet and a coil are included. Kinetic harvesting is particularly attractive for applications with repeated vibration, e.g. industrial machinery or transportation systems.

Radio frequency (RF) energy harvesting is a developing energy harvesting technology that exploits available ambient electromagnetic waves of RF sources such as Wi-Fi routers, cellular towers, radio broadcasts. The low power density of RF energy typically precludes its use in such applications, however, increasing antenna design and power management circuit capabilities are yielding this approach more viable for low powered IoT devices in the urban setting. Although it's less common in small-scale WSNs, wind energy harvesting is being used in environmental monitoring and agricultural IoT devices. For sensor nodes deployed outdoors, micro wind turbines can generate power in open areas with consistent air movement when used as a complimentary energy source to solar harvesting (Figure 2).

Along with this comes the research in acoustic energy harvesting whereby the sound waves can be turned into electrical energy for niche applications in high noise environment. This technique is still in its infancy, but holds great promise for powering sensors in industrial type settings and in urban areas with high ambient noise levels. An active area of research in which we are interested is biohydraulic energy harvesting, or energy harvesting from biological processes or chemical reaction. And there are microbial fuel cells (MFCs) that derive electricity from the decomposition of organic

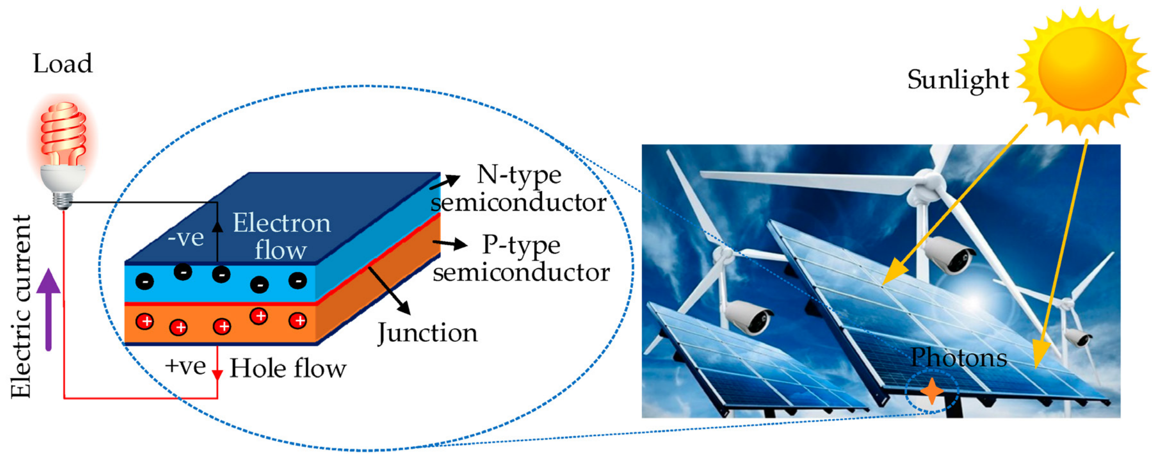

Fig. 2: Solar Energy Harvesting for WSNs.

matter and enzymatic biofuel cells (EBFC) that capture energy in bodily fluid. Each of these energy harvesting methods carries different merits and demerits and their efficiency depends on the unique environmental conditions and the relevant application requirements. With this research, we are seeing the growth of hybrid systems that combine several harvesting methods to serve as more stable power sources for WSN node. The diversity of energy harvesting techniques mirrors the multitude and different places where IoT devices live. By using a chosen harvesting method that best fits the particular conditions of each deployment, the WSNs power supply can be optimised, maintained for longer durations with better functionality. The more we delve into these techniques and their limitations, the more we realize that energy harvesting is not merely a fit for a power problem, but that energy harvesting is a central enabler for the next wave of IoT applications.[15-17]

