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Study on IoT networks with the combined use of wireless power transmission and solar energy harvesting

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Abstract. The efficiency of Internet of Things (IoT) mobile networks is limited by the battery's capacity in IoT devices. In addition to their replacement/recharge problem, batteries delimit devices' processing and data forwarding capabilities, hence degrading the performance of IoT networks. Recent advances in Wireless Power Transmission (WPT) technology provide an attractive solution, namely Wireless Powered Communication (WPC), in which wireless devices are charged through wireless power transmitters. However, the design and prospect of WPC applications are challenged by the poor efficiency of long-distance WPT. On the other hand, solar energy harvesting is a conventional and natural method for conveying energy wirelessly to devices. This article reviews WPT technology as well as solar energy harvesting and investigates their challenges in IoT networks. It is shown that smart integration of these two energy supply methods to power IoT networks wirelessly leads to more efficient WPCs called green WPC. Three frameworks for green WPC have been investigated in this article. These methods are simulated and analyzed in a network and energy model in separate scenarios. Green WPC is a potential solution to create networks with a longer lifetime and higher reliability and flexibility than conventional battery-based methods.

Keywords. Wireless power transmission; Internet of things; solar energy harvesting; green wireless power communication.

1. Introduction

In wireless networks, the devices transmit information to each other without being physically connected. The ability to establish a distributed network of small and mobile devices is an essential advantage of such networks. Batteries have been used as an energy source in mobile wireless devices since the emergence of these networks.

The Internet of Things (IoT) is a paradigm that connects different objects around us to the Internet. IoT can provide advanced and diverse services by enabling data transmission, collection, and processing by objects without human intervention [1]. IoT is used today in various fields such as e-health, smart cities, smart home, smart buildings, and other sensing and monitoring applications [2–4]. Currently, the IoT has attracted much attention as the main architecture of the next-generation mobile communication system [5]. Meanwhile, most devices in IoT have limited resources, including battery power. Hence, one of the biggest challenges for expanding IoT in the future is overcoming the power constraints of IoT devices [5]. Considering the large number of IoT devices in use, frequent replacing/recharging batteries is often expensive and even impossible in many important cases, such as sensors in structures and implantable medical devices [6–8].

Several works have been done on analyzing IoT network energy consumption [9]. Much work has suggested energy reduction techniques of IoT devices in order to prolong their lifetime, such as sleep scheduling [10], use of clustering approach to reduce the transmission distance of IoT devices [11, 12], shifting computation load to the cloud [13], and implementing low-power communication protocols [14–16]. But in any case, the battery lifetime is limited. Today, the focus can be on permanent wireless power sources, which can ensure that the devices always remain operational and network connections remain stable.

For accomplishing this goal, Wireless Powered Communication (WPC) has arisen in recent years as a promising candidate. The wireless nodes in WPC use Wireless Power Transmission (WPT) technology and can be equipped with hardware with the capability of extracting energy from wireless signals, which means that their batteries can be recharged anywhere without being physically connected [17]. Wireless power transmission means the transmission of electrical power from one place to another without using any wire or physical connection.

WPC networks can be used in many applications where wireless devices need low power to operate. Research

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shows that these networks are an important component of many popular commercial and industrial systems in the future, including IoT networks, which comprise a lot of devices, sensors, and RFID tags.

This article aims to investigate two key technologies for providing energy to low-power devices in an IoT network without any physical connection. The first solution is WPT through power transmitters. In such solutions, a power transmitter, which can be a network access point (AP) or a separate device, transmits power to recharge the battery of network devices without wire [18, 19]. Another competing technology is solar energy harvesting, which has been used for many years to supply electricity in various applications [20]. Solar energy has been proposed as the source of power for wireless network devices in some studies [21–24].

There are several studies in the literature that have examined either WPT or solar energy harvesting in wireless networks. Studies indicate that scarcity of proper frequency band and intense reduction of power transfer efficiency in the distance are some major challenges for WPT solutions in wireless networks [25]. On the other hand, solar energy harvesting is not always suitable as the only source of energy for wireless devices due to its dynamic nature [12]. While fewer studies have addressed the simultaneous use of these two technologies, this article focuses on combinations of these two methods. This article shows that a smart combination of these technologies can be an effective solution for higher power efficiency and lead us to green and self-sustaining WPC networks. This article examines the solutions for simultaneous application of these technologies considering the situation and available facilities in IoT networks and divides the existing studies into three categories based on the combination of these two technologies.

The main contribution of the article is elaborated as follows:

- A comprehensive classification of WPT technologies is provided that also includes the latest methods introduced.
- We provide WPC architecture in IoT networks by considering different components of the network.
- We investigate the two-way relationship between IoT and solar energy harvesting.
- Furthermore, we categorize three possible methods to combine the two methods of energy harvesting to achieve green self-sustainable IoT networks. We also provide simulation assessments and qualitative comparisons among these categories.

The continuation of this article is as follows: Section 2 presents the methods, models, and challenges of WPT in IoT networks. Section 3 deals with environmental energy harvesting methods with an emphasis on solar energy harvesting. The simultaneous applications of the two power harvesting methods are discussed in section 4. In section 5, network and energy models are provided as a case study, and then three scenarios considering the three integration methods are simulated and discussed. Conclusion and future directions are drawn in section 6.

2. Wireless power transmission in IoT

The main difference between WPT and wireless information transmission is in transmission efficiency. In telecommunication systems, although a radio frequency (RF) signal is received at the receiver, the electric power generated in the receiver circuit is very low. However, due to the purpose of data extraction from the received signal, low transmission efficiency is not a major issue. On the other hand, sufficient efficiency of power transmission is an important issue, and in fact, the main purpose of power transmission. Therefore, the methods used in telecommunication systems cannot be used for power transmission.

2.1 *WPT methods*

Although WPT has popularized in recent years, it has been developing for more than a century [6]. Generally, there are two main types of WPT: radiation (based on electromagnetic waves) and non-radiation (based on coupling) [17, 26–32]. Non-radiation wireless charging, such as inductive coupling and magnetic resonance, is the most suitable solution for power transmission over short distances, which can provide high power and also higher power conversion efficiency. In contrast, wireless radiation transmission, which uses RF waves, is suitable for long-distance transmission.

