Review

Wireless power transfer and energy harvesting in distributed sensor networks: Survey, opportunities, and challenges

Gerald K Ijemaru[1], Kenneth Li-Minn Ang[1] (iD) and
Jasmine KP Seng[2,*] (iD)

Abstract

Distributed sensor networks have emerged as part of the advancements in sensing and wireless technologies and currently support several applications, including continuous environmental monitoring, surveillance, tracking, and so on which are running in wireless sensor network environments, and large-scale wireless sensor network multimedia applications that require large amounts of data transmission to an access point. However, these applications are often hampered because sensor nodes are energy-constrained, low-powered, with limited operational lifetime and low processing and limited power-storage capabilities. Current research shows that sensors deployed for distributed sensor network applications are low-power and low-cost devices characterized with multifunctional abilities. This contributes to their quick battery drainage, if they are to operate for long time durations. Owing to the associated cost implications and mode of deployments of the sensor nodes, battery recharging/replacements have significant disadvantages. Energy harvesting and wireless power transfer have therefore become very critical for applications running for longer time durations. This survey focuses on presenting a comprehensive review of the current literature on several wireless power transfer and energy harvesting technologies and highlights their opportunities and challenges in distributed sensor networks. This review highlights updated studies which are specific to wireless power transfer and energy harvesting technologies, including their opportunities, potential applications, limitations and challenges, classifications and comparisons. The final section presents some practical considerations and real-time implementation of a radio frequency–based energy harvesting wireless power transfer technique using Powercast™ power harvesters, and performance analysis of the two radio frequency–based power harvesters is discussed. Experimental results show both short-range and long-range applications of the two radio frequency–based energy harvesters with high power transfer efficiency.

[1]School of Science, Technology and Engineering, University of the Sunshine Coast, Petrie, QLD, Australia
[2]School of AI and Advanced Computing, Xian Jiaotong Liverpool University, Suzhou, China

[*]This author is now affiliated to School of Computer Science, Queensland University of Technology, Brisbane, QLD, Australia.

Corresponding author:
Kenneth Li-Minn Ang, School of Science, Technology and Engineering, University of the Sunshine Coast, Moreton Bay Campus, 1 Moreton Parade, Petrie, QLD 4502, Australia.
Email: lang@usc.edu.au

Introduction

A wireless sensor network (WSN) comprises the distribution of a huge number of static sensors which are mostly constrained with both limited processing and low power abilities. These sensors always communicate
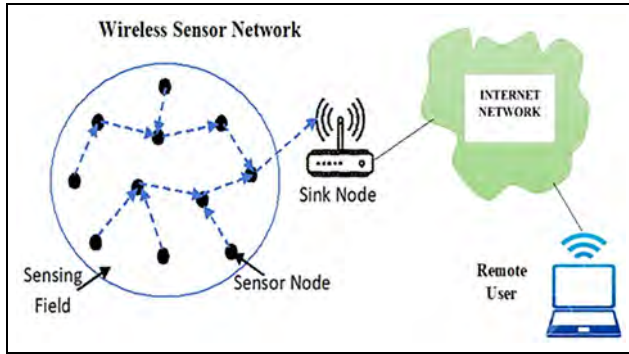
**Figure 1.** Architecture of a typical WSN scenario.

at short ranges over undependable wireless channels. Figure 1 shows a typical architecture of a WSN for different application scenarios. A WSN is also characterized by a power base station called the *sink node*, which has become an integral part of a WSN.[1] The sink assumes the position of a mediator between the sensors and other applications occurring in the sensor network environments. Recently, WSN has advanced to the use of mobile elements for opportunistic data collection and transmission. A sensor node is typified by three basic subsystems as shown in Figure 2: (1) the sensing unit, which senses and captures data; (2) the processing unit, which processes data; and (3) the communication unit used for information transmission. Figure 2 shows the basic internal operational units of a sensor node architecture—sensing, processing, and communication.

One of the fundamental limitations of wireless and mobile devices is that they are energy-constrained. Owing to the pervasiveness of wireless and mobile devices, battery charging has become a fundamental problem. A distributed sensor network (DSN) is characterized by the deployment of several sensor nodes

with various sensing capabilities, communication, and computation for application-specific analysis. A widely known application classification is the deployment of battery-powered sensor nodes across even the most difficult areas. A battery-powered sensor node has the huge limitation of finite node lifetime.

Nodes arbitrarily cease to operate when their batteries are depleted, thereby leading to short duty cycle or reduced sensing reliability and short range of transmission. Nodes may, however, choose to exploit large batteries to achieve longer sensing durations, but this will incur increased size, weight, and cost occasioned by higher power requirements.[2] Current WSNs are mostly energy-constrained at a sensor node with limited operational lifetime. Many research efforts are currently in vogue at every layer, including MAC layer, topology layer, application layer, and physical layer with a view to devising techniques for prolonging the network lifetime. In spite of these concerted efforts, the operational lifetime of a WSN still faces some routine bottlenecks, which possibly are the major contributors that limit its large-scale deployments.[2]

WSNs are widely applied in several areas, including environmental monitoring and tracking applications,[3] battleground surveillance, and household automation.[4] According to Bala et al.,[3] monitoring operations may range from military to farming, habitat to structural and industrial monitoring and can also find application in air pollution, detection of forest fires and floods, and tracking of humans or animals. Despite these wide applications, in practical terms, their wide applications and deployments are hindered as a result of limited battery capacity and difficulty in battery replacement after deployment, especially in hostile and inaccessible environments.[1] Sensor nodes are typically energy-constrained owing to the limited availability of energy sources and recharging/battery replacements are no
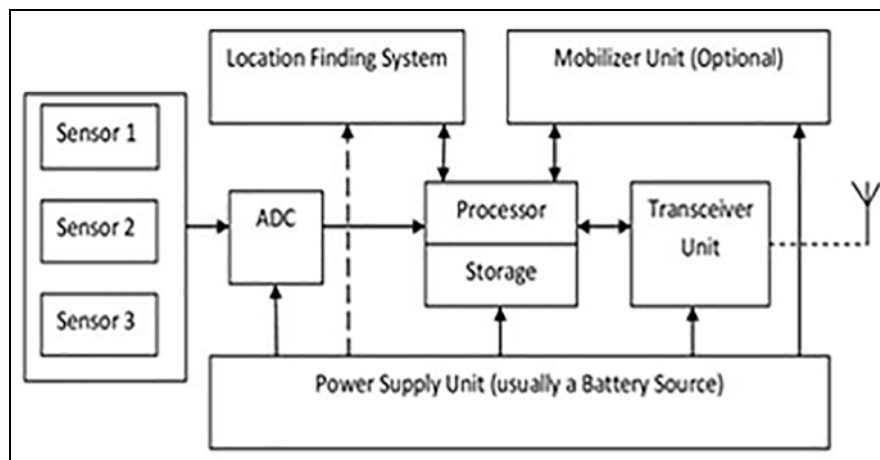
Figure 2. Internal architecture of a WSN node.

options due to the associated cost implications and/or mode of deployments of the sensor nodes.[5] This invariably has motivated a robust research into the development of energy harvesting (EH) techniques whereby sensor nodes are able to capture and transform ambient energy (solar, thermal, mechanical vibrations, etc.) into electrical energy and be able to prolong their operational lifetime through self-replenishment.

Due to limited battery capacity of a sensor node, a WSN does not remain operational in perpetuity. To prolong the network operational lifetime, many strategies and techniques have emerged; the most recent being the EH technique.[6–15] Sudevalayam and Kulkarni[16] define EH as a technique of acquiring/scavenging energy from either environmental sources or other sources and further utilizing the harnessed energy (electrically converted) to power the sensor nodes to improve their operational lifetime and capability. EH techniques have shown strong potentials to address the finite node lifetime challenge of a WSN. However, the success of this technique for WSNs remains limited in operation due to the uncertainty surrounding the stochastic nature of their energy arrival[5] and their strong dependence on environmental conditions.[4] For instance, the natural sources of EH such as sunlight (for solar energy) have shown several limitations in terms of weather and seasonal constraints and cannot be suitably employed for WSN applications or other mission critical applications due to the stochastic mode of their energy arrival and their seeming non-availability when needed.[4,5,17] The EH technique heavily relies on the energy extraction from the environment. The most popular technique of EH is the conversion of solar energy to electrical energy.[5] This type of energy harvestable source is faced with several limitations that border around difficulty in controlling the intensity of direct sunlight which may be affected by variations in weather conditions and seasonal patterns. For instance, the solar and wind sources of EH are limited by the durations and strengths attached to solar radiation or wind,[17] which are subject to weather or seasonal constraints. Besides, there may be inadequate sunlight at night to generate energy to power IoT sensor nodes[18] and the size of an EH device may trigger deployment issues especially in a situation where the EH equipment is much bigger in size than the sensor node that needs to be powered.[5]

Interestingly, the latest breakthrough in wireless power transfer (WPT) technology has shown its strong and high potentials to address these fundamental bottlenecks surrounding the finite node lifetime and operational performance of IoT-WSN applications. WPT refers to the transfer of electrical energy between two devices wirelessly. In terms of extending the operational lifetime of sensor nodes used for IoT-WSNs applications, several authors such as Hong et al.,[4] Ijemaru

et al.,[5] Ko and Kim,[11] Huang and Lau,[13] Barman et al.,[15] Zhong and Wang,[19] Xie et al.,[20] and Setiawan et al.[21] agree that WPT has acquired some promising potentials. For instance, Hong et al.[4] opined that sensor nodes can be proactively charged in a wireless passive sensor network by exploiting radio frequency (RF)-based WPT technologies and thus make them ready on demand. However, they also noted the effect of the charging operations on the operational performance of the sensor network and suggested considering a cross-layer target application in the design. Notably, implementation of WPT technology can occur in any of the following techniques: near-field (e.g. resonant coupling, inductive coupling) and far-field (e.g. EM radiation[4,5]). The latter is specifically used to charge WSNs deployed across a wide geographical area. This shall be discussed in detail under the classification of WPT technology.