Solar Energy Harvesting for WSNs

Wireless sensor networks (WSNs) for Internet of Things (IoT) applications are showing the emergence of solar energy harvesting as their leading power source, an environmentally-friendly and sustainable alternative to longer, wired power lines, which are becoming less and less viable as buildings become embedded with WSNs due to densely populated cities. The intricacies of the solar energy harvesting techniques are explored, their applications to WSNs, and the latest advances emerging with this technique that are pushing this technology to its limit. Photovoltaic (PV) cells are at the heart of solar energy harvesting, and convert light energy into electrical energy through the photovoltaic effect. For outdoor applications, traditional silicon based solar cells have been long standing standard but during recent years have experienced significant improvements in efficiency and cost effectiveness. Today, conversion from sunlight to usable electricity is more efficient by high efficiency monocrystalline and polycrystalline silicon cells, and so they increasingly become more viable for compact WSN nodes on limited area.

The predictability and abundance of solar energy harvesting in outdoor environments makes it one of the key advantages for solar energy harvesting in WSNs. Reliable generation of power in agricultural fields, urban infrastructure monitoring, or environmental observation stations can be achieved with sensor nodes oppositely deployed using solar cells to provide power during daylight hours and batteries or cyclocapacitors for nighttime operation. It provides predictability for more efficient power management strategies: nodes can determine which duty cycles and data transmission schedules to use that are most likely to maximize power availability. Thin film solar technologies continue to advance, opening the door to new opportunities for flexible and light weight solar harvester systems. And they can be more seamlessly integrated into the design of the sensor node, such that their deployment is possible in a wider range of environments and in form factors.

Progress toward indoor solar harvesting has also been made to meet the energy autonomous sensor requirements of smart buildings and industrial IoT. However, indoor PV cells have now been designed and fabricated that are specialized for artificial light sources and can generate usable power from ambient indoor lighting, albeit with lower efficiency than outdoor solar. Of particular value for WSNs operating in indoor environments such as office buildings, warehouses, etc., where battery replacement would be cumbersome in traditional environments. Solar energy harvesting integration with other power management technologies is improving the efficiency and reliability of WSN nodes. Solar cells are continuously operated at best voltage and current levels of maximum power point tracking (MPPT) algorithms to extract the maximum amount of energy under varying light conditions. And such autonomous sensor nodes, which can operate forever as long as they have solar harvesting combined with energy-efficient microcontrollers and low power wireless protocols, are possible.[18-20]

However, solar energy harvesting using solar panels continues to pose challenges for their broad acceptance in WSNs in environments with little or inconsistent sunlight. These problems are being tackled towards various paths, such as the development of hybrid energy harvesting systems using solar, as well as other methods such as thermal, or kinetic harvesting. More consistent power generation is achieved over a broad spectrum of environmental conditions for these multi modal systems. Looming in the future is the potential for even higher efficiencies and lower costs from emerging technologies like perovskite photovoltaics. However, these next generation solar materials may enable next generation solar energy harvesting for WSNs with superior performance in low light conditions and more easily integrated into sensor node designs. Along with this, solar energy harvesting technology is set to have a larger role to play in powering WSNs for IoT applications. This combination of increased efficiency and decreasing costs plus innovative integration strategies is making groundings solar powered sensor nodes a more attractive solution to a variety of IoT deployments. This trend not only responds to the power limitations of WSNs, but also coincides with the wider effort towards sustainable and green IoT.

Thermal Energy Harvesting Innovations

With the advent of Internet of Things (IoT) applications, thermal energy harvesting has been raised as a promising technique for supplying power to wireless sensor networks (WSNs), especially in the case where temperature differentials are easily available. It then looks at the most recent breakthroughs in thermal energy harvesting, its applicability in WSNs, and the prospects for using the same to build self-sustained IoT devices. The thermoelectric effect is the heart of thermal energy harvesting wherein temperature differences can be directly converted into electrical energy. This principle is exploited by thermoelectric generators (TEGs), which usually consist of arrays of thermocouples that we are told are of semiconductor materials. The electrical current generated by a temperature gradient induced when one side of the TEG is subjected to a heat source & the other to a cooler temperature.