The classification of different types of wireless power transfer (WPT) technologies is shown in figure 1. As can be seen in this figure, for a wireless network which the power transmitter can reach near the network devices, non-radiation methods can be utilized. On the other hand, the radiation method can be used to transmit power in WPC networks to low-power devices that are not near the power transmitter. In practice, the radiation method uses inexpensive power receivers that can be flexibly placed and fit in very small commercial IoT devices. Furthermore, due to the propagation of electromagnetic waves, power can be easily transmitted to multiple receivers at the same time. The main limitation of this method is that radio waves severely attenuate with distance. However, it is expected that as the power requirements of the devices continue to decrease (as little as a few microwatts for some RFID tags) and with the recent application of multi-input multi-output antenna (MIMO) technology, which significantly increases the wireless power transmission efficiency, many more applications can be expected to be equipped with the radiating type of wireless energy transmission in the future [6, 18].

Table 1 shows the different characteristics of the main WPT techniques and their applications.

2.2 *WPC architecture in IoT networks*

It is predicted that future wireless systems will be a combination of wireless information transmission and wireless power transmission, and WPC is, in fact, an important technology for the next generation of networks. The architecture of WPC IoT networks with the use of WPT along with information flow is explained in this section.

IoT networks include IoT devices (ID) such as sensors and RFID tags. Two types of access points (AP) can exist in IoT networks. The information AP is a device in the infrastructure-based wireless network that all information signals are sent and received to/from it. This AP is used as the gateway to the Internet. The power AP is a power transmitter equipped with a stable power source to transmit power to IDs.

There are two types of power transmitters in terms of motion: fixed power transmitter, which is deployed in a fixed location such as base stations [33–35], and mobile power transmitter, which is deployed on a moving vehicle. Some studies considered the use of drones [22, 36–39], while some other use terrestrial mobile charging vehicles to move inside the wireless network in order to resolve the charging needs [12, 40–42].

In a network with distributed IoT devices, If the non-radiation methods are used as the WPT method, mobile transmitters will often be used due to the need for proximity between the transmitter and receiver. On the other hand, both fixed and mobile transmitters have been considered in the studies with the RF signal transmission method.

Mobile transmitters can go near power-hungry devices thus have higher power efficiency due to shorter distances. Arial transmitters are more convenient to create line-of-sight links with IDs. However, how the mobile power transmitter moves among the IDs in order to provide on-demand services is a new challenge [37].

In [19], relays have been used between fixed access points and network nodes. This study has shown that the use of relays has an effective role in both energy and information transfer. Mobile energy transmitters are known as relays in some studies because they cannot be the source of energy themselves. Due to their limited energy, these transmitters must return to their station for charging before they are powered off [38]. Also, a significant part of their energy is spent on their movement. The mobile transmitters can also play the role of a data collector in the network. This approach has advantages compared to the conventional data forwarding approach, including more uniform energy consumption of wireless devices [43].

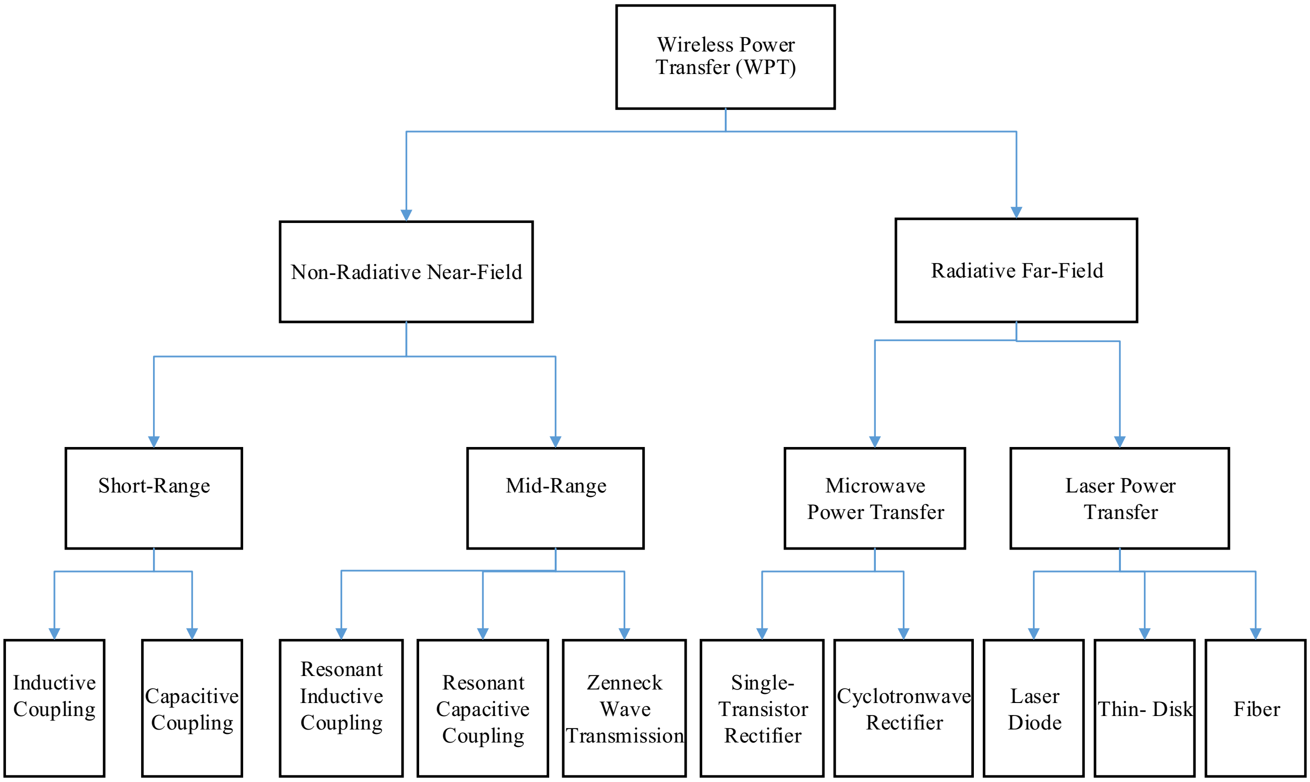

Figure 1. The classification of wireless power transfer technologies.