This research study has been structured to first give a comprehensive review of the current state-of-the-art techniques in EH-WPT that can be exploited for applications running in DSNs. It then highlights their various opportunities, potential applications, limitations and challenges, classifications, and comparisons. In addition, we discuss different application models of WPT techniques in a DSN environment and present a classification based on radiative and non-radiative techniques. The article also considers some WPT charging frameworks for DSNs and presents a comparative study of WPT technologies for IoT-WSN applications. A comprehensive study of the opportunities and challenges inherent with EH-WPT technologies in DSNs is also highlighted. Finally, after carefully studying the EH-WPT technologies, we present a practical approach and real-time implementation of an RF-based EH-WPT technique using Powercast™ energy harvesters.

The rest of the article is structured as follows. "Related works: an overview of WPT and EH in DSNs" section presents some related works and overview of EH-WPT in DSNs. "Distributed WPT for IoT-WSNs" section describes distributed WPT for IoT-WSNs. This section also presents some application models of WPT in a DSN. "Applications of WPT and EH in DSNs" section presents some applications of WPT and EH in DSNs, while "Opportunities and challenges of EH-WPT in DSNs" section gives an in-depth study of the opportunities and challenges related to EH-WPT in DSNs and provides some insights into future research directions. "Application of RF-based EH-WPT with Powercast energy harvester" section presents a practical implementation of an RF-based EH-WPT technique using Powercast energy harvesters, which can be exploited for DSN applications. Experimental results and analysis are also given. Finally, "Conclusion" section concludes the work.

Related works: an overview of WPT and EH in DSNs

This section presents an overview of recent developments in WPT and EH technologies. The technology behind wireless power transmission dated back to the early 20th century and is credited to Nikola Tesla.[5] Back then, not much progress was witnessed until the early 1990s which saw the need for the re-emergence of WPT with the proliferation of portable electronic devices, including laptops, cell phones, and personal digital assistants (PDAs). The conventional power supply with the use of cords and wires has dramatically become extinct because they prohibit a large-scale deployment, utilization, and mobility.[22] In addition, battery replacements for power cords cannot give optimal solution since batteries have short operational life-cycle with cost and weight implications on the hardware. On the contrary, huge operational costs are incurred through battery charging/replacement, thus making them infeasible. Recent advancements have shown the use of EM wave to wirelessly transfer power from the source (transmitter) to the destination (receiver), thereby giving birth to what is known as the WPT technique. Jawad et al.[22] gave some insights into the recent applications of WPT technology in the following areas: medical implants, unmanned aerial vehicles (UAVs), mobile phones, WSNs, electric vehicles, and audio players. A comprehensive review on near-field WPT may be found in Jawad et al.[22]

Zhou et al.[23] provided a comprehensive review of the different feasible environmental EH technologies and their suitability for the actual WSN applications. Their study also highlighted some of the defects with the current environmental EH technologies. The authors classified EH based on the different forms of energy and provided a comprehensive table of comparison of various solar cells. Xie et al.[24] studied the physical characteristics, strengths, and weaknesses of three classes of WPT technologies: inductive coupling, magnetic resonant coupling, and EM radiation, with a focus to exploring their suitability for WSN applications. In their assessment, inductive coupling was found to be vital and a popular technology that wirelessly transfers power due to its simplicity, safety, and convenience, and has attracted successful commercialization to several products such as cellphone and laptop charging, electric toothbrush, and medical implants. However, inductive WPT technology is still treading into future advancements in WPT technology as it does not guarantee efficient power transfer even at very short distances. It works best only at short distances between the power transmitter and the receiver and requires an accurate alignment in the charging direction. These strong factors limit the suitability of inductive coupling for WSN applications. Compared with inductive coupling, magnetic resonant coupling achieved greater power transmission efficiency.

The highlight of the study by Xie et al.[24] was that with magnetic resonant coupling, it was possible to power a 60 W bulb within a distance of 2 m at 40% transfer efficiency and with a charging distance of about 4 times that of the coil diameter (0.5 m). It is instructive to note that both inductive coupling and magnetic resonant coupling are two forms of non-radiative WPT technologies. Conversely, EM radiation is a form of radiative WPT technology, which may be either omnidirectional or unidirectional depending on the power transmitter. Although it can be suitable for transmitting information, omnidirectional WPT suffers much power transfer efficiency problem as a result of attenuation of EM wave over increasing distance. Xie et al.[24] reported 1.5% power transfer efficiency at a range of 30 cm between the transmitter and the receiver. Besides having low power transmission efficiency, omnidirectional radiation comes with some inherent health hazards, which ostensibly limit their application to low sensor nodes with low sensing activities such as temperature, light, and moisture. With a clear line-of-sight (LOS) propagation pathway, unidirectional WPT exploiting microwave or laser beam can significantly deliver huge amount of transmission power over a considerable range in the neighborhood of kilometers. In comparison with EM wave, resonant coupling WPT technique is more advantageous by offering higher efficiency of wireless power transmission even under omnidirectional, without needing LOS. A comprehensive comparison is given in Table 3 under the "Applications of WPT and EH in DSNs" section.

Fan et al.[25] discussed an In-N-Out scheme which is a software–hardware approach for far-field WPT. Relying on the potential drawbacks of the near-field system in which the reduction of the coil size resulted in a significant drop in the charging efficiency with low flexibility, the authors proposed a far-field WPT system with much flexibility that does not necessitate users wearing huge charging devices, and with the potentials of charging medical implants in the human tissue. Many discussions on the current advances in EH-WPT technology that employ near-field technique present inductive coupling as having great potentials and is followed by RF-based WPT.[26] Besides, in terms of commercialization, near-field WPT is well commercialized compared with far-field. For instance, near-field WPT has been applied in China and Europe using wireless chargers in public buses at frequencies of 20/85 kHz and power from 60 to 200 kW.[26] Moreover, 2017 marked the promotion of Qi standard in Apple Inc., which is a cordless wireless charger used for charging mobile phones. Recent advances in antenna designs employed for RF-based EH-WPT applications are reviewed by Wagih et al.,[27] while Sanislav et al.[28]

discussed recent advances in EH techniques suitable for IoT devices and presented some future technical challenges for large-scale EH deployment solutions for IoT-based applications.

EH in WSNs

Shaikh and Zeadally[1] and Tan and Panda[29] described EH as a mechanism that generates energy from various ambient sources, including solar, vibrational, wind, and thermal and converts the harvested energy into usable electrical energy for specific sensing operations and for the overall WSN applications. Sensor nodes are powered by devices whose energies are derived from external sources in order to boost or prolong the network lifetime. EH techniques have shown strong potentials to address the trade-offs between sensor node lifetime and performance parameters and to provide a lasting solution for the energy-hungry electronic devices.[1,30] The use of battery power remains the major source of energy supply to sensor nodes. However, there are many constraints with this source of energy and some of them are listed in Shaikh and Zeadally[1] and include battery leakages (even when not in use); battery breakdown as a result of extreme weather conditions, thereby leading to environmental problems; and limited energy density of the battery which limits the operational lifetime of the sensor node. Many mechanisms are in place to fill the energy gap and EH is one of such mechanisms. Accordingly, EH mechanism is the generation and provision of a continuous energy replenishment for the operations of a sensor node and that of the WSN at large. EH is critical for applications running for longer time durations. Some of the applications include environmental monitoring,[31] multimedia WSN applications, and structural health monitoring data.[30,32]

EH sources can be classified into two main types: (1) ambient sources (direct energy transformation from ambient sources to electrical energy, which is further exploited to charge the sensor nodes without requiring any battery storage) and (2) external sources (storage is required for the converted electrical energy before being supplied to the sensors). Generally, ambient EH sources are available at no cost in the environment and include (1) RF-based EH, (2) solar-based EH, (3) thermal-based EH, and (4) flow-based EH (e.g. wind and hydro-based EH). Conversely, external EH sources are clearly deployed for EH purposes in the environments, and include mechanical-based and human-based EH sources. A comprehensive review is given in Shaikh and Zeadally,[1] Zhou et al.,[23] Tan and Panda,[29] Sherazi et al.,[30] Adu-Manu et al.,[32] Kausar et al.,[33] and Ahmed et al.[34] Figure 3 depicts the block diagram of an EH system. Shaikh and Zeadally[1] presented a comprehensive taxonomy of the different EH sources that are applicable to WSNs and also highlighted some recent
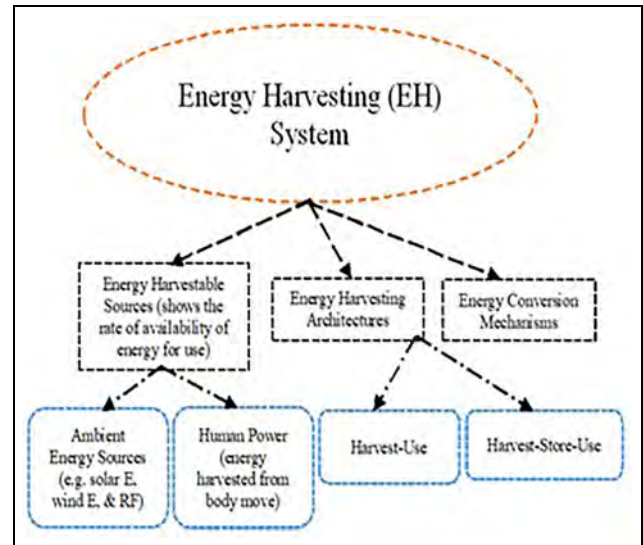

Figure 3. Block diagram of an EH system.

energy prediction models with potentials to maximize the harvested energy in WSNs. Sherazi et al.[30] provided a comprehensive analysis of the existing EH systems for WSNs and highlighted the pros and cons of important MAC protocols used for EH-WSNs while focusing on the basic techniques, evaluation approaches, and important performance indicators. Tan and Panda[29] provided a review of EH technologies that are applicable for sustainable WSNs. Authors made a comparison of power density of EH sources and provided some of the benefits of EH to include reduction of battery power dependency, installation cost, maintenance cost, and provision of sensing abilities in remote and inaccessible environments and lasting solutions that enable self-powered sensor nodes. Dziadak et al.[31] and Adu-Manu et al.[32] provided some detailed study of the recent state-of-the-art EH technologies for some environmental monitoring applications running in WSNs, including animal tracking, disaster monitoring, and air/water quality monitoring. The authors first discussed the EH sources currently being utilized for WSN applications and then presented some technological implementations for harvesting the various energy sources. EH resource allocation mechanisms were studied in Ahmed et al.[34] with a view to addressing the energy cooperation aspect in EH systems. Energy cooperation, which has emerged as an attractive area of research in EH, entails techniques used in EH systems that enable the sharing of information and energy resources among the various nodes in the sensor network to improve the energy efficiency metric.