In recent years, much progress had been made in thermoelectric materials, and the efficiency of thermal energy harvesting had been significantly increased. Newer compounds and nanostructured materials, that are higher thermoelectric figures of merit (ZT), measures of how well a material performs as a thermoelectric, are being developed by researchers. Bismuth telluride alloys and skutterudites are demonstrating performance promise for boosting the output power of TEGs to make them a more feasible power source for WSN nodes with low temperature differences. Development of flexible and thin film thermoelectric generators are one of the major innovations in thermal energy harvesting for WSNs. On the other hand, these devices can be able to fit curved surfaces, or can have been integrated directly into sensor node housings, making heat capture from many sources more efficient. Flexible TEGs are ideal for wearable IoT applications, which are capable to harvest body heat for power health monitoring sensor .[21-22]

Integration of thermal energy harvesting with other power management technologies improves its effectiveness for WSN applications. Power conditioning circuits with advanced capability and maximum power point tracking (MPPT) algorithms are being developed to improve the energy extraction from TEGs operated under different temperature conditions. These systems assure the thermal energy harvested will be efficiently converted and stored so as to increase the lifetime of sensor nodes. Thermal energy harvesting innovations are a prime target for industrial IoT applications. In the manufacturing environment, thermal energy is available from waste heat taking place on the machinery and in the processes. TEG equipped WSN nodes have the ability to utilize this waste heat to power sensors monitoring the equipment performance, environmental conditions, or process parameters. It doesn’t only meet the power requirements of the sensors, but also helps to improve the overall efficiency for the energy by converting heat that would otherwise be lost.

Another area in which thermal energy harvesting is gaining ground is environmental monitoring. Temperature differentials between air and soil, or between various liquid levels in aquatic environments, can be used by sensors deployed in remote locations to power themselves. This is especially useful for long term monitoring project where battery replacement is either impractical or cost prohibitive. Along with this, researchers are investigating hybrid energy harvesting systems involving more than thermal techniques. Computational modeling was used to analyze power supply from solar thermal hybrid harvesters that generate power from either light or heat, yielding a more uniform energy source in different conditions. In particular, outdoor WSN deployments in diverse climates are particularly promising to be served by these multi-modal approaches.

Although there exist challenges in scaling thermal energy harvesting for large area WSN use cases, notably in environments with low or highly unsteady temperature gradients, there also exist opportunities for using them in smaller areas. For that, researchers are building up more sensitive TEGs that could work work properly under the conditions of low temperature gradients. Also, efforts have been made to improve the sensor node's thermal management to maximize the temperature gradient over TEG and thus increase overall energy harvesting efficiency. The future looks bright for thermal energy harvesting for WSNs in IoT applications. Phonon engineering and topological materials offer even more promising promising ways to create more efficient thermoelectric devices. With these innovations developing further, we can expect the number of self powered WSN nodes in an IoT scenario to grow from smart buildings and industrial automation up to environmental monitoring and wearable technologies.. The ongoing developments in thermal energy harvesting are not incremental advances in technology. But a much needed change towards more sustainable and self reliant IoT ecosystems. These innovations harness waste heat and ambient temperature differentials to create a new generation of WSNs that are more energy efficient and environmentally friendly, with a direct impact on the larger sustainable technology development as part of the IoT landscape.[23]

Kinetic Energy Harvesting Techniques.

As a versatile and promising approach to power wireless sensor networks (WSNs) in IoT applications, kinetic energy harvesting has gained attention. This technique converts the mechanical energy generated by motion, vibration or deformation into electrical energy and can provide a sustainable power supply for sensor nodes in dynamic environments. We begin by looking at the state of the art in kinetic energy harvesting, its use within WSNs, and the recently developed means of exploiting its full potential. Piezoelectric generators are at the forefront of kinetic energy harvesting materials that generate an electric charge when exposed to mechanical stress. More recently, recent innovations in piezoelectric materials — such as lead free compositions and nanostructured ceramics — have vastly improved the device efficiency and environmental friendliness. Piezoelectric harvesters are being developed to harvest energy from a range of motions, from low frequency human activities to higher frequency industrial vibrations.