Table 1. Comparison of the main wireless power transfer (WPT) technologies.

			Frequency	Advantages	Disadvantages	Applications
Non-radiative	Short-range	Inductive coupling	kHz–MHz	Efficiency $> 90\%$, Power transfer up to several kilowatts	Limited distance from cm to m	Low power smartphones to high power electric vehicles (EV), induction stovetops, and industrial heaters
		Capacitive Coupling	Hz–MHz	Power transfer up to several kilowatts, efficiency at the range of 70%–80%, though it can reach 90% in some applications	Short distance within the hundreds of mm range	Small size applications, charging portable devices, but also can be used in large size applications, such as EV, Smartcards, biomedical implants
	Mid-Range	Resonant Inductive Coupling	kHz–MHz	90% to 30% efficiency for distances of 0.75 m to 2.25 m	The transmission power needs to be improved, high cost	Mobile phones, medical sensors, and implantable devices
Radiative		Microwave power transfer	GHz	Long effective transmission distance up to several km, potential to transfer several kilowatts power	biological harmfulness, great interference to communication equipment, Low efficiency less than 10%, complex implementation	Satellite and spacecraft, suitable for mobile applications
	Far-field	Laser Power Transfer	> THz	Long effective transmission distance up to several km, Flexible device, potential to transfer several kilowatts power	Low efficiency around 20% or less, line-of-sight to the receiver	powering drone aircraft, powering space elevator climbers, suitable for mobile applications

Figure 2 shows some network models to better illustrate WPC in IoT networks. The APs and relays are assumed fixed. As seen, power APs and information APs exist in the networks. IDs can use the received power from power AP to send information to the uplink information AP (such as ID1 sending data to AP2 in figure 2(a)) or to receive information from the downlink information AP (such as ID2 receiving data from AP2 figure 2(a)). Moreover, APs of power and information can be located in a joint power-information AP called hybrid AP (for example, AP1 in figure 2(b)), which both transmit power and provides information access to IDs.

In general, there are three common operating modes for the connections between the APs and the IoT devices, in terms of energy flow and information flow, which are as follows.

- WPT: Power transmission occurs in a downlink connection (e.g., AP1 to ID2 in figure 2(a) and AP1 to ID1 in figure 2(b)). In this case, the network devices receive the power they need from power AP to perform their tasks, such as charging the sensors for their sensing operations.
- SWIPT (simultaneous wireless information and power transfer): Transmission of power and information occurs in downlink connection simultaneously (e.g., AP1 to ID3 in figure 2(b)). In this case, the wireless devices use the received signal in the downlink connection both for energy harvesting and information receiving from the AP (e.g., a self-sustaining power distribution network) [19, 44]. In this method, the energy receiver and information receiver can share the same antennas [28]. For the simultaneous transfer of information and energy, the RF energy transfer method must be used.
- WPCN (wireless powered communication networks): Power transmission occurs in downlink connection, and information transfer occurs in uplink connection (for example, AP1 to ID2 in figure 2(b)). In this so-called"harvest and then transmit"protocol, the wireless device in the downlink connection receives power from AP and sends its information to that AP with the received power, such as charging sensor batteries to collect their data in wireless sensor networks [40].

Note that in figure 2, infrastructure-based architectures are illustrated. Networks for decentralized architectures are the same except that instead of an information AP, there are direct communication links among nodes.

Practically, a WPC network can have a variety of other network models, consisting of information APs, power APs, hybrid APs, as well as IDs with different operating modes. For example, in figure 2(a), ID1 receives its power from AP1 and sends information to AP2. In figure 2(b), AP1 sends power and information to two different devices, ID1 and ID4, respectively. As mentioned earlier, relays can also be used in the WPC network. In figure 2(c), R1 receives both information and power signals from AP1. It then sends them to the IDs. ID1 receives its data from R1, while ID2 receives both information and power passed through two relays.

Two strategies for manipulating the received power in nodes can be used, harvest-use and harvest-store-use. A device with the harvest-use method, uses the harvested power immediately. In harvest-store-use, which is a more common strategy, energy storage (e.g., battery) is used to store extra power whenever the harvested energy is greater than the device consumption [28, 45].

2.3 *Challenges of WPC networks*

In general, designing and applying WPC faces new challenges that are presented below.

- The radio spectrum used to transmit power in the RF transfer method is limited and is often dedicated to wireless information transmission. Therefore, providing a frequency band to send power is one of the main

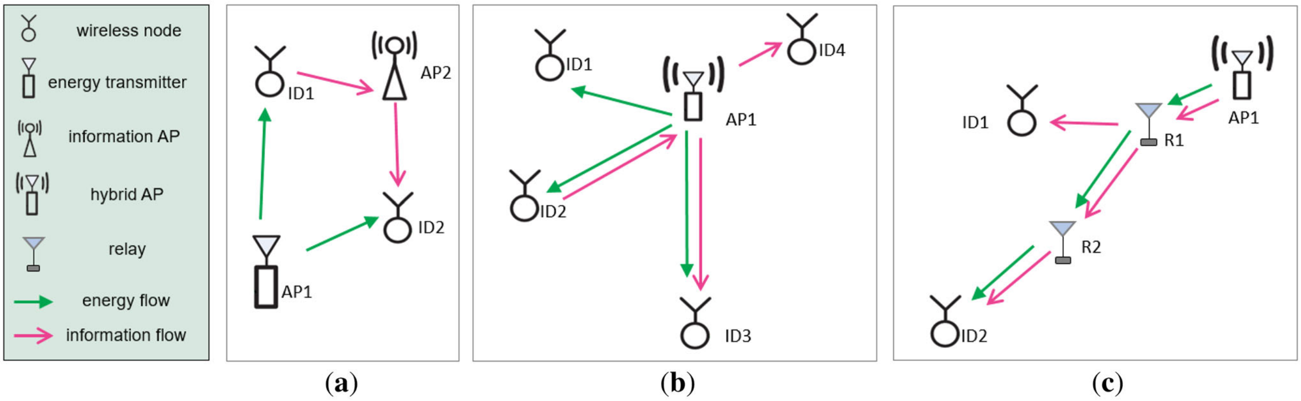

Figure 2. Operating modes of power and information connections in IoT networks.

challenges of this network type. One solution is to transmit power in the same frequency band as that for information transmission, which can interfere with the information receivers. For these types of networks, it is necessary to provide a design for both power and information transmissions, which is complicated and requires new methods of sending information in the network's physical layer [25].