Distributed WPT for IoT-WSNs

Distributed WPT system has been identified as having strong potential to overcome the challenges of low-
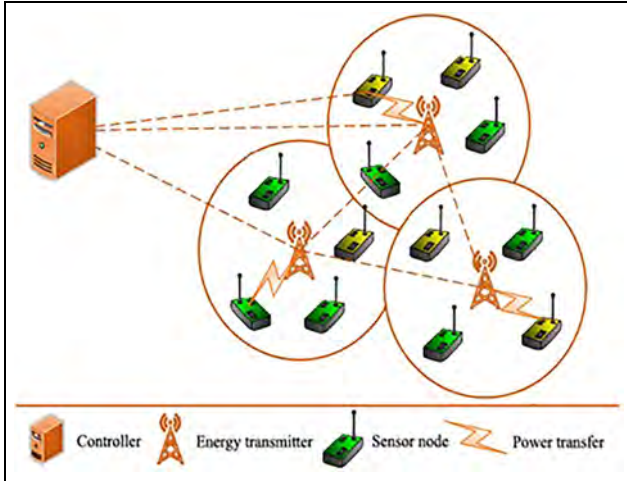
Figure 4. Architecture of efficient WPT in DSNs.

power efficiency. This type of system allows a number of distributed multiple power transmitters to wirelessly transmit power or energy to recharge IoT sensor devices. The big challenge is that each power transmitter contains an oscillator and controller, which makes it difficult to achieve phase and frequency synchronization among the power beacons, to possibly give room for optimal distributed beamforming. Choi et al.[35] studied the performance of distributed WPT system and showed that distributed wireless charging has many advantages in terms of coverage probability provided that the optimal beamforming is available in the distributed WPT system. Due to severe power attenuation of EM wave, RF-WPT systems used to supply power to IoT devices face the challenge of low-power transfer efficiency. The choice of distributed antenna system as a viable solution to the problem of attenuation of EM wave was considered in Choi et al.[35] and Zeng et al.[36] The reason being that multi-antenna systems with collocated antennas have the potential to effectively transfer power to only a restricted area within the vicinity of the antennas. The distributed WPT system has been studied in Madhja et al.,[2] Hong et al.,[4] Mai et al.,[37] Lee and Zhang,[38] Choi et al.,[39] Luo et al.,[40] Tanaka et al.,[41] Huang et al.,[42] Salem et al.,[43] Yuan et al.,[44] and Wang et al.[45] Hong et al.[4] examined the beam pattern selection and challenges of power charging allocation for distributed estimation applications in WSNs utilizing WPT to recharge sensors.

Figure 4 shows the architecture of efficient WPT technique in DSNs.

Application models of WPT in a DSN

This section presents a review of the different application models of WPT for DSNs. For a large-scale wireless sensor network (LS-WSN), the sensor nodes are in large quantities and are spatially distributed with random locations. RF-enabled WPT can be exploited to prolong the network lifetime by providing sustainable energy supply to the distributed sensor nodes through EM waves. RF-enabled WPT can provide a sustainable and controllable energy to the sensor nodes by charging their batteries via EM waves. The WPT model in a DSN can be classified into two main types: (1) omnidirectional WPT and (2) directional WPT. For the first category, RF energy signal is broadcasted equally by the energy transmitter (ET) (or power beacon) in all directions notwithstanding the locations of the energy receivers (ERs). In the second category, the radiated energy from the transmitter (power beacon) is directed in the locations of the power receivers through an energy beamforming. Two major design challenges with directional WPT for an LS-WSN are discussed in Wang et al.[45]

Distributed WPT for IoT-based system model

In this particular model,[39] multiple power beacons with RF energy are utilized to energize an IoT device (a receiver) wirelessly through the emission of RF wave. Each power performs energy beamforming by utilizing multiple transmit antennas. The model assumes k number of power beacons with n number of transmit antennas. A feature of this model is that by a cooperation between the power beacons, an optimal delivery of RF power to the IoT devices can be realized. Equation (1) shows a relationship between RF signal at time t with n number of antennas of k beacon

$$k_{k,n}(t) = Re[y_{k,n}(t)\text{Exp}(j2\pi f_c t)] \qquad (1)$$

where $y_{k,n}(t)$ denote the baseband transmit signal at time t with n antenna of k beacon, and f_c is the RF signal frequency. The transmit signal $y_{k,n}(t)$ can be obtained by the distributed beamforming algorithm. The transmit power with antenna impedance, Z_0, utilizing n number of antennas with k number of beacons is denoted by

$$P_{k,n}(t) = \frac{|y_{k,n}(t)|^2}{2Z_0} \qquad (2)$$

The gain from the channel of n number of antennas with k number of beacons to energize IoT devices is given by $g_{k,n}$. Each IoT device has an antenna with RF signal denoted by

$$\gamma(t) = Re[p(t)\text{Exp}(j2\pi f_c t)] \qquad (3)$$

where $p(t)$ is the baseband signal received at a time t given in equation (4) as

$$p(t) = \sum_{k=1}^{K} \sum_{n=1}^{N} g_{k,n} y_{k,n}(t) = \sum_{k=1}^{K} g_k^T y_k(t) \quad (4)$$

where g_k and y_k are, respectively, the channel gain vector and the transmit signal vector. The received signal power transmitted to the port of the sensor devices is denoted by

$$w(t) = \frac{|p(t)|^2}{2Z_0} \quad (5)$$

The received signal RF power at the sensor node is first converted (rectified) to dc voltage which is then used to power the sensor device.

WPT distributed estimation system model with a power transmitter and spatially distributed sensors

In this model,[37] an n_r antenna fusion center (FC) collects data from n_s spatially distributed sensor nodes. The model assumes that all sensor nodes initially lack conventional energy supplies and therefore need to harvest energy from the RF signal transmitted by the antenna FC for future use. Another assumption is that the sensors are not cooperating among themselves since they are spatially distributed. The model has two phases and adopts a time-switching harvest-then-forward protocol, whereby for every τT amount of time (here T is the length of a time slot), the FC transmitter sends its RF energy signal to the sensor nodes, and for $(1 - \tau) T$ remaining amount of time, the sensors utilize the harvested RF power to make observations and then forward same to the FC for estimation. The first phase is typically the EH phase, whereby the FC broadcasts its RF energy signal to the sensors for EH through the energy beamforming. Equation (6) shows the energy signal received at the nth sensor

$$r_k = g^{\dagger}_{k} x_e + m_k = g^{\dagger}_{k} \sum_{i=1}^{n_b} w_i s_i + m_k \quad (6)$$

where $x_e = \sum_{i=1}^{n_b} w_i s_i$ denotes the transmitted energy signal from the FC antenna; s_i denotes the energy-carrying signal for the ith energy beam, n_b is the number of beamforming, $w_i \in \mathbb{C}^{n_r \times 1}$ is the ith energy beamforming vector, while m_k denotes the additive noise at the nth sensor. Equation (7) represents the scavenged energy at the nth sensor, after ignoring the background noise for simplicity

$$E_K = \frac{\zeta_k T}{2} \sum_{i=1}^{n_b} |w_i^{\dagger} g_k|^2 \quad (7)$$

where $0 \leq \zeta_k \leq 1$ indicates the efficiency of EH at the nth sensor. The second stage is the information transmission phase whereby the sensors transmit their observations to the FC for estimation while using the harvested energy from the RF signal. Equation (8) shows the average power P_k used at the kth sensor for the information transmission phase

$$P_k = \frac{2(E_k - E_k^{cir})}{T} = \zeta_k \sum_{i=1}^{n_b} |w_i^{\dagger} g_k|^2 - \frac{2E_k^{cir}}{T} \quad (8)$$

where $E_k^{cir} \geq 0$ and denotes the circuit energy consumption at the kth sensor. Details of the model are discussed in Mai et al.[37]

WPT system model employing power chargers and an FC

This model[4] consists of a wireless passive sensor network having S passive sensor nodes, N RF-based power chargers, and an FC. In this model, there is a wireless power charger (h) having directional antennas to form P_n patterns of beam, and sensors with each having an omnidirectional antenna that is capable of wireless charging. The sensors can only receive energy from only the N chargers. The model adopts two phases of charging operation, which include (1) an exploration charging stage and (2) energy replenishment and data transmission operational phase. The first stage enables the system to locate the sensors (i.e. exploring the locations of the sensors and their accessibility). This phase also makes some mathematical computations of some important parameters of the channel. The last phase requires the ETs to transmit RF power to energize the energy-constrained sensors so that they can transmit their data to the FC. The stage ostensibly entails the transmission of RF energy by the power chargers to first replenish the energy-hungry sensor devices to enable them transmit their data. These transmissions are highly organized at the MAC layer. Details of the procedures adopted during the exploration stage and the impact it has on the channel state information (CSI) are provided in Hong et al.[4] The total power received by sensor i (sum of energy received from all power chargers) can be expressed in equation (9) as

$$\mathcal{E}_i(b, Q) \triangleq \sum_{n=1}^{N} \left(\sum_{p=1}^{P_n} a_{(n,p)} \gamma_{(n,p),i} \right) P_n T_c \quad (9)$$

where $b \underline{\Delta} [b_{(1,1)}, \ldots, b_{(1,p_1)} \ldots, b_{(N,1)} \ldots, b_{(N,P_N)}]^T \mathbb{Z}$ and $Q \underline{\Delta} [Q_1 Q_2, \ldots, Q_N]^T$. The vector signal received at the sensor t at the FC is denoted by equation (10)

$$r_t = h_t \sqrt{\frac{\mathcal{E}_t(b, Q)}{L_t}} (2b_t - 1) + w_t \quad (10)$$

where h_t denotes the coefficient of channel between the sensor t and the FC, and w_t is the channel noise vector.

