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On-Site and External Energy Harvesting in Underground Wireless

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Abstract: Energy efficiency is vital for uninterrupted long-term operation of wireless underground communication nodes in the field of decision agriculture. In this paper, energy harvesting and wireless power transfer techniques are discussed with applications in underground wireless communications (UWC). Various external wireless power transfer techniques are explored. Moreover, key energy harvesting technologies are presented that utilize available energy sources in the field such as vibration, solar, and wind. In this regard, the Electromagnetic(EM)- and Magnetic Induction(MI)-based approaches are explained. Furthermore, the vibration-based energy harvesting models are reviewed as well. These energy harvesting approaches lead to design of an efficient wireless underground communication system to power underground nodes for prolonged field operation in decision agriculture.

Keywords: soil sensing; decision agriculture; smart farming

1. Introduction

Wireless Underground Sensor Networks (WUSNs) is a subset of Wireless Sensor Network (WSN) paradigm. It is becoming a popular and developing area [1,2], and there is a large margin of improvements to resolve research challenges. WUSN have buried sensor nodes, which use communication technologies to communicate the geological data in real-time. It is considered as a promising paradigm for the monitoring of various underground applications [3]. Some of the important and valuable application areas of WUSNs include sports, agriculture, environment, border patrolling and health [1,4–6]. However, adoption of WUSNs faces many implementation challenges. WUSN accomplishes wireless communication via Electromagnetic (EM) waves propagation through soil [7]. EM waves, through soil, suffer more attenuation compared to when they are propagated through air [8–10]. Moreover, changes in soil parameters, e.g., soil moisture and temperature, further affect real-time communication [11–13]. For example, some studies [14,15] are researching and mitigating soil moisture effect using microwave heating. Similarly, in [16], authors have proposed a Microwave and Meteorological fusion (MMF) strategy to downscale soil moisture. Due to these challenges, many researchers are working to investigate WUSNs empirically and model the underground wireless communication channel [5,8,11,17–19].

One of the challengess in WUSN is the provision of sustainable renewable energy to the sensors deployed in the field [20]. In the last decade, there have been many technological advancements in natural and renewable energy sources with an aim to reduce climate change effects and extend the battery life of sensor nodes [21,22]. For any cost-efficient WUSN application, a WUSN device is expected to have a lifetime of several years [20]. There has been a lot of efforts in conserving energy by using energy-efficient communication protocols and hardware; however, communicating through soil

is still a power hungry process. In some WUSN applications, sensors are either partly or completely buried in the soil. Researchers have investigated battery replacements as an alternative method to extend the network life. However, replacing the battery is a very time-consuming, laborious and expensive process. Moreover, it might not always be possible to easily access the sensor power source for replacement or maintenance. Therefore, replacing the battery of sensor nodes is not applicable to large-scale WUSN deployments [23].

From the above discussion, it is evident that a potential solution must be developed to overcome the energy challenges in WUSNs. To that end, two general approaches to power up the underground sensor networks are:

- Wireless Power Transfer (WPT): WPT converts wireless Radio Frequency (RF) signals into electrical energy to power up the buried nodes [24]. Numerous wireless methods, e.g., electromagnetic induction, electromagnetic resonance, or radiation, can be used to transfer energy [25–28]. WPT techniques have been reviewed in detail in Section 2.
- Energy Harvesting (EH): EH is a method to extract energy from natural energy resources, e.g., solar [29,30], Human Body Area Network (HBAN) [31,32], water and wind flow [33–35], radio frequencies [36,37], and vibrations generated from different objects [33,38,39]. The extracted energy is then converted into electrical energy to power up the sensor nodes. Underground sensor nodes can be integrated with an energy harvesting component. This harvesting component uses natural energy sources, e.g., solar energy [40] from the environment to preserve energy. Energy Harvesting techniques have been reviewed in detail in Section 3.

The purpose of this work is to educate about the above mentioned techniques and review the existing energy scavenging techniques in the literature. To that end, this paper is divided into two major sections (see Figure 1): WPT techniques have been reviewed in Section 2 along with recent advancements and future research possibilities. EH techniques have been reviewed in detail in Section 3 along-with techniques and future research considerations explained in subsequent subsections.
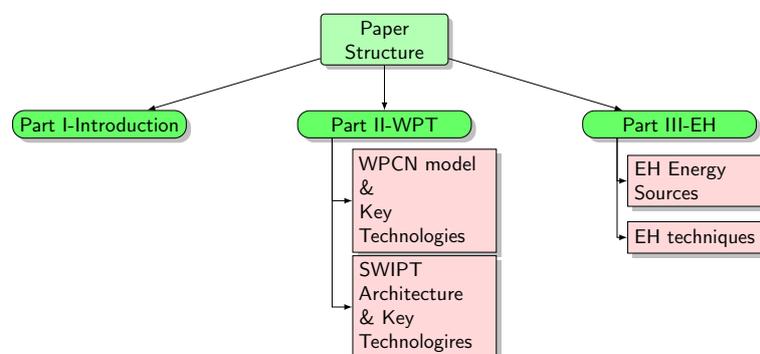

Figure 1. The organization of the article.