- Another challenge of WPC is the low efficiency of WPT over long distances.
- Although wireless power transmission is a promising technique that can reliably supply power to hundreds of nodes in the network, it uses higher energy waves than telecommunication systems, and the increase in the energy demand of the network increases exposure to electromagnetic waves [46]. Therefore, human safety should be considered in such systems. Therefore, energy transmitters should comply with the standards of the Federal Communications Commission (FCC), and their emission power should be limited to power density that is considered safe for human exposure (1 mW/cm^2) [12].

Another solution to provide power for IoT devices, which does not have the challenges expressed in WPT, will be examined in the following section.

3. Solar energy harvesting in IoT

Another competitive technology for wireless devices'energy supply is called environmental energy harvesting. Renewable energies include different forms of energy in the environment that can be converted into electrical power. The harvested energy can be used to maintain the performance of IoT devices in the network. Renewable energy sources are free and not polluting. Numerous studies have investigated environmental energies such as solar energy, geothermal energy, and wind energy for large-scale applications. However, when the goal is to harvest and store this natural energy on a small scale, such as miniature IoT devices, the problem changes, and previously mature technologies (large-scale energy harvesting) no longer work. Recently, studies have investigated the use of environmental energy in wireless network nodes, including self-sustaining sensor nodes [12, 40, 43].

With the increase in the number of IoT devices, harvesting environmental energy sources can be the key to eliminating maintenance costs and extending the network lifetime. In the case that all components are powered by renewable energy sources, zero-energy wireless-powered IoT networks can be achieved [23].

As shown in [24], among the various energy harvesting techniques, solar energy harvesting through photovoltaics has the highest power density (15 mW/cm^2). Solar power is one of the most common sources of renewable energy. Its pervasive nature, less need for maintenance, and easy harvesting installation have made it an ideal option in most parts of the world [47].

Since the electrical power produced by solar energy depends largely on the light intensity, solar cells are usually placed in environments with proper lighting conditions to obtain more power. Solar panels can be connected in series to produce the required voltage. Due to the declining cost of solar panel manufacturing, solar energy has become an acceptable technical solution for supplying energy for IoT devices [48]. Practically, a solar panel appropriate for the sensor's size may be sufficient to meet the energy needs of a sensor node [12].

However, the availability of sunlight is highly sensitive to environmental dynamics. The main weakness of solar energy is that it can only be used during the day (outdoors) or during office hours (indoors). Even the outcome of the reduced solar radiation on cloudy days is not efficient enough. Statistical studies show that the solar energy received in sunny environments is up to a thousand times different from that harvested in shady and cloudy environments [49]. Not only climatic conditions have a direct effect on harvesting rate, but also a set of spatiotemporal factors such as sunrise and sunset times, location and surroundings, influence the location of harvesting sensors [12].

Since the use of solar energy on Earth has many obstacles, some researchers have considered using it in space. They believe that harvesting solar energy from space without any obstacles has a higher priority for investment and is more suitable for meeting the growing demand for energy in the future [50].

The IoT technology and renewable energy harvesting, especially solar energy, can be combined in two ways. The first method is to use IoT technology for energy monitoring and management. For example, traditional PLC technology cannot be used to remotely control and monitor the activities of a solar power plant. Therefore, the IoT approach has been introduced to manage solar energy systems. Solar power generation can be controlled and improved using this novel technology. The rotation and topology of solar panels can be managed using servomotors as per the sun direction, hence enhancing power harvesting efficiency [51].

Intelligent grids use information and communication technology capabilities, especially IoT, to take advantage of the quality, sustainability, and performance of both producing and demand forecasting of energy. At the same time, they can reduce the use of resources and improve the integration of renewable energy. For example, [52] provides an IoT solution that can perform intelligent and real-time collection and monitoring of power production and environmental conditions of solar stations with the use of an ESP32 microcontroller. In [53], a device and its related software are proposed in order to monitor fault detection and solar array management intelligently. With the use of IoT, this system can control solar farms, perform

Table 2. A qualitative comparison of some network factors for energy supply methods.

	Solar energy harvesting	Wireless power transfer	Use of solar energy or WPT according to the node's role	Hybrid use of WPT and solar energy in each node	Solar energy conversion to WPT
Energy source cost	No cost	High	Medium	Medium	No cost
Manufacturing and deploying costs	High	Low	Medium	High	Low
Ability to control the power transfer	Low	High	Medium	High	Low
Sensitive to environment dynamics	High	Not sensitive	Medium	Low	High
The size of an energy-harvesting device	High	Low	Medium	High	Low

fault detection and fix, help for power optimization under dynamic conditions, and reduction in inverter transients.

The second method of IoT and solar energy combination tries to use renewable energy sources, especially solar energy, to supply the required energy of sensors and other IoT devices. The concept of a self-powered IoT device is proven in [54] such that"a self-powered device is maintenance-free and completely self-sustainable through energy harvesting."Renewable energy sources may comfort the deployment of IoT devices where access to a persistent power supply is often limited. In [55], experimental work is reported for the feasibility evaluation of the operation of a sustainable IoT device from an autonomous power supply composed of a photovoltaic energy source, batteries, and a controller. A combination of the concept of solar power inverter and wireless power transfer is shown in [56]. The produced power in this system can be used in the application of home automation, where the devices are controlled by IoT.

To have stable IoT systems, forecasting of solar-power is an important challenge for optimized performance such that scheduling devices to perform power-intensive tasks in periods with additional energy. In areas with unstable weather, this requires taking the weather prediction into account. The problem is how to provide accurate solar energy forecasting for large-scale IoT systems with different devices in an autonomous way. In [57], a detailed study on machine-learning approaches is proposed to predict solar power for large-scale IoT systems in which devices with no preliminary data are placed, and machine learning models for each sensor are continuously trained as a form of online learning.