Table 1. Classification of WPT in terms of radiative and non-radiative techniques.

WPT techniques			
Griffin and Detweiler,[14] Jawad et al.,[22] Xie et al.,[24] and Shinohara[26,49]	Radiative techniques	Non-radiative techniques	
	RF-based WPT	Magnetic resonant coupling	Inductive coupling
Field	Electromagnetic (EM)	Electric E, Magnetic (H), or EM	Magnetic (H)
Method	Antenna	Resonator	Coil
Efficiency	Low to High	High	High
Distance	Short to long	Medium	Short
Power	Low to high	High	High
Safety	EM	None (Evanescent)	Magnetic
Regulation	Radio wave	Under discussion	Under discussion
Frequency	GHz; $\geq$ THz	Up to GHz	Up to MHz
Directivity	High	Low	Low
Antenna devices	Dishes, rectennas, phased arrays, lenses, lasers, photocells	Tuned wire coils	Wire coils
Current/future applications	Solar-powered satellite, aircrafts, wireless and portable devices, space climbing, electric vehicles	To recharge mobile devices, powering buses, trains, biomedical implants, electric vehicles, RFID, smartcards, implantable devices, and WSNs	Mobile phones, electric brush, razor charging, pads, laptops, industrial heaters, and induction stovetops

WPT: wireless power transfer; EM: electromagnetic; RFID: radio frequency identification; WSN: wireless sensor network.

Details on wireless chargers' deployment when the locations of the sensors are known can be found in Sheikhi et al.,[46] Zhang et al.,[47] and Dai et al.[48]

Adaptive directional WPT system model

The system model[45] considers a wireless charging network where power beacons (PBs) are employed to wirelessly charge a sensor network via energy beamforming strategy. The beamforming strategy is adopted for the location of the sensors and RF energy is directed to only the nearby sensors that meet certain network requirements. This model considers the attenuation of EM radiation over distance; hence, there is need to limit the transmitted energy to mainly charge the sensors within the charging vicinity of the power transmitters. This system shows some similarity with omnidirectional WPT having uniform gain as seen in equations (11) and (12) when $P = 0$ or $P = Q$

$$G_P = 1 \ \text{for} P = 0 \tag{11}$$

where P is denoted as the number of sensors randomly active within a PB (e.g. $0 \leq P \leq Q$) and G is antenna gain (i.e. $G \geq 1$)

$$G_P = \frac{Q}{P}, \text{for } P = 1, \ldots, Q \tag{12}$$

The aggregate power received at the sensor, E_s, is calculated by summing the total power received from all the nearby power transmitters $E_{s,n}$, and those received from transmitters transmitting from afar $E_{s,f}$, which are radiated toward the sensor node at the origin 0 (0,0). Hence, we have

$$E_s = E_{s,n} + E_{s,f} \tag{13}$$

Details of calculating each of $P_{s,n}$ and $P_{s,f}$ can be found in Wang et al.[45]

Classification of WPT technologies for WSN applications

WPT technologies can be classified into two major categories: *radiative* and *non-radiative* techniques. Radiative techniques employ EM waves, especially RF waves, as a means of transferring power over longer distances. Conversely, non-radiative methods exploit both inductive coupling and resonant coupling as a means of transferring power at short distances to a wide range of appliances. Table 1 shows a classification of WPT in terms radiative and non-radiative techniques. Table 1 also shows the characteristics and different applications of WPT technologies for IoT-WSN scenarios. WPT technologies may also be classified as near-field and far-field WPT.[21,22,50] A technique is considered as near-field if the transfer distance[22] is shorter than the wavelength of the EM signal. In this case, the resonant frequency is relatively low (less than 5 MHz) with a short transfer distance of about 5 cm. In this

Table 2. WPT-based charging frameworks for DSNs.

WPT charging methods for DSNs	
Classification	References
Directional WPT	Wang et al.,[45] Li et al.,[50] Duan et al.,[53] Lin et al.,[54] Dai et al.,[55] Yang et al.,[56] Li et al.,[57] and Moraes et al.[58]
Omnidirectional WPT	Hong et al.,[4] Choi et al.,[35] Mai et al.,[37] Che et al.,[59] Wang et al.,[60] and Dai et al.[61]
Bidirectional WPT	Ding et al.,[62] Leung et al.,[63] Ota et al.,[64] and Liao and Lin[65]

WPT: wireless power transfer.

case, power is delivered to only nearby devices. Examples of near-field WPT include (1) magnetic inductive coupling,[11,14,15,21] (2) magnetic resonant coupling,[12,14,15,21] (3) capacitive coupling,[22] and (4) magneto dynamic coupling.[22] By contrast, far-field WPT techniques have the EM signal wavelength shorter than the transfer distance and power is delivered to far-reaching or remotely located devices.[5,22,51] Examples include radio waves[5,21,22,51,52] and microwaves.[22,51,52] However, the use of far-field RF energy transfer is associated with path loss which consequently reduces the RF power on the rectifying antenna (rectenna). Visser[52] proposed a method to optimize the propagation channel and subsystems of the rectenna to improve the RF energy transport efficiency.

WPT can further be classified based on methods of charging frameworks. In directional-based WPT, RF energy signal is directly transmitted toward the locations of the power receivers. In omnidirectional-based WPT, RF energy signal is broadcasted to the sensors for EH via the energy beamforming. Omnidirectional WPT may be critical especially for such cases when the locations of the sensor devices are indeterminate or cannot be controlled. This method has been applied for EH in a WSN, especially to deploy wireless chargers and employ some mobile robot to harvest RF energy signals.[23] The other method is bidirectional-based WPT. Power flow is bidirectional implies that the transmitter is also a receiver and vice versa. By this method, two sensor devices can be charged simultaneously without affecting the optimum power transfer efficiency. Table 2 shows WPT-based charging frameworks for DSNs.

Applications of WPT and EH in DSNs

EH and WPT have emerged with the capability of handling the challenges of energy demand in DSNs. The major disparity between the centralized and EH-WPT WSNs revolves around the life span of the senor

network. The conventional WSNs are energy-constrained and have limited lifetime of operation, which requires an optimization of the network lifetime. Conversely, the EH-WPT WSNs are intended to take adequate cognizance of the network's operational lifetime in order to achieve an unlimited lifetime of operation through an energy neutrality when deployed with a constant energy supply within an environment. For DSNs, EH-WPT has enjoyed many practical applications in the following areas: (1) environmental monitoring:[31–33] which includes air quality and water monitoring; (2) healthcare monitoring;[32,33] (3) disaster monitoring;[31,32] (4) safety, security, and military applications;[33] (5) structural monitoring;[32] (6) transportation, energy, smart buildings, defense, civil infrastructure, manufacturing and production;[28] (7) farming and foresting monitoring;[31] (8) animal tracking and control;[32,33] and (9) fire and flood detection.[50,66]

Environmental monitoring is a widely considered application area of EH-WPT technique for DSN scenarios. Some examples of environmental monitoring applications include monitoring of air parameters, especially in the urban areas where pollutants are likely to exceed permissible concentration limits. Other monitoring applications include temperature, conductivity, current, turbidity, and pressure monitoring. Animal tracking and control (both domestic and wildlife) presents some huge challenges in WSNs.[33] EH-WSNs have been applied in animal tracking and control to monitor animals' behavioral patterns and controlling them, observe the roaming of wild animals across a wide area and their breeding behaviors,[33] and give information about the various species of animals.[32,67] The information gathered as a result can guide researchers for effective protection, sustainability, and scientific management of wildlife resources.[68]

Safety, security, and military applications exploit unmanned aerial vehicles (UAVs) to perform different application terrains, including supporting rescue operations, military trainings, tracing the location of a sniper, and tracking the direction of a bullet. For instance, EH-WPT is used to recharge the batteries of UAVs to prolong their operational lifetime. UAVs equipped with microwave power transfer (MPT) capability can be remotely applied to recharge the batteries of the sensor devices in order to harvest their data. A study of this application was conducted in Li et al.,[50] Wang et al.,[66] and Zeng et al.[69] as a practical means of deploying a large number of wireless powered sensor nodes into even the most difficult harsh terrains and inaccessible areas. A comprehensive study on the opportunities and challenges of wireless communications with UAVs is given in Zeng et al.[69] Some key limitations of UAV-assisted MPT technique are presented in Li et al.[50] and include that EH and data transmission operations can be hampered by the movements of the UAV and that

Table 3. A comparative summary of WPT technologies for IoT scenarios.