Another important category for kinetic energy harvesters are electromagnetic energy harvesters. Devices in these cases generally consist of a magnet moving with respect to a coil, inducing a current in the coil by electromagnetic induction. The power output of these harvesters is being improved by advancements in magnet technologies and coil designs with improvements in power has made them more viable for WSN applications. A variety of micro-scale electromagnetic harvesters that are well suited for integration into compact sensor nodes, and that can generate power from even slight movements or vibrations, are developed. Kinetic energy harvesting is an emerging technology, and one of the candidates is that of tricobelectic nanogenerators (TENGs). These devices are based on the triboelectric effect, i.e. the charging of a material is generated by separating it along with other materials from the one with which it had been brought into contact. Compared to conventional energy harvesters, TENGs possess great promise for the harvesting of energy from many human activities and environmental sources, with high power density and flexible design (Table 2).

The matching of the harvester's resonant frequency to the dominant frequency of the ambient vibrations is one of the key challenges in kinetic energy harvesting. To achieve that, researchers are developing broadband and multi modal energy harvesters to capture energy over a wide range of frequencies. Frequency up-conversion techniques or arrays of harvesters tuned to different frequencies are used in these adaptive systems to generate a more

Table 2: Key Advantages of Energy Harvesting for Wireless Sensor Networks

Advantage	Benefit
Sustainability	Sustainability reduces reliance on battery replacements and minimizes waste by using renewable energy sources, contributing to long-term network sustainability.
Cost Efficiency	Cost efficiency lowers operational and maintenance costs by eliminating the need for frequent battery replacements, especially in large-scale IoT deployments.
Autonomous Operation	Autonomous operation enables IoT devices to function independently without external power sources, increasing deployment flexibility and scalability in remote areas.
Extended Lifespan	Extended lifespan reduces the need for servicing IoT devices, allowing for longer operational periods in hard-to-reach areas without maintenance interruptions.
Environmentally Friendly	Environmentally friendly energy sources, such as solar and wind power, reduce the environmental impact of traditional battery-powered devices in IoT networks.
Wireless Operation	Wireless operation enables fully autonomous and wireless IoT sensor networks, ensuring ease of deployment without the need for complicated power cabling or connectors.

consistent power generation in variable environments. We open the door to new IoT domains related to WSNs where kinetic energy harvesting is integrated with WSNs. Vibration energy harvesters mounted on machinery can power sensors to monitor equipment health and performance, this fostering predictive maintenance or better operational efficiency. They also comprise self-powered sensors that mean there is no replacement of batteries where these are hard to reach in industrial plants.[24]

Kinetic energy harvesters are currently being used in transportation and infrastructure monitoring to power WSN nodes in bridges, railways and vehicles. Such systems can capture energy from vibration caused by traffic or structural movement, and can be used to power sensor observation of structural integrity, traffic flow, or environmental conditions on a continuous rather than a scheduled basis. Kinetic energy harvesting is another cool area to use wearable IoT devices. Harvesters that are flexible and stretchable enough to be an intrinsic accessory or garment are being developed to harvest energy from the body's bounces and movements and send the power to health monitoring sensor and device batteries. Developed with great promise as a way to create truly autonomous wearable IoT systems without frequent recharging.

Advancements in kinetic energy harvesting are also reaching smart buildings and home automation systems. Sensors that monitor occupancy, control lighting or climate systems can be powered by energy harvesters, which capture energy from everyday activities, from door hinges, floor tiles or window frames for instance. This also reduces reliance on batteries and, in turn, helps to increase the total number of functions that buildings can perform with lower energies. The integration of kinetic energy harvesting with other emerging technologies should looking to the future given the possible. For example, by using kinetic harvesters in combination with artificial intelligence algorithms it is possible to obtain more adaption and more efficient energy management systems. It is possible to design these smart harvesters to predict energy availability from patterns of motion or vibration and power consumption of WSN nodes to match. With increasing advances in research in kinetic energy harvesting, we are sure to see even more expansive application in the IoT landscape. Kinetic energy harvesting is poised to be important for the next generation of WSNs from self powered sensors in smart cities to autonomous environmental monitoring systems in remote locations. This technology is not only addressing the power challenge, but also opening a pathway to exploration of paradigm changes in sustainable, pervasive sensing for IoT applications by tapping nature's ubiquity of motion and vibration everywhere.[25]