In another work [58], to power IoT devices, an ultra-low-power solar energy harvesting system with a power management module (SEHSPMU) is proposed. With harvesting energy from a solar cell, The SEHSPMU can provide regulated voltages of 3.3 V, 1.8 V, 1 V, and 0.5 V. A micro-scale solar power management architecture for a self-powered IoT node is presented in [59]. In this architecture, a complete on-chip switched capacitor-based power converter is used instead of a linear regulator in order to improve end-to-end efficiency.

In general, the most important challenges of using solar energy harvesting methods for wireless networks are as follows: (1) The energy harvest systems must meet the

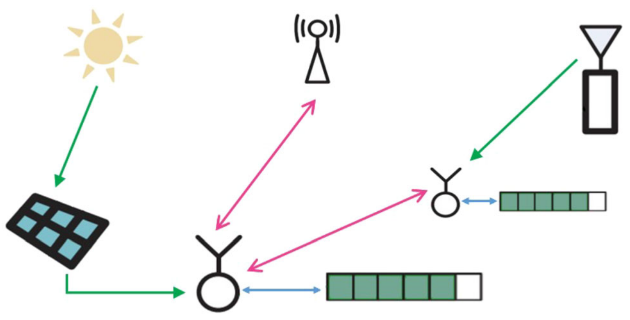

Figure 3. A green WPC with two types of IoT nodes.

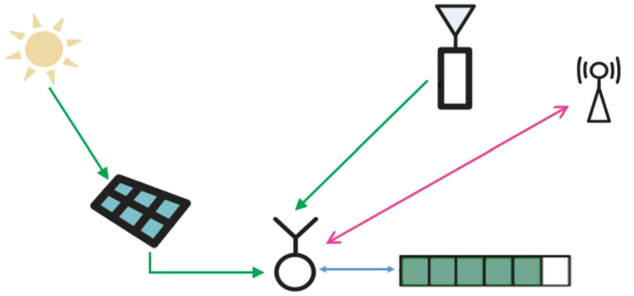

Figure 4. A green WPC network with combined energy for each node.

requirements of the small-scale wireless devices. (2) The energy harvested by devices must be stored efficiently. (3) This type of energy harvesting method cannot be used as the only energy source in a reliable system in most cases because of its dynamic nature. That is why it has been suggested to design an energy collection system for wireless nodes that can collect different types of energy from the environment [60].

4. Integration of WPC with solar energy harvesting

Since solar energy availability and intensity are largely accidental and time-dependent, solar-based methods alone cannot supply stable, demand-based energy for IoT devices. Instead, the power transmitter in the WPC network has complete control over the transmitted power, waveform, time/ frequency dimensions and can provide stable energy in different physical conditions and for various service requirements by adjusting all of these variables.

Given that both technologies have their own pros and cons, using integration methods to combine their benefits and overcome their problems can lead to a better and more practical solution in the IoT networks. The use of solar energy in the WPC network creates a green and self-sustaining WPC network. Several studies have investigated the integration of these two methods in recent years.

Three different frameworks for the combined use of these two technologies are discussed in this article below. The purpose of these smart combinations includes higher network stability, demand-based energy supply to the network nodes with lower energy consumption than that with fixed energy transmitters, and lower installation, and equipment maintenance cost than that with solar harvesting. Table 2 compares five network factors for two energy extraction methods as well as the three integration methods. The qualitative value entered for each factor indicates its average value for the whole network devices.

4.1 *Use of solar energy or WPT according to the node's role*

There are different nodes with different roles in a non-homogeneous network. Accordingly, the network nodes have different energy consumptions. For example, in some wireless sensor networks, some nodes are responsible for the data collection (like cluster heads in clustered sensor networks) and consume much higher levels of energy (10–100 mW), considering high receiving and transmitting traffic flow [61]. Given the limited energy of the WPT battery, the battery of these high-consuming nodes drains after a while, and the network's disconnection happens in these nodes.

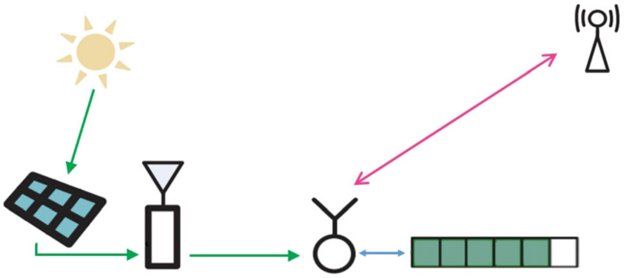

Figure 5. A green WPC network with an energy transmitter.

An appropriate combined solution is to use solar energy harvesting technology due to its relatively high construction and deployment costs only for nodes that need higher energy. Other network nodes receive their power from power transmitters because WPT equipment costs less. For example, rectenna or rechargeable coils can be made of inexpensive copper wires. Figure 3 shows a model of this type of green WPC network. In this figure the harvest-store-use model is considered for all the network nodes.

Unlike the homogeneous sensor networks in [40, 43], where all nodes are charged by WPT, in reference [12], in a clustered sensor network, nodes responsible for data collection which are fewer in number than other nodes, are equipped with solar panels to handle large volumes of data transfer. In the proposed solution, a mobile vehicle with power transmitters moves to resolve the wireless node charging requests and collect data from the clusters.

This combination framework poses several new challenges, including (1) determining the wireless nodes with higher energy consumption, (2) determining where they should be set up to minimize total cost, (3) specifying how network connection and stability can be ensured when there is no sunlight (e.g., on cloudy/rainy days).

4.2 *Hybrid use of WPT and solar energy harvesting in each network node*

In each IoT node, environmental energy harvesting methods can be combined with WPT methods so that less energy will be required from fixed energy transmitters [25, 56]. This integration requires the implementation of both energy receiving methods in network nodes. An example of such a network is shown in figure 4. In this figure, the harvest-store-use model is considered for all the network nodes. A wireless node can opportunistically harvest solar energy and store it in a rechargeable battery. In this network, in the case of strong intensity of solar energy in most wireless nodes, the energy transmitters can switch off energy transmission, to prevent energy wastage due to the limited capacity of the batteries. On the other hand, wireless energy transmission is used when effective harvesting of solar energy is not possible in most wireless devices.

Table 3. A Comparison of recent works using WPT in wireless networks.