2. Wireless Power Transfer (WPT)

WPT is a method of transferring power using wireless technology. It was first introduced by Nikola Tesla in 1890s [41]. It is used to build a Wireless Powered Communication Network (WPCN). WPCN is a promising technology in which networks of Wireless Devices (WD) are wirelessly energized using RF signal with the help of dedicated power transmitters [42–45]. WPCN distinguishes itself from traditional battery-powered wireless networks in that it does not require manual replacement or recharging of battery. Instead, it completely controls its power transfer process by tuning various parameters such as waveform, transmit power, time and frequency domains. This reduces the operational cost while enhancing communication performance of the network.

Although the transfer range depends on the local emission regulations and differs from location to location, WPT can transfer tens of micro-watts of RF power to devices at a distance of more than 10 m (Please visit: htttp://www.powercastco.com for detailed product specifications.) [42].

It makes them suitable for implementation in low-powered applications such as WUSNs, Radio Frequency Identification (RFID) and Internet of Underground Things (IOUT) [46,47]. WPCN, when deployed in WUSNs or IOUTs, has its own implementation challenges. As WDs are buried underground, the received energy can be very low because of reduced signal power (attenuation) in an underground environment [7]. This can cause severe performance degradation and unfairness between the devices [48,49]. This degradation of signals due to an unfavorable sub-surface environment has been studied in detail in the literature [6,50–53]. This literature investigates this problem by proposing different underground channel models based on Magnetic Induction (MI), EM, and acoustic technologies. However, it is out of the scope of this paper to discuss these techniques.

Another WUSN challenge is the joint transfer of E&I. It is important because information and energy are interrelated as underground WDs are required to harvest enough energy by WPT before transmitting the information. To that end, a WPT-related technology to wirelessly energize a sensor node known as Simultaneous Wireless Information and Power Transfer (SWIPT) [24,54] is also reviewed. Unlike traditional WPT, SWIPT simultaneously transfers information and power in the same signal instead of transferring power only. Moreover, energy transfer and communication channel may share the common channel which can cause co-channel interference. In coming sections, we have discussed both WPT and SWIPT techniques of wireless transfer of energy.

2.1. WPCN Model

Figure 2 shows the components of WPCN [55]. The basic building blocks of WPCN consist of: Energy Nodes (EN), which transmits energy; WDs, which harvest energy; Access Points (APs), which receives information and energy from WDs. ENs sends the energy to WDs in down-link, and WDs use this energy to send information by communicating with the APs in an uplink (Figure 2a).
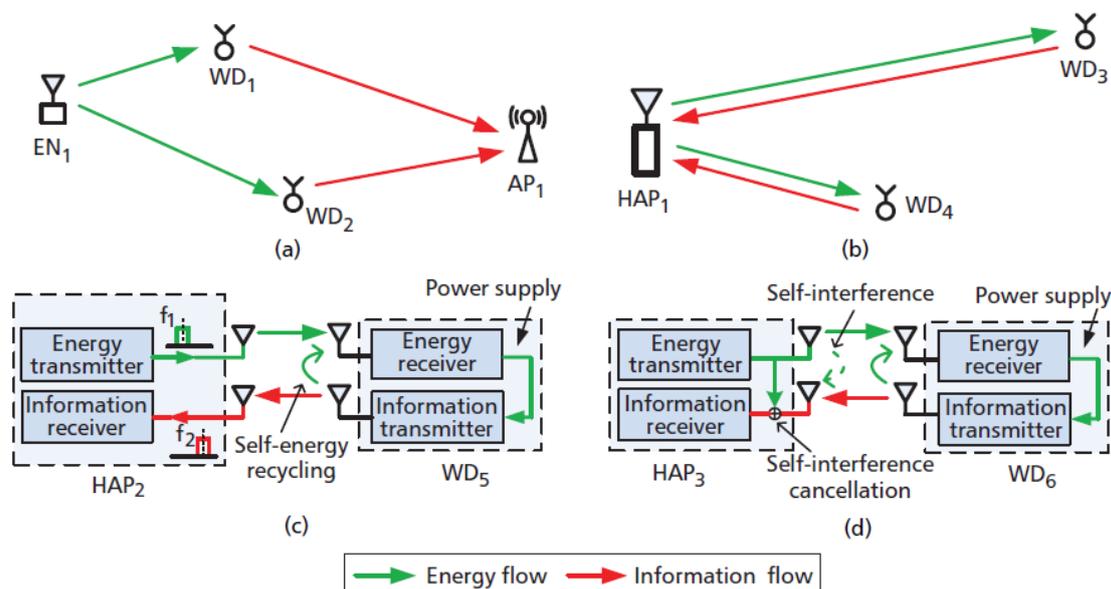