WPT technologies	Strengths	Weaknesses
Magnetic inductive coupling[11,14,15,22,24]	Short energy-transfer distance It is simple and non-radiative High power transfer efficiency (95%) at short ranges Simple implementation Most widely used as charging pad for all phones and electric toothbrushes	The power transfer efficiency is drastically reduced as the distance between Tx and Rx widens apart Requires accurate alignment in charging direction Produces Eddy current (heating effect) over metal Short charging distance Inappropriate for mobile use
Magnetic resonant coupling[14,15,22,72]	Long energy-transfer distance LOS is not needed High power transfer efficiency using omnidirectional antenna Unaffected by weather conditions Suitable for everyday use/mobile apps Does not require alignment in the charging direction Can concurrently charge several devices on different power	Low transfer power for consumer devices with increased heating Low efficiency due to axial mismatch btw receiver and transmitter coils Not applicable for long-range battery charging Axial mismatch between transmitter and receiver and interference Decreased efficiency with increased distance Complex implementation
MPT[13–15]	LOS is needed to transfer energy through EM radiation successfully. RF waves are used to recharge the battery Have large charging coverage	Requires a clear LOS between Tx and Rx Weather and physical objects can obstruct the LOS between Tx and Rx and prevent the transfer of power Suffers from propagation loss due to long distance transmission RF exposure can cause health impairments Power transfer is difficult at longer distances with a highly directional antenna
RF energy transfer[20,73,74]	Can be used to realize far-field WPT in inaccessible environments Can reduce the energy consumption in smart buildings and can achieve RF to DC conversion efficiency Energy is provided to many receivers at the same time	Low RF energy transfer efficiency RF power transfer efficiency diminishes over increasing distance Required sophisticated tracking mechanism Sensitive to obstructions Raises strong safety concerns

WPT: wireless power transfer; LOS: line of sight; MPT: microwave power transfer; RF: radio frequency.

an up-to-date information about the ground sensors (battery level, data queue length, etc.) is not usually available to the UAV. A comprehensive review on near-field WPT technologies for UAV applications is provided in De Moraes et al.[70] The authors highlighted current studies exploiting near-field WPT techniques to deploy UAVs and investigated common challenges such as charging distances, transfer efficiency, and transfer power affecting UAV applications. Some near-field WPT methods were also investigated and it was found that both inductive coupling and magnetic resonant coupling are more suitable options than the capacitive coupling for both power transfer and UAV charging.

EH-WPT applications in health sector entail providing energy to the body sensors used for patients' monitoring, drug administration, and patients/doctors' tracking.[33] Body sensor networks are employed in the medical sector for such application-specifics. They are deployed as a wireless body area network (WBAN) for preventive healthcare, including monitoring the activities of human body and physical functions.[32] EH-WPT enables WBANs to be more practically efficient since both system size and equipment costs are drastically minimized.[32,71] Table 3 gives a comparative summary of WPT technologies for IoT scenarios.

An exciting research area of WPT applications as posited in Shinohara[49] is the wireless charging of EVs. The different WPT technologies in Table 3 can be applied to charge electric vehicles (EVs). There are discussions on regulation and safety issues, which reveal that inductive coupling WPT is leading ahead of RF-based technique with very promising potential approaches.[26] However, magnetic resonant WPT is considered above other WPT techniques owing to its high efficiency at mid-range transmissions, adequate safety, and absence of interference effects.[14,49]

Microwave power transfer (MPT) charging has the advantage of being employed in multipurpose functions for the simultaneous transmission of both power and data over the same channel.

To show the pervasiveness of EH-WPT technologies, it has been demonstrated by a considerable number of companies capitalizing on WPT ideas. Some of the companies which have applied WPT ideas include[73] WiTricity, Ossia, Energous, Proxi, and Powercast. These technologies are employed to demonstrate the practical approaches whereby energy can be efficiently harvested from an ET by the energy harvesters wirelessly.

Far-field RF-based WPT has remained poorly commercialized[26] due to regulations in radio wave. Although recently being promoted by two US-based companies, the use of far-field WPT is yet at infancy stage. Conversely, near-field WPT has already received commercialization. For instance, we already have countless wireless chargers used for mobile phones termed the Qi standard by Apple, Inc. Another area of application of inductive coupling is found in the electric vehicle (EV) and bus industries. For instance, Europe and China have used near-field wireless chargers for their public buses.

Opportunities and challenges of EH-WPT in DSNs

This section presents a study of the opportunities and challenges of EH-WPT technologies in DSNs. Many sources of EH have been known but the harvesting mechanisms still remain a big challenge in most cases. Recently, research efforts have shifted toward the following most common sources of ambient EH from the environment for WSN applications: wind, vibrational, solar, water, EM, thermal, and RF-based energy sources, which are transformed to electrical energy. Unfortunately, EH for small-power devices used for WSN applications is challenging due to their size and compatibility with the harvesting devices.[30] And designing EH circuits has also posed a very serious challenging and complex task owing to their high reliance on the source of EH, energy storage devices, underlying application's requirements, and power management capabilities. Incidentally, the solar power EH mechanisms are the most widely used owing to their availability on-demand and consistent EH capabilities during the day. However, solar power EH suffers some challenges due to some operational bottlenecks in their accessibility at night periods or extreme bad weather conditions.[30]

As discussed earlier, the most popular technique of EH is the solar power EH mechanism.[5,16] Solar EH has been employed for environmental monitoring implementations. While solar EH may be a preferred option for such applications running in remote and inaccessible areas, the amount of harvested energy is still subject to seasonal constraints and the deployment areas of the solar panels. This type of EH mechanism is greeted with several challenges, including difficulty in controlling the intensity of direct sunlight, which may be further affected by variations in seasonal patterns and weather conditions. For example, environmental applications may require the deployment of nodes to areas that do not receive substantial amount of light during the day and do not receive at all at nights. This will gravely affect the operational cycle of the sensors. Therefore, solar and wind EH mechanisms are limited by the durations and strengths attached to radiation or wind,[5,17] which are subject to weather or seasonal constraints.[5,30] For instance, there may be insufficient sunlight at night to generate the required energy.[18] However, such solar EH mechanisms can only remain operational especially during non-harvestable periods by utilizing some storage banks such as battery or supercapacitors. Besides, due to the incompatibility in the size of wind turbines in respect of WSN applications,[30] wind EH has been greeted with many challenges.

The importance of safety and security considerations for efficient and dependable operations in EH-WPT networks is now being given serious considerations. Researchers have mainly focused on the opportunities offered by WPT and EH techniques, especially RF-based WPT techniques. However, these opportunities also come with inherent challenges, including safety and security considerations, which are yet to draw the needed attention of researchers. New solutions are needed to address the recent security and safety concerns raised as a result of the long-range application of RF-based WPT. Basically, security for RF-based WPT systems is mainly focused on ensuring the traditional security mechanisms, including integrity, confidentiality, and availability.[73,75]

Security considerations

Owing to the open nature of the transmission medium, a WSN is susceptible to security attacks. Security has become even more critical owing to the large-scale deployments of these sensor devices. As WSNs find applications in diverse areas, confidentiality is crucial to secure data communication between the sensor devices of a network or between the sensors and the sink node.[76] And transmitted information needs to be verified that an adversary has not hijacked the transmission channel. A compendium of security threats affecting WSN applications include spoofing attacks, denial of service, node subversion, sinkhole attacks, jamming attacks, and Sybil attacks. A comprehensive

study of the various security threats, issues, and challenges in WSNs is provided in Sharma et al.,[77] Bangash et al.,[78] Yang et al.,[79] Ijemaru et al.,[80] Teymourzadeh et al.,[81] and Kumar et al.[82] Owing to the high necessity for mobility, sustainability, and large-scale distribution of sensor devices, the conventional power cords have automatically and dramatically gone into extinction since they prohibit these demands. Besides, battery replenishment is generally infeasible and incurs huge costs. Fortunately, these demands have given rise to the emergence of EH-WPT technologies. However, the use of RF-based WPT technologies for powering cyber-physical systems (CPSs) has also come with increasing challenges.

A fundamental challenge of RF-based WPT approaches is the security of data being transmitted over the cyber network. Due to the free-space nature of the communication medium of WPT networks, an adversary harvester can interfere with the process of charging operation and either hack some useful information or expose the system to unexpected security and safety vulnerabilities. CPSs are described as smart systems employing cyber technologies embedded in and cooperating with physical components.[83–85] The key CPS challenges are discussed in Leitão et al.[85] while Radanliev et al.[83] outline some of the security measures. As a countermeasure for preventing CPS vulnerabilities, Radanliev et al.[83] and Zhu et al.[84] proposed an anti-malicious and anti-tamper system engineering and the development of unique security solutions that can fill the gap where information technology (IT) solutions do not apply.

The potential vulnerabilities and threats associated with a mobile WPT technique, particularly the Qi wireless charging for mobile devices, were studied in Wu et al.[86] Authors discussed the possibility of an adversary injecting some adversarial coil with malicious data into the communication channel. The effect of this can be very disastrous as the adversary can minimize the efficiency of charging by increasing the power going to the sensors and cause overheating, battery explosion, or abruptly terminate the power to starve the sensors of energy replenishment. Following conversations on cyber risks for RF-based WPT networks, a six-layered security architecture is proposed in Zhu et al.[84] for CPS motivated by the OSI. Table 4 provides a summary of the security and safety considerations in a WSN and their countermeasures.