Ref.	Wireless power transmission method	Power transmitter	Integrating with solar energy harvesting	Operating mode
Y. Shi *et al* [41]	Resonant coupling	Terrestrial mobile charger	No	WPT
S. Sharma *et al* [19]	RF signals	Fixed base station, Using Relay	No	WPCN, SWIPT
S. Guo *et al* [43]	Resonant coupling	Terrestrial mobile charger	No	WPCN
M. Zhao *et al* [40]	Resonant coupling	Terrestrial mobile charger	No	WPCN
C. Wang *et al* [12]	Resonant coupling	Terrestrial mobile charger	Yes, Use of solar energy or WPT according to the node's role	WPCN
Q. Wu *et al* [33]	RF signals	Fixed base station	No	WPT
H. Ju *et al* [34]	RF signals	Fixed base station	No	WPCN
Q. Wu *et al* [64]	RF signals	Fixed base station	No	WPCN
L. Xie *et al* [65]	Resonant coupling	Terrestrial mobile charger	No	WPT
I. Krikidis *et al* [66]	RF signals	Fixed base station	No	SWIPT
B. Swain *et al* [7]	Resonant coupling	Fixed base station	Yes, Solar energy conversion to WPT	WPT
S. Le *et al* [35]	RF signals	Fixed base station, Using Relay	No	WPT
H. Lee *et al* [67]	RF signals	Fixed base station	No	WPT
W. Feng *et al* [36]	RF signals	Aerial mobile charger	No	WPCN
C. M. Angelopoulos [42]	Resonant coupling	Terrestrial mobile charger	No	WPT
C. Su *et al* [38]	RF signals	Aerial mobile charger	No	WPT
S. Lhazmir *et al* [37]	RF signals	Aerial mobile charger	No	WPCN
K. Panda *et al* [56]	Resonant coupling	Fixed base station	Yes, Hybrid use of WPT and solar energy harvesting in each network node	WPT
A. Jeganathan *et at* [39]	RF signals	Aerial mobile charger Using Relay	No	WPCN

Between these two modes, a hybrid power method can be adopted using both energy harvesting and WPT. Where energy transmitters completely control their transmission powers according to the environmental conditions or use different energy beams for the nodes so that they can transmit power to those wireless nodes that do not harvest sufficient environmental energy.

The two main challenges in designing such a hybrid method are (1) specifying the time of swapping between different energy harvesting modes, (2) designing efficient energy transmission strategies with the aim to minimize the energy transmitted by fixed energy transmitters and yet, meet the performance requirements of network communications [25]. Generally, in the optimal design of this network, several factors have to be concurrently considered, such as intensity of the current and predicted environmental energy and information about IDs battery state and wireless channel conditions.

4.3 *Solar energy conversion to WPT*

Environmental energy harvesting methods can be applied to power transmitters in addition to IoT devices such that the power transmitter uses solar energy as an energy source [25]. In [7], authors have used this energy conversion to charge biomedical electronic sensors implanted in the body. Photovoltaic module and resonant wireless power transfer are used in this system. The maximum power transfer occurs when the output of the resonant converter in power AP is synchronized with the resonant inductive link in the implantable device. Another device outside the body receives signals containing sensed data from the implantable device.

In order to use solar energy conversion to transfer wireless energy to longer distances, the RF signal method must be used. To this end, it is necessary to install circuits in the power transmitter that use DC current from sunlight to bias the active oscillators of the antenna. These oscillators generate and emit an electromagnetic signal at the same frequency as oscillation. To make the design compact, solar cells are placed in the same area as the antenna components [62]. A demonstration of this framework is presented in figure 5. In this figure the harvest-store-use model is considered for the network nodes.

As an example, Space Solar Power System (SSPS) satellites on GEO orbit produce much higher power than conventional satellites. Current conventional satellites generate power only to meet their operational requirements, while SSPS satellites should generate power to meet the Earth's energy needs [47, 50]. Furthermore, a wide range of rectifying antennas are used on the Earth to collect the transmitted microwaves [47].

The solar to electromagnetic energy converter has been designed to charge low-power devices. For example, such a power source can be used to charge RFID nodes wirelessly. In this type of network, the RF signal emitted from the power transmitter is received by a rectenna on RFID [63]. Therefore, these nodes receive their power from the power transmitter and receive the data signal from an RFID reader, which reduces the amount of power that the RFID reader needs to send to the RFID nodes.

Table 3 presents a list of several recent WPT schemes in wireless networks. The second column shows the wireless power transfer method. Network architecture, including the power transmitter type, relay existence, and operating mode, is illustrated in the third and fifth columns. The fourth column shows whether solar energy harvesting is also considered in the study. It also indicates the method of combination of two power receiving methods in its final solution.

Considering the current works on WPT in IoT networks, it can be seen that limited studies have utilize the combination of the two energy harvesting methods. Therefore, applying the three proposed frameworks or even combining them are open for further investigation and development.

5. Case study

This section simulates three IoT network scenarios, each deploying one of the integration methods presented in section 4. In the first scenario, either solar energy or WPT method is deployed and used for any ID energy harvesting according to its role and energy consumption. In the second scenario, all the IDs are equipped with both WPT and solar energy harvesting technologies and switch between them according to their situation. In the third scenario, the power AP itself uses a solar panel as its power supply instead of a fixed electric supply.

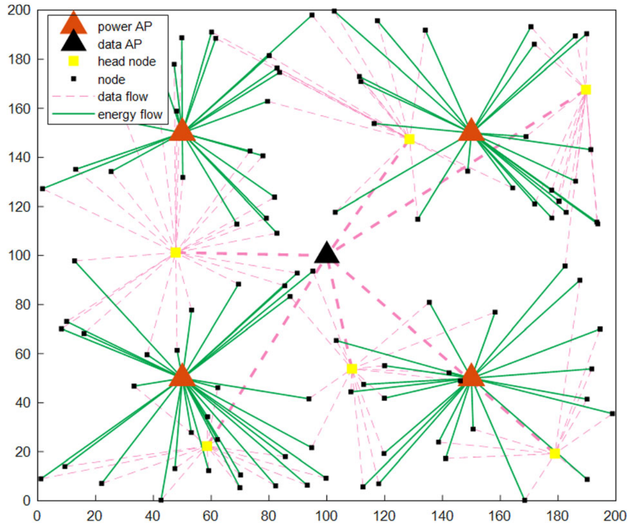

Figure 6. Network elements, data, and energy flows in the first scenario.