Electromagnetic Energy Harvesting Advancements

Energy harvesting from electromagnetic sources has recently been seen as a very promising approach to power wireless sensor networks (WSNs) in the Internet of Things (IoT) ecosystem, especially in ambient electromagnetic rich environments. Detailing recent progress in electromagnetic energy harvesting, its use in WSN applications, and new approaches to capture this easily available source of energy, this section explores this development. Directly at its core, electromagnetic energy harvesting entails that some electromagnetic fields are captured from the ambient and converted to useful electrical power. This technique basically deals with collecting the radio energy from Wi-Fi router, cellular tower, and broadcasting transmitter. The recent antenna design and rectifier circuit advancements have greatly increased the RF energy harvesting efficiency and are now viable power sources for such low power IoT devices.

The wideband and multi band antennas developed in this area constitute one of the innovations in this field by which the energy can be harvested for a wide spectrum of frequencies. With the introduction of these advanced antenna designs, WSN nodes can harvest energy from several RF sources at once, resulting in an overall increased power harvested. For the applications such as small IoT devices, researchers are trying metamaterial based antennas and fractal antenna designs that will provide better efficiency and compact form factor. Imperfections in rectenna technology, which combine antenna with rectifying circuit for converting RF energy to DC power, are greatly improved. To maximize the RF energy captured, high efficiency rectifier circuits using Schottky diodes or CMOS based rectifier circuits are being developed. Their existence is pushing the boundaries of what is possible in terms of power output from ambient RF fields, which are making electromagnetic energy harvesting more and more practical for WSN applications.

The integration of other power management technologies off with electromagnetic energy harvesting is making its effectiveness better in WSNs. Development work is being continued on adaptive power management systems that can change the sensor nodes' operating mode based on the available harvested energy. Often these systems incorporate energy storage elements such as supercapacitors or thin-film batteries to store excess energy to use during time of low power availability. Electricity generation using electromagnetic harvesting has particularly attractive prospects given the dense networks of wireless communication systems typical of urban environments. The ambient RF energy can be used to power sensors deployed in smart city applications — monitoring air quality, traffic flow or infrastructure health — in WSN nodes. In addition, this approach not only supports the power requirements of these sensors, but also reduces the batteries needed for smart city applications, an aspect that helps make the initiative sustainable.

Electromagnetic energy harvesting is recently gaining foothold in industrial IoT settings to power sensors in environments where not traditional power sources are feasible. For example, sensors monitoring equipment in a hazardous or inaccessible area can extract RF energy from nearby wireless communication systems and then power the equipment without the requirement of a wired power connection, frequent battery replacement, etc. Electromagnetic energy harvesting is also making serious advances in the healthcare sector. Harvesting RF energy from patient's surroundings can potentially power the implantable medical devices and wearable health monitors, potentially eliminating the need for invasive procedures to replace the batteries. Features of this technology point to its potential to enable long lasting, autonomous medical IoT devices that can continuously monitor patient health without the limitation of battery life.

They are also investigating whether combining electromagnetic energy harvesting with other harvesting techniques could make for hybrid energy systems. For example, the integration of RF harvesting with solar or thermal harvesting offers a more reliable and autonomous power supply to WSN nodes that vary in ambient conditions. With this trend, it is expected that the density in the wireless communication network will rise as well, which would increase the chances to harvest electromagnetic energy. Due to the higher frequencies and denser networks presented by future 5G and beyond networks, new paths for RF energy harvesting may be opened up to the point where the power available to WSN nodes could increase. Nevertheless, the ability to scale electromagnetic energy harvesting for general WSN applications is limited due to low RF energy density in many places. This has motivated researchers to develop ultra low power sensor node designs capable of operating with minimum harvested energy. More, meanwhile, are being done to increase the overall system efficiency, between capture of harvest RF energy and storage and use of it to reach such usable power. The future of electromagnetic energy harvesting for WSNs in IoT and MN applications looks promising. The likelihood of RF energy harvesting increases as wireless communication technology matures and proliferates. Not only does this technology provide a solution to the power restraints of WSNs, it also fits within an arising industry trend towards sustainable and energy efficient IoT deployments. It is in tapping into the ubiquitous electromagnetic fields surrounding us that electromagnetic energy harvesting is leading the path of the way towards creating a new wave of self sustainable autonomous WSN nodes to power the AIoT revolution.