Safety considerations

RF-based WPT technologies utilize EM wave radiation to wirelessly transmit power to the sensor-based devices in the DSNs. Due to safety considerations, RF-based WPT technique cannot be employed to radiate EM waves of high magnitudes of power, thus restricting the

Table 4. Security and safety considerations in EH-WPT networks and their countermeasures.[73]

Security attack type	Potential countermeasure
Jamming	Conduct scheduling, and interference alignment
Safety	RF exposure and temperature estimation
Beamforming	Dynamic power, frequency, and phase adaptation
Software	Running trusted applications and checking application signatures
Charging	Scavenged energy estimation
Monitoring	Conduct period scanning of the transmission channel
Spoofing	Authorization and authentication

RF: radio frequency.

full exploitation of this technology and bringing restrictions to the charging coverage of the power transmitter. Safety and security issues surrounding RF-WPT are robustly discussed in Liu et al.,[73] Collado et al.,[87] Li et al.,[88] and Dai et al.[89] Li et al.[88] discussed the vulnerabilities associated with RF-based WPT channel (as there is no encryption or authentication of the wirelessly transmitted energy), thus raising users' safety and security concerns. In a bid to quench the thirst of power-hungry sensor devices, there may be cases of more deployments of power transmitters across the networks. This deployment may incidentally expose users to more harmful effects of EM radiation. Hence, an efficient safe-charging operation must guarantee the safety of users from the exposure of EM radiation exceeding a safety threshold. A detailed survey on challenges for safe WPT networks is given in Liu et al.[73]

The following are some of the major highlights from certain aspects of safety and security considerations in RF-based communication networks:[73]

- It will be difficult to either encrypt or authenticate wirelessly transmitted energy in a bid to ensuring confidentiality of replenishing an energy-hungry node. Because wireless power transmission channels are highly vulnerable, users' security and safety are not guaranteed and efficient transmission of power may be unattainable.
- Compared with the radiated power from the traditional RF communication transmitters, it is expected that, on the average, the commercial WPT network systems have much higher radiated power. Unless safety regulations are applied to wireless power transmissions, safety concerns will continue be on the increase as there are possibilities that safety thresholds may be breached.

- Provision of adequate security under limited energy resources will be challenging since RF-based WPT networks will not likely provide the required energy at the node to perform security-related computations required by the conventional security mechanisms.

Charging conflicts as a result of improper coordination

Charging conflicts may arise in a situation whereby a request from an ER to a power transmitter causes a sudden rise in the RF exposure of the networks above the safety threshold because another ET is already responding to an energy request from another receiver by radiating (or transmitting) its energy to the receiver. In the midst of several ETs and receivers, a malicious ER which is fully charged may prevent other ERs from being replenished by reporting a high RF value above the threshold and subsequently prompt ETs to switch off their power transceivers or significantly minimize their rate of power transmission and consequently deprive many neighboring nodes of energy replenishment. Because power transmitters always expect requests and feedback from the receivers, a malicious ER can purposely inject malicious feedback to undermine the general transmission efficiency. A situation may also arise whereby greedy and cheating ERs become the most beneficiary by continuously sending charging requests to the power transmitters with the intention of starving other neighboring receivers of energy replenishment. This becomes more problematic in such cases where the power transmitters are equipped with directional antennas. Others in this category include free-rider ER and greedy and cheating ER and are discussed in detail in Liu et al.[73]

Scheduling problems

Scheduling the WPT and data collection has become very critical in order to prolong the battery lifetime of the sensors and also reduce packet loss. Moreover, inadequate scheduling can result in unprecedented wastage of harvested power which could be used for data transmission activities and battery drainage of the sensor devices. Therefore, it is expedient to optimize scheduling operations of ETs and data collectors to minimize cost.

In Ijemaru et al.,[5] Liu et al.,[73] Collado et al.,[87] and Dai et al.,[89] a simplified safe charger scheduling scheme was proposed whereby power chargers are scheduled to recharge the energy-hungry devices without accommodating the risks inherent in RF radiation. The goal is to maximize charging efficiency so that more charging energy can be harvested at a normal threshold value of EM radiation.

RF-based EH-WPT

RF-based EH refers to a mechanism whereby the rectifying antennas (rectennas) are employed to capture EM signals emitted from nearby sources capable of generating high EM fields (e.g. mobile phones, TV signals, or radio stations) and convert to usable DC voltage. A rectenna is a key technology in EH-WPT architectures. The components consist of an antenna—used for receiving microwave power, a low-pass filter—to prevent higher harmonics entry to the rectifier, a rectifier with diodes and output filter—for rectifying received signals. Among the various EH mechanisms, RF-based EH-WPT mechanism has shown the most promising alternative even though it has the least power density.[90] This is because RF energy signals are pervasive whose systems have the potentials of harvesting adequate energy to power many sensor devices. Hence, RF energy harvesters deliver more viable energy source for WSN and IoT-based applications. A comprehensive review is given in Cansiz et al.[90] RF-based EH-WPT is considered to be suitable for low-power applications.[34]

EH-WPT networks are formed by ET devices and ER devices. The ETs can manage power transmissions in order to charge the various kinds of energy-hungry ERs with harvestable circuits used to convert the harvested RF signal to usable dc for battery charging operations. RF-based EH-WPT has drawn significant attention as approaches that promote battery-free sustainable wireless networks. The keystone of RF-based EH-WPT systems is the rectennas (rectifying antennas)—described as antennas connected to rectifiers for harvesting RF energy, which critically determine the amount of energy (dc power) harvested at the load. Figure 5 is the circuit diagram of an RF EH system, showing the major components.

Although RF-based EH can be harvested without limits, there are still several drawbacks associated with the technique and they include low power density and low efficiency that is proportional to the distance.[28,91] However, from the various reviews,[1,23,28–34] we state that RF-based EH remains the best solution for various application scenarios related to low-energy IoT devices. Eltresy et al.,[92] Caselli et al.,[93] and Lin et al.[94] highlight the RF-based EH potentials for IoT-based environmental and healthcare monitoring applications. There are other approaches exploiting RF-based EH techniques and include opportunistic charging from nearby smartphones.[95]

Advantages of RF-based WPT

Future advancements in the efficiency of WPT will create myriads of opportunities for the indispensability of the technology to numerous embedded systems, including sensors and wireless cameras. Some of the many
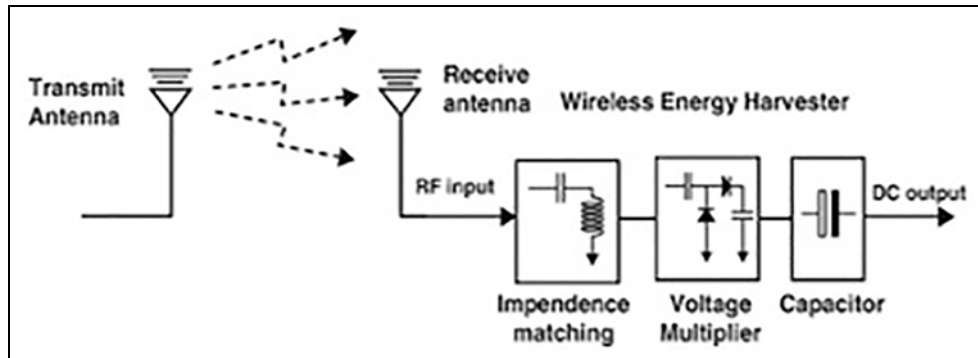
Figure 5. An RF energy harvesting system.

practical advantages exhibited by WPT as discussed in Liu et al.[73] include the following:

- Simultaneous provision of energy to several receivers via its broadcast nature,
- Low complexity,
- Size and cost of the ER hardware,
- Sustainability for mobile devices,
- Can be applied for small-power sensor devices, including RFID tags.

Application of RF-based EH-WPT with Powercast energy harvester

We present a practical and real-time implementation of RF-based EH-WPT technique using the Powercast harvesters. This approach relies on the intentional EH in which an active component (e.g. RF transmitter) is used to supply the desired energy needed in the environment for the devices. This approach is supported by Powercast with RF transmitter (3 W, 915 MHz) and receivers (P2110 and P1110). The Powercast has a continuing mission to achieve long-range wireless power that could remotely charge enabled devices and an increased efficiency by which RF energy can be harvested to power embedded devices. Powercast has helped in finding solutions to various wireless charging challenges, including powering WSNs, waterproof designs, radio frequency identification (RFID) tags, and reusable smart bands. Powercast employs its contactless charging technology to provide wireless power to several enabled devices that are within the charging range without requiring any direct LOS.[96]

Powercaster power transmitter-TX91501

The Power transmitter from Powercast is an RF-based transmitter specially meant to transmit both data and power to ERs embedded with Powercast P2110 or P1110 energy harvesters.[97] The TX91501 transmitter is stored in a robust plastic case containing many mounting options. TX91501 transmitter sends RF energy to Powercast power harvester receiver implanted in a device. The harvested energy is converted by the ERs to DC (achieving up to 80% conversion efficiency)[96] which is used to power the battery of the device.[96] The power harvesters operate across a wide RF energy (as low as -17 dBm) and frequency range of 10 MHz–6 GHz. The TX91501 transmitter operates at regulated voltage of 5 V DC, an output power of 3 W Equivalent Isotropic Radiated Power (EIRP), and a frequency of 915 MHz. In terms of modulation, TX9150 transmitter uses the direct sequence spread spectrum (DSSS) for power and the amplitude shift keying (ASK) for data. Some of the descriptions are contained in Table 5. The TX91501 Powercaster transmitter has been applied in several applications, including monitoring, automation, battery charging, wireless trigger, and low-power electronic devices. Both data and power can be broadcasted from a distance of 40 ft to the ERs.

Powercast power harvester receivers

The Powercast power harvester receivers are RF EH devices that convert RF to DC. The receivers provide RF harvesting and power management to battery-free and micro-power devices. The converted DC is stored in a capacitor. Charging is automatically disabled when the charging threshold is attained. The present study considers two power harvester receiver chips and modules: P1110 and P2110. Table 6 shows a comparison of the two power harvesters used in the experiments.

Advantages of RF-based powercast technology

Powercast technology provides several advantages using RF-based technology. Some of these benefits include the following:[100]

- High RF-to-DC conversion efficiency: The power harvesters can achieve over 75%

Table 5. Basic descriptions of TX91501 Powercaster 915 MHz Transmitter.