5.1 *Network and energy modeling*

A network with 200 × 200 m is considered in which 100 IoT nodes are randomly distributed based on a uniform distribution. The nodes here are smart sensors of a low-bandwidth IoT application. They have periodic data transmission (send few data periodically) to information AP. An infrastructure-based architecture is used in which an information AP with a fixed electric supply is located in the middle of this square.

Network nodes must harvest energy for their operations. Each node must have sufficient energy for data transmission and reception and for its idle time. According to [9], the consumed power of an IoT node is comprised of a static part and a dynamic part, and for the interval of T is computed as

$$\begin{aligned} P^{IoTnode} &= P^{IoTnode}_{static} + P^{IoTnode}_{dynamic} \\ &= \frac{P_{idle} \times (T - T_{RX} - T_{TX})}{T} \\ &\quad + \frac{P_{RX} \times T_{RX} + P_{TX} \times T_{TX}}{T} \end{aligned} \tag{1}$$

where T_{TX} and T_{RX} are the duration of transmission and reception. P_{idle}, P_{TX} and P_{RX} are the power required in each mode. The dynamic part power of a node is dependent on the frequency of transmission and reception, its bit rate, and its distance from the information AP.

In general, for the network scale of this evaluation, and considering low-bandwidth applications, a power consumption in μW power level can be considered for the nodes.

Due to the distance scale and the fact that we need fixed WPT transmitters, RF methods should be used, and microwave signals are used due to the distribution of the nodes.

Since the energy receiver requires higher power efficiency, the energy harvesting range is smaller than the information transmission range. In our network setup, in the case of the need to the power transmitter, four numbers of them are deployed.

In the case of using microwave signal, the available power at an antenna in far-field can be computed as

$$P_r = P_T G_T G_r \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2}$$

where P_T is the output power of the transmitter and P_r is the available power at the receiver. G_T and G_r are the transmitter and receiver antenna gain, respectively. d is the distance and λ is the wavelength of the microwave signal [68].

As in [69], RF power APs provide signals at the 868 MHz band which is of European Industrial, Scientific, and Medical (ISM) band with the maximum allowed power of 3.28 W.

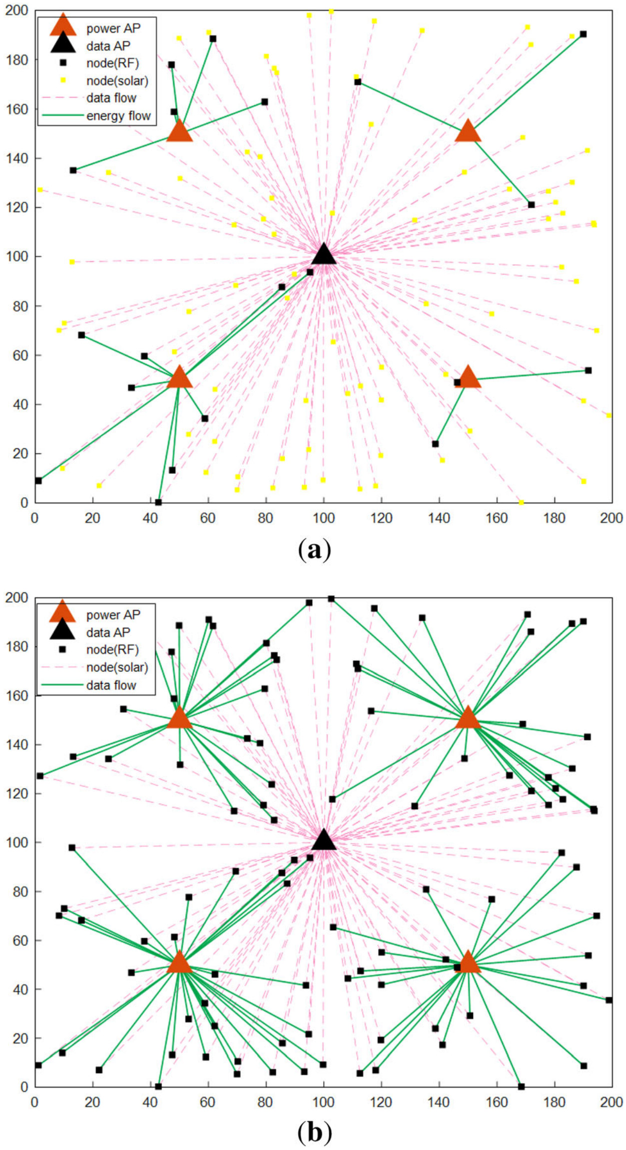

Figure 7. Network elements, data, and energy flows in the second scenario (**a**) in a sunny day (**b**) at night.

In the following scenarios in this section, solar harvesting is integrated with the WPT method. The power density of outdoor PV cells is 10–100 mW/cm^2 [45]. In our simulation, the harvesting power of 15 mW in one cm^2 is considered.

5.2 *First scenario*

In this scenario, four power APs with fixed locations are considered for providing the power supply of nodes in this area. As seen in figure 6, six nodes are selected as the cluster heads, which are the interface for sending data from the nodes in their cluster to the information AP. Pink dashed lines indicate data flow. This architecture reduces the energy consumption of non-head nodes due to the shortening of their information transmission distance, but instead, the head nodes consume much higher energy and μW power level is not enough for their operations. Each head node has tens of times more transmitting and receiving operations than a non-head node.

As a result, it is sufficient to use WPT for non-head nodes while the head nodes are equipped with solar panels with dimensions 2×2 cm. In figure 6, the head nodes are yellow, indicating solar energy harvesting while other nodes receive RF power from power APs and their energy flows are illustrated with green lines. The average power received is 60 mW in head nodes and 2.53 μW in other nodes.