Harvest Power Energy Storage Solutions

Due to the ongoing advancement of energy harvesting techniques for wireless sensor networks (WSNs) in Internet of Things (IoT) applications, the demand for an efficient and reliable energy storage solution is becoming more and more important. They fill the gap between the intermittent energy harvesting of the solar array and the continuous power necessities of the WSN node. This section reviews recent progress in energy storage technologies geared for harvested power in WSN, and discusses their potential impacts on future IoT. In particular, ultracapacitors, or supercapacitors, have been explored as a promising energy storage solution for harvesting powered WSNs. First of all, these devices have a number of advantages over traditional batteries, they have a very high power density, they are fast charging and discharging, and their life is long. In recent times, the effort to improve energy density and lower self discharge rates in supercapacitors has been a focus for the technology. Supercapacitors are currently based on commercially available electrode materials, but researchers are developing new materials, including carbon nanotubes and graphene, that vastly increase supercapacitor capacity and efficiency.

A development of hybrid energy storage solutions has arisen from the integration of supercapacitors with energy harvesting systems. These systems consist of supercapacitors with high power density and batteries with high energy density, in a balanced approach to energy storage for WSN nodes. Efficient energy capture and storage from intermittent sources is combined with stable power capability to the sensor node to maximize overall system performance. Another innovative storage solution of harvested energy in WSNs is thin film batteries. As these ultra thin, flexible batteries can be easily integrated into the design of sensor nodes, they provide a compact, light weight energy storage option. In recent years, however, a great deal of development has been focused on the direction of improving energy density, cycle life, and manufacturing processes of thin-film batteries. Solid state electrolytes and advanced cathode materials are being pushed to increase the performance and safety of these batteries that now become increasingly attractive for IoT applications.

Meanwhile, a design of WSN nodes powered by harvested energy has encountered the concept of energy neutral operation. The objective of this approach is to harvest energy on par with the energy consumed and maintain long-term sustainable operation. New energy management systems that can dynamically adjust the amount of power a node can consume are being developed and that depends on the amount of available harvested energy and storage levels. Often, these systems utilize predictive algorithms to predict future energy availability to best utilize on board stored energy..

Design solutions are actively searched for micro scale energy storage solutions for ultra compact nodes in WSN. The batteries and capacitors researchers are developing are miniaturized, and may be directly integrated into a housing for a sensor chip or some such package. These microscale storage devices are based on MEMS (micro electro mechanical systems) technology and have the potentiality for truly autonomous low energy consumption IoT sensor devices.

Integration of energy storage with energy harvesting and power management circuits is resulting in the development of complete power management integrated circuits (PMICs) for the WSN nodes. For these all in one solutions, energy harvesting, storage and power regulation functions are integrated into a single chip, making sensor node with energy autonomy design and implementation easier. Features included in advanced PMICs are maximum power point tracking (MPPT) for achieving the best energy harvesting from the environment as well as intelligent power distribution to optimize the usage of stored energy.

Solid-state batteries, an emerging technology, is promising for next generation energy storage in WSNs. The improved energy density, safety, and possibly increased cycle life of these batteries compared to traditional lithium-ion batteries enable their use. However, solid state battery technology continues to mature and, if so, may offer a more reliable and energy efficient means of energy storage for WSN nodes operating in challenging environments. Energy storage solutions are also an important consideration in developing sustainable IoT systems, and their environmental impact is also of great concern. Through research into eco friendly materials and manufacturing for WSN battery and supercapacitor manufacturing, we work towards the reduction of the environmental footprint of WSN deployment. The development aligns with overarching goals of sustainable technology development in the area of biodegradable, recyclable energy storage solutions. As WSNs enter diverse and challenging environments, robust and adaptable energy storage solution becomes more critical. Storage systems that can work well over a wide range of temperatures and environmental conditions are being developed by researchers. Such performance in extreme environments is ensured by the use of specialized electrolytes and protective encapsulations.