Element	Description
Frequency	915 MHz center frequency
Output power	3 W EIRP
Modulation	Power: DSSS
	Data: ASK
Data communications	An 8-bit, randomly broadcasts up to 10 ms with ASK mod.
Beam pattern	60° width, 60° height
Installation environment	Indoor use
Power	5 V DC/1 amp

EIRP: equivalent isotropic radiated power; DSSS: direct sequence spread spectrum; ASK: amplitude shift keying.

conversion efficiency, thus permitting high range of power transmission.

- Large efficiency range: The modules are meant to achieve high efficiency over a range of input power and frequency. The receiver has capabilities of receiving power concurrently from several harmonics.
- Achieves distant power transfer and eliminates the need for base charging stations.

- Devices are recharged wirelessly.
- Multiple units can be recharged concurrently.
- Embed with ease.
- Adaptability: The power harvester module is adaptable with any correct frequency band.
- Eliminates charging ports.

Figures 6 and 7 show the functional block diagrams of two RF power harvester receivers P1110 and P2110, respectively, which operate at 915 MHz and harvest the RF input power in the range of -5 to $+20$ dBm. The RF energy harvesters convert the RF energy (radio waves) into dc power, which can be stored in a supercapacitor or used to directly power a circuit. Since the input power is constant, the charging current decreases as the voltage on V_{OUT} pin increases. P1110 monitors the voltage on the storage element and turns off V_{OUT} when it is fully charged. The maximum output voltage from the harvester can be adjusted between 0 and 4.2 V. The functional descriptions of all the pins in the diagrams are provided in Table 7.

Evaluation of the received RF power and gains

Our experiment has utilized power meters—this provides correct measurement of RF power, the simplified

**Table 6.** A comparison of two RF power harvester receivers.

A comparison of RF power harvester receivers

Receivers	Similarities	Differences	Applications
P2110[98]	High conversion efficiency, >70% Internally matched to 50Ω Wide RF range application Capabilities and I/O to provide RSSI No external RF components are required Industrial temp. range	Designed for battery-free devices Configured, regulated output voltage of 5.5 V Long-range, pulsed power receiving module Small RF input for an extended operation RF harvestable range can reach -12 dBm input Can transform small-level RF signals to enable long-range application. The I/O is interfaced to microcontrollers for intelligent control and power usage is optimized using a microprocessor	Non-battery-operated wireless sensors Battery recharging Wireless triggers Small-power electronic devices
P1110[99]	High conversion efficiency, >70% Internally matched to 50Ω Wide RF range application Capabilities and I/O to provide RSSI No external RF components are required Industrial temp. range	Designed for battery charging devices Configurable maximum output voltage up to 4.2 V Short-range, higher power receiving module High efficiency of charging at short distance RF harvestable range down to -6 dBm input Low power consumption Connect directly to rechargeable batteries such as Li-ion and Alkaline	Wireless battery charging Remote battery charging Non-battery-operated wireless sensors Wireless triggers Low-power displays Data logging

RF: radio frequency; I/O: input/output; RSSI: received signal strength indication.

Table 7. Pin functional description.

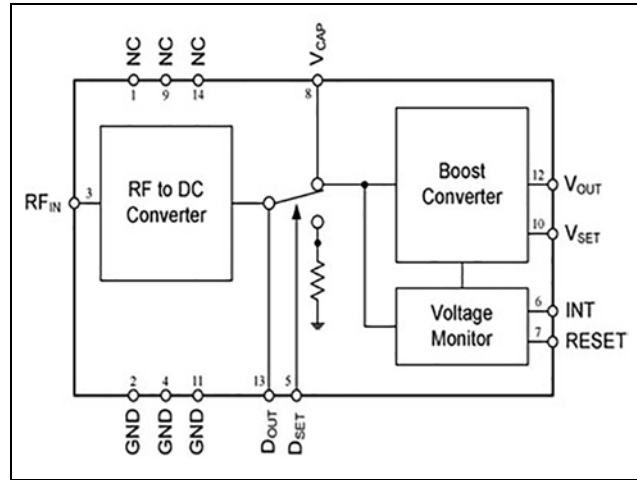| Pin	Label	Function/description
I	L1	li-ion/L1P0 recharging pin. Connects directly to the analog ground plane for 4.2 V max. recharging.
2, 4, 7	GND	RF Ground. Connects to analog ground plane
3	RF_{IN}	RF Input. Connects to 50Ω antenna through a 50Ω transmission line. Add a DC block if antenna is a DC short
5	D_{SET}	Digital Input. Set to enable measurement of harvested power. If this function is not desired leave no connection (NC).
6	V_{SET}	Maximum output voltage adjustment. Sets the max. output voltage on the V_{OUT} pin. Connects to an external resistor. No connection when using L1 or ALK pin
8	V_{OUT}	DC output. Connects to external storage device. Maximum output voltage set by V_{SET}, L1, or ALK pin.
9	D_{OUT}	Analog output. Provides an analog voltage level corresponding to the harvested power.
10	ALK	Alkaline recharging pin. Connects directly to the analog ground plane for 3.3 V maximum recharging.

RF: radio frequency.
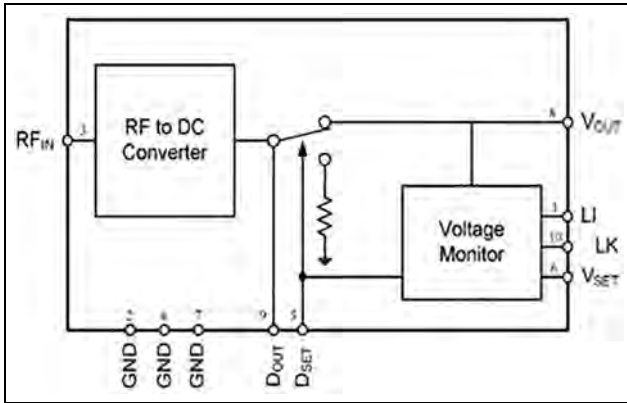
Figure 6. A block diagram of RF-based energy receiver (Powercast P1110).

Figure 7. A block diagram of RF-based energy receiver (Powercast P2110).

Friis equation—this gives a practical estimation of the total received power that is ready for use. The beam efficiency is evaluated using Friis free-space propagation model in equation (14). The Friis propagation model can be applied at a far-field since the model assumes far-field for a plane wave and near-field for a spherical wave.[5] The relationship between the received power P_r (watts), transmitted power P_t (watts), and the WPT is usually associated with Friis free-space propagation model given by

$$\frac{P}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \qquad (14)$$

where G_t and G_r are the transmitting antenna gain and receiving antenna gain, respectively, λ denotes the wavelength of signal power in meter, and R is the power transfer distance (in meters) between the transmitter and the receiver.

The Friis free-space propagation model is used to model an LOS path loss experienced in free-space environment. It has validity in the far-field area of the transmitted antenna[70,101,102] and derives its basis from the inverse square law of distance which states that the energy received at a given distance from the ET is inversely proportional to the square of the distance. Equation (14) is employed for RF transmission and in situations where one of the antennas needs to be found, if their distance of separation is known. The gain of the antennas (in decibels) can be changed to power ratio in equation (15)

$$G = 10^{\frac{G_{dB}}{10}} \qquad (15)$$

where
$G_{dB} = 10 \times \log \left(\frac{\pi R}{\lambda}\right)^2$

or

$$G_{dB} = 10 \times \log G \qquad (16)$$

The antenna gain gives the ratio of the signal power received or transmitted by a given antenna to an isotropic or dipole antenna. It is achieved by making an antenna directional and can be evaluated by comparing the measured transmitted/received power by the antenna in a definite direction to the transmitted/received power by a hypothetical ideal antenna in the same direction. The wavelength of the signal power λ can be calculated using equation (17)

$$\lambda = c/f \qquad (17)$$

where c denotes the speed of light given as $c = 3 \times 10^8 \text{m/s}$ and f denotes the frequency.

For a quick and easier evaluation, a simplified form of Friis propagation formula is given on a spreadsheet by the Powercast company in Powercast,[103] where a practical estimation of the total radiated power, received power, and available power for usage is evaluated. The radiated power from a transmitting antenna has a uniform power density in every direction. The power density (P_D) at a given range R refers to the ratio of the transferred power by the area of surface of a sphere ($4\pi R^2$) at the distance. Equation (18) shows that the power density (P_D) decreases by the square of the distance

$$P_D = \frac{P_t}{4\pi R^2} \qquad (18)$$

where P_t denotes the average power and R denotes the separation between the transmitting and receiving antennas. Most of the radiated energy is broadcasted using directional antennas in a specified direction. The antenna gain G_t denotes the ratio of radiated power in the specified direction in comparison with the radiated power from an ideal antenna in the same direction. Hence

$$G_t = \frac{\text{max. power of actual antenna}}{\text{power of isotropic antenna with same input}}$$

The power density at a distant position of a radar with an antenna gain G_t denotes the power density of an ideal/isotropic antenna times the radar antenna gain and is given as

$$P_D = \frac{P_t G_t}{4\pi R^2} \qquad (19)$$

Experimental results and analysis

The Powercast wireless power calculator is used. This calculator is based on the simplified form of Friis equation and gives a realistic approach and practical estimation of the total received power/energy and available power for use. The following denote the settings and components used: input parameters (frequency = 915 MHz, wavelength, λ = 0.328 m), P2110 at a regulated output voltage up to 5.25 V, 50 mA output current, and 1150mAh battery capacity, and P1110 at a regulated output voltage of 4.2 V, output current of 50 mA and 1150mAh battery capacity. In the tables, P denotes the available DC power after conversion (i.e. the output of power harvester), while P_r denotes the received RF power before conversion (i.e. the input to the power harvester). The distance R between the antennas is varied and readings are tabulated as shown in Tables 8–14. Figures 8–11 show some graphical analysis of the results obtained from the experiments.