5.3 *Second scenario*

Due to the unstable environmental conditions, in this scenario, we have equipped each node with two energy harvesting methods. Each node has a solar panel of size 1× 1 cm and also has a WPT receiver. Four power APs are deployed in the area to cover the power supply of nods if needed. Due to the fact that all nodes are equipped with solar panels, it is more economical to use solar energy harvesting as much as possible and to use WPT power transmitters only in necessary conditions. In figure 7(a), 20% of nodes are in a shady areas, thus requiring power from WPT transmitters. Yellow nodes use solar energy harvesting, and other nodes are connected to power APs. Figure 7(b) shows the network status at night, in which all the nodes are connected to power AP. This method has a higher deployment cost than other methods, but it is instead more adaptable to environmental conditions.

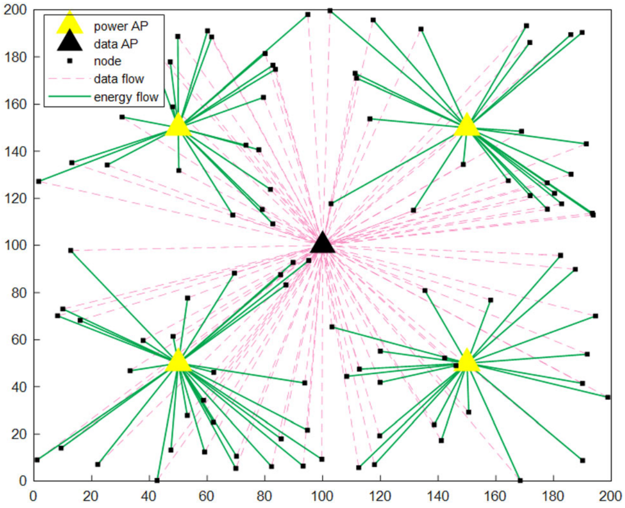

Figure 8. Network elements, data, and energy flows in the third scenario.

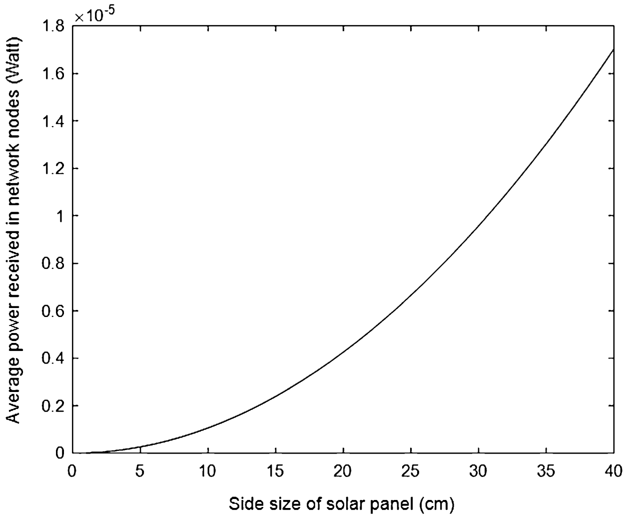

Figure 9. Evaluating the average power harvested by network nodes in the third scenario.

In figure 7(a), the average power received is 15 mW in nodes in sunny areas and 6.7 μW in nodes in shady areas.

5.4 *Third scenario*

In this scenario, there is no any power AP with a fixed electric supply. Instead, there are four power APs that are supplied with solar energy harvesting and are illustrated by yellow triangles in figure 8. Solar panel with dimensions 20 × 20 cm is used in each power AP. The harvested power is converted to RF signal with a power conversion efficiency of 0.5. Due to the dependence of this network on sunlight conditions, the power transmitters must be equipped with batteries. The received power in power AP is 6 W, and the average received power in nodes is 4.26 μW.

In an environment with sufficient sunlight and proper use of energy storage in power AP, this method does not require any fixed energy source to power the nodes and is, therefore a self-sustainable solution.

Figure 9 illustrates the effect of increasing the solar panel size installed on the power AP on the average energy harvested in network nodes. With an increase in the panel size, the harvested energy at AP increases, and therefore, the RF signal with higher power can be sent.

In the case of the limitation of the maximum transmitting power of the power AP at 868 MHz to 3.28 W, large panel sizes are not required. Therefore, in this scenario, according to the conversion efficiency of 0.5, the maximum allowable side size of the panel is 20.91 cm, which creates an average power of 4.66 μW in the nodes. The larger panel can store the extra energy.

6. Conclusion

In this paper, we have studied the methods of wireless energy replenishment for low-consuming IoT devices against the conventional method of using batteries and physically charging them. Two competing technologies have been discussed for this purpose. In the first method, a WPC network is made by setting up power transmitters and adding a simple and inexpensive structure in wireless nodes, which increases the lifetime and reliability of the wireless network. In the second approach, power supply for IoT nodes is provided by implementing solar energy harvesting capability in devices. We studied smart combinations of these two technologies for wireless networks. The review of the literature yielded three hybrid frameworks. Simultaneous use of both technologies to create a green WPC network attempts to provide wireless networks with self-sustaining energy nodes while minimizing the energy sent from energy transmitters.

Three integration methods are simulated and evaluated in the case study section in three scenarios. Data flow and energy flow are displayed in each scenario. For each network element, the energy harvesting method and the amount of received power are obtained. It is shown that the second method has better adaptability to variable environmental conditions, and the third method can be a completely self-sustainable solution.

With the proper combination of these two technologies in the future, networks with higher reliability will be achieved, which will remain operational forever. In fact, by providing sufficient power to IoT devices wirelessly and solving the problem of recharging them, especially in a green and self-sustaining way, more comprehensive applications of IoT will be introduced. With this possibility, many of the hardware and communication constraints that have always been considered in the design of IoT devices due to energy constraints will be removed. Analyzing these applications can be an interesting topic.

List of symbols

$P^{IoTnode}$	consumed power of an IoT device
$P^{IoTnode}_{static}$	static part of consumed power
$P^{IoTnode}_{dynamic}$	dynamic part of consumed power
P_{idle}	power required in idle mode
P_{RX}	power required in reception mode
P_{TX}	power required in transmission mode
P_r	available power at the receiver
P_T	output power of the transmitter
T	time interval
T_{RX}	duration of reception
T_{TX}	duration of transmission
G_T	transmitter antenna gain
G_r	receiver antenna gain
λ	wavelength of the microwave signal
d	distance

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