The integration of energy storage systems with artificial intelligence and machine learning algorithms may look to the future. Such smart storage solutions could learn about usage patterns and environmental conditions and optimize (store and distribute) energy for WSN nodes further enhancing their (WSN) node autonomy and efficiency. What the various energy storage solutions for harvested power imply are not just technical improvements, but rather a paradigm change in how we optimize WSNs for IoT applications through design and deployment. These innovations are enabling development of truly autonomous and sustainable sensor networks through the provision of reliable and efficient means for storing and utilizing harvested energy. We can also expect the complex of energy storage solutions to become increasingly sophisticated and synergistic, taking the leading role in the next generation of IoT-based devices and applications.

Future Directions and Challenges

Looking towards the future, several promising directions are emerging in the field of energy harvesting for WSNs:

1. Multi-source energy harvesting: We expect that future WSN nodes will employ different forms of harvesting technologies to concurrently harvest energy from multiple environments. More reliable and autonomous sensor nodes can be achieved based on this approach through more consistent power generation over a wider range of conditions.
2. Integration of artificial intelligence: In WSNs, it is expected that AI and machine learning algorithms will be critical for the optimization of the energy harvesting and management. Tools developed from these technologies can be used to perform predictive energy harvesting, adaptive power management, and intelligent load balancing yielding the most efficient usage of energy in sensor networks.
3. Advances in materials science: Research in that area focuses on developing new materials with higher energy harvesting properties. We explore the use of novel piezoelectric materials, high efficiency photovoltaic compounds, and advanced thermoelectric materials that can enhance energy harvester performance.
4. Wireless power transfer: Integrating wireless power transfer technologies with energy harvesting system opens up the possibility of powering WSN nodes in difficult environment. It could involve the use of dedicated RF power transmitters or the embedding of the transcutaneous-sensor chip in such a manner that it receives ambient RF energy to supplement other harvesting methods.
5. Energy-aware communication protocols: It is believed that energy harvesting will become an important element in future WSN protocols, as they will be designed in such a way that accept or rely on energy availability in routing decisions and data transmission decisions.

The lack of energy resources for wireless sensor network (WSN) applications within Internet of Things (IoT) imposes unique challenges for this field of energy harvesting while also offering exciting new opportunities for future application development. We present this section through the lens of the current hurdles in energy harvesting solutions for WSNs, and the upcoming trends and future paths which shape the power management landscape of IoT. Energy sources in WSNs are highly variable and unpredictable, which makes one of the primary challenges in energy harvesting for WSNs. Solar, thermal and kinetic energy sources vary wildly based on environmental conditions, time of day, or user activity. This variability makes power supply to sensor nodes highly variable making it difficult to guarantee that the sensor nodes will always have their power supply. To overcome this challenge, researchers devise more sophisticated energy prediction algorithms and adaptive power management systems capable of executing power management with some optimality on available energy. The main hurdle for the efficiency of energy conversion is still significant, especially for small scale harvesters suitable for compact WSN nodes. While the technologies used to harvest have progressed to some extent, there remains a large difference between maximum and actual efficiencies in real world applications. Currently, research is ongoing to improve system performance through development of novel materials, optimization of design, and enhancement of power conditioning circuits.

Conclusion

Another challenge is miniaturized energy harvesting and storage components in the context of devices with ultra or implantable sensors. This is particularly true as small IoT devices that integrate increasingly more capability are also being made smaller. This challenge has spurred research into micro and nano scale energy harvesting technologies and compact energy storage solutions that fit in such tiny sensor packages. Limitations of cost effectiveness of energy harvesting solutions over traditional battery operated systems prevent widespread adoption. However, the upfront investment in harvesting and storage technologies can be greater than conventional power sources in reducing long term maintenance costs. Paralell efforts are made to develop more cost effective manufacturing processes and material to make the energy harvesting solutions economically viable for large scale WSN deployment.

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