Results showed that both energy harvesters reached an optimum point in their recharging times with high conversion efficiencies in their different applications. The experimental results present P2110 power harvester to be more efficient for long-range applications, while P1110 power harvester showed higher efficiency for short-range applications. The experimental results also showed that for the same transmission range, P1110 power harvester showed a higher RF-to-DC conversion efficiency than P2110 power harvester (as seen in Figure 10). However, it has a longer recharge time than P2110 power harvester for the same transmission distance (as seen in Figure 11). These results essentially give useful insights into the uniqueness of the two RF-based power harvesters for their different requirements and application scenarios in DSNs.

One of the necessary conditions to apply the Friis equation is that the distance (R) between the transmitting and receiving antennas must be far greater than the wavelength of the signal power (i.e. $R >> \lambda$) such that both antennas are in the far-field of each other. Hence, the distance R is large enough to ensure a plane wave front at the receive antenna is sufficiently approximated by $R \geqslant 2d^2/\lambda$ where d is the largest linear dimension of either of the antennas. Friis free-space propagation model is valid only in the far-field region of the transmitting antenna. The far-field condition necessary to apply Friis model may not be completely satisfied at distances of 1 and 2 m for the wavelength of λ = 0.328 m. That is, the distance R must be far greater than the wavelength λ to meet the far-field Friis condition. Thus, this could be a cause of the very high efficiencies seen at these distances and a sudden jump from 51.6% to 54.1% in Table 8.

Conclusion

Recent research efforts in devising techniques for prolonging the network lifetime of a WSN have mainly

Table 8. Power harvested by P2110 at a linear gain of 3.98 dB.

P2110 harvester

Distance (m)	P (μW)	I (μA)	Recharge time (h)	Efficiency (%)	P_r (μW)
1	4186	3488	24.24	51.6	8119
2	1097	915	92.46	54.1	2030
3	413	344	245.86	45.8	902
4	238	198	426.61	46.9	507
5	159	133	637.49	49.0	325
6	107	90	943.98	47.7	226
7	70	58	1446.14	42.3	166
8	45	37	2258.20	35.4	127
10	11	9	9653.33	12.9	81
11	1	1	87,957.96	1.7	67

Table 9. Power harvested by P2110 at a linear gain of 13 dB.

P2110 harvester

Distance (m)	P (μW)	I (μA)	Recharge time (h)	Efficiency (%)	P_r (μW)
2	3537	2948	28.69	53.4	6628
4	875	729	115.94	52.8	1657
6	328	273	309.62	44.5	736
8	200	167	506.82	48.3	414
10	129	108	785.37	48.7	265
12	82	68	1239.35	44.5	184
15	36	30	2828.79	30.4	118
17	18	15	5759.31	19.2	92
19	5	4	18,841.66	7.3	73
20	1	1	89,044.36	1.7	66

Table 10. Power harvested by P1110 at a linear gain of 13 dB.

P1110 harvester

Distance (m)	P (μW)	I (μA)	Recharge time (h)	Efficiency (%)	P_r (μW)
2	3538	884	27.09	53.4	6628
4	1043	261	91.91	62.9	1657
6	249	62	385.51	33.8	736
7	28	7	3484.47	5.1	541
7.5	12	3	8000.07	2.5	471

Table 11. Energy harvested by P2110 with patch antenna at a gain of 6 dB.

P2110 harvester using patch antenna

Distance (m)	P_r (μW)	I (μA)	Efficiency (%)	P (μW)
2	2039.39	1010	59.21	1210
4	509.85	220	50.74	260
6	226.60	80	42.89	100
7	166.48	50	33.18	60
10	81.58	10	8.52	10

Table 12. Energy harvested by P1110 with patch antenna at a gain of 6 dB.

P1110 harvester using patch antenna

Distance (m)	P_r (μW)	I (μA)	Efficiency (%)	P (μW)
2	26510	4910	74.10	19650
4	6630	1160	69.91	4630
6	2945.79	490	66.67	1960
7	2164.25	340	63.39	1370
10	1060.48	90	32.69	350
11	876.43	30	12.58	110

**Table 13.** Power harvested by P2110 using Dipole Antenna at a gain of 6 dB.

P2110 harvester using dipole antenna

Distance (m)	P_r (μW)	I (μA)	Efficiency (%)	P (μW)
2	9940	4040	48.74	4850
4	2485.51	1230	59.28	1470
6	1104.67	540	58.55	650
7	811.59	380	57.03	460
9	490.96	210	50.74	250
12	276.17	100	42.89	120
15	176.75	50	33.18	60
17	137.61	30	26.94	40
19	110.16	20	18.37	20
20	99.42	20	18.37	20
22	82.17	10	8.52	10
23	75.18	10	8.52	10

Table 14. Power harvested by P1110 using Dipole Antenna at a gain of 6 dB.

P1110 harvester using dipole antenna

Distance (m)	P_r (μW)	I (μA)	Recharge time (h)	Efficiency (%)	P (μW)
2	9940	1890	62.50	76.03	7560
4	2485.51	410	220.78	66.16	1640
6	1104.67	90	898.72	32.69	360
7	811.59	300	2600.87	12.58	100
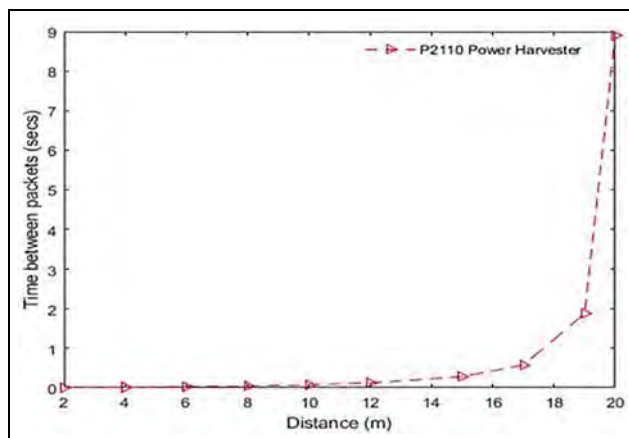
Figure 8. Variation of time interval between packets with distance (P2110 power harvester).
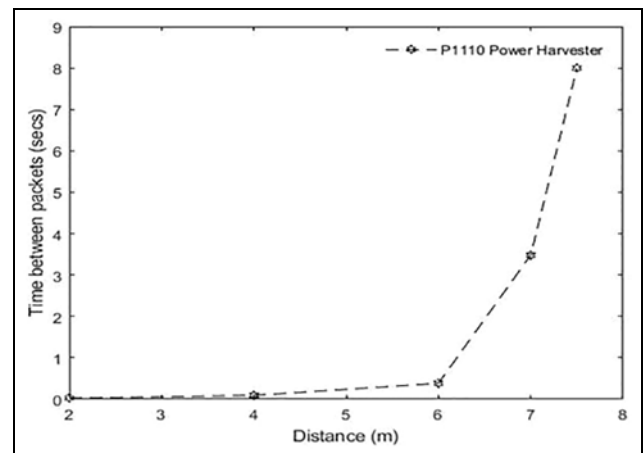
Figure 9. Variation of time interval between packets with distance (P1110 power harvester).
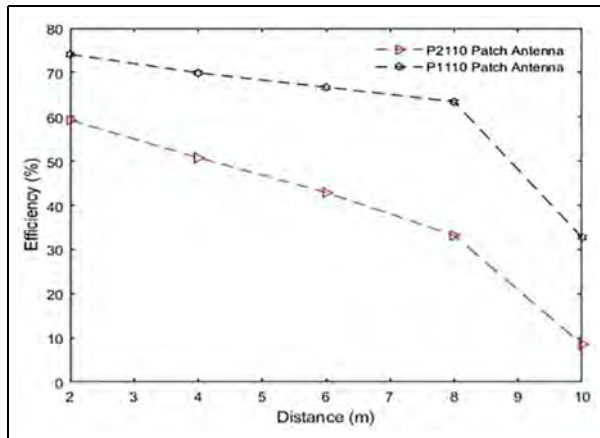
Figure 10. Comparison of RF-to-DC conversion efficiency using different patch antennas.
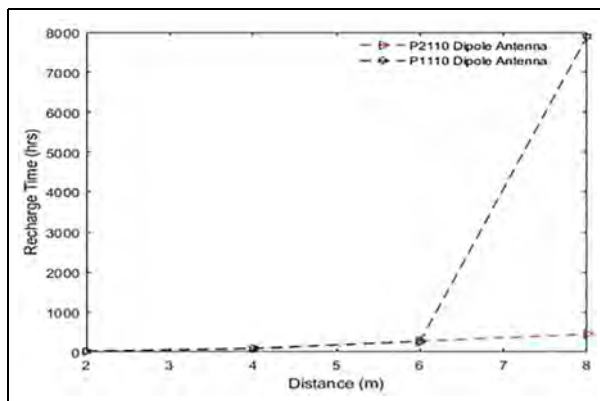
Figure 11. Comparison of battery recharge time of two dipole antennas.

focused on the opportunities offered by EH-WPT technologies, especially the RF-based EH-WPT technique. However, these opportunities also come with inherent challenges. This article has therefore presented a comprehensive study of the current state-of-the-art EH and WPT technologies to prolong the lifetime of the sensor nodes used for DSN applications and highlighted their various opportunities, potentials applications, limitations and challenges, classifications, and comparisons, including application models of WPT that are specially designed for DSNs. A comparative analysis of WPT technologies for IoT-WSN scenarios and that of two RF-based power harvesters was also discussed. Some practical considerations and real-time implementation of an RF-based EH-WPT technique using Powercast power harvesters were also presented.

Declaration of conflicting interests

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ORCID iDs

Kenneth Li-Minn Ang   https://orcid.org/0000-0002-2402-7529
Jasmine KP Seng   https://orcid.org/0000-0002-8071-9044

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