Figure 2. Wireless Powered Communication Network (WPCN) models with different transmitter and receiver schemes: (**a**) Physically different energy transmitter and information receiver, (**b**) Energy transmitter and information receiver co-located in same physical entity, (**c**) out-of-band transmission of information and energy and (**d**) full-duplex transmission of energy and information.

Normally, ENs and APs are separated [56]; however, they can be combined in a single device also known as Hybrid APs (HAP) as shown in (Figure 2b). HAP has an advantage of being cost-efficient in terms of production, operation, coordination and management of Energy and Information (E&I) transfer in a network. However, it can also introduce unfairness into the network. For example, in (Figure 2b), WD_3 will harvest less energy as compared to WD_4 because of the distance. On the contrary, in Figure 2a, WD_2 will harvest less energy from EN_1 than WD_1; however, it will also require

less energy for communication because of less distance to AP. The circuitry for E&I transfer is different. For example, sensitivity of received signal power, sent by HAP, for information receiver is −60 dBm and that for energy receiver is −10 dBm [42]. Therefore, a practical WPT-based WD has two antennas: one for harvesting energy and other for transmitting information. Similarly, HAP with combined energy transmitter and information receiver also have two sets of antennas.

The E&I transmission can either be done in-band or out-band. Out-band means using different frequencies for transmission to eliminate interference; however, it has to satisfy the additional constraints imposed by Federal Communication Commission (FCC) on its operational frequency. In-band means same frequency band for E&I transmission, which suffers from co-channel interference especially in the HAP case. This can be solved by using full-duplex WDs and full duplex HAPs. Full-duplex, in the current context, refers to the ability of HAP to simultaneously transmit energy and information. This duplex operation also enables WDs to harvest energy from its own transmitted information. This phenomenon is known as self-energy recycling and is shown in Figure 2c [57]. Similarly, full-duplex HAP has the ability to cancel the high self-interference (Figure 2d), which arises due to energy transmission and severely affects information decoding.

2.2. Key WPCN Technologies

The performance of WPCN is limited by the low efficiency and range of WPT. There are some techniques that can be used to enhance the performance of WPCNs. This section discusses those techniques. These technologies can be used to extend the operation of WPCN to make it a viable solution for a broader set of applications.

2.2.1. Energy Beamforming

WPT in LOS links uses conventional large antennas with large aperture (dish or horn antennas). However, in an IOUT/WUSN environment with mobile application and dynamically changing environment, a more suitable solution is to use an electronically steered array antenna with energy beamforming enabled [42,58]. Energy beamforming superimposes the weighted signals from different antennas at Energy Receivers (ERs)). One requirement, to maximize the level of received signal, is to have complete Channel State Information (CSI). The CSI includes magnitude and phase shift from transmit to receive antenna of ERs. Figure 3c shows one of the methods for CSI at Energy Transmitters (ETs) is via froward-link (ET to ER) training and reverse-link (ER to ET). This training design of WPT channel is limited by energy available to ER for channel estimation and sending feedback rather than bandwidth/time. Hence, accuracy of CSI knowledge at ET is highly dependent upon the energy used by ERs for the channel estimation and feedback, i.e., more available energy will result in more accurate CSI. However, energy cost at ER can increase the energy gain at ET, especially for the ET with a large number of antennas because CSI overhead increases with the increase in antennas. Therefore, reverse-link training seems a more feasible option where ER sends a training signal in reverse, and ET determines the CSI. This procedure saves ER from channel estimation and feedback, and training overhead is not dependent on the number of antennas. In addition to energy constraints of ER, WPT training design may also face challenges of hardware processing abilities, e.g., having sensors with not enough base-band processing units for estimating CSI [59,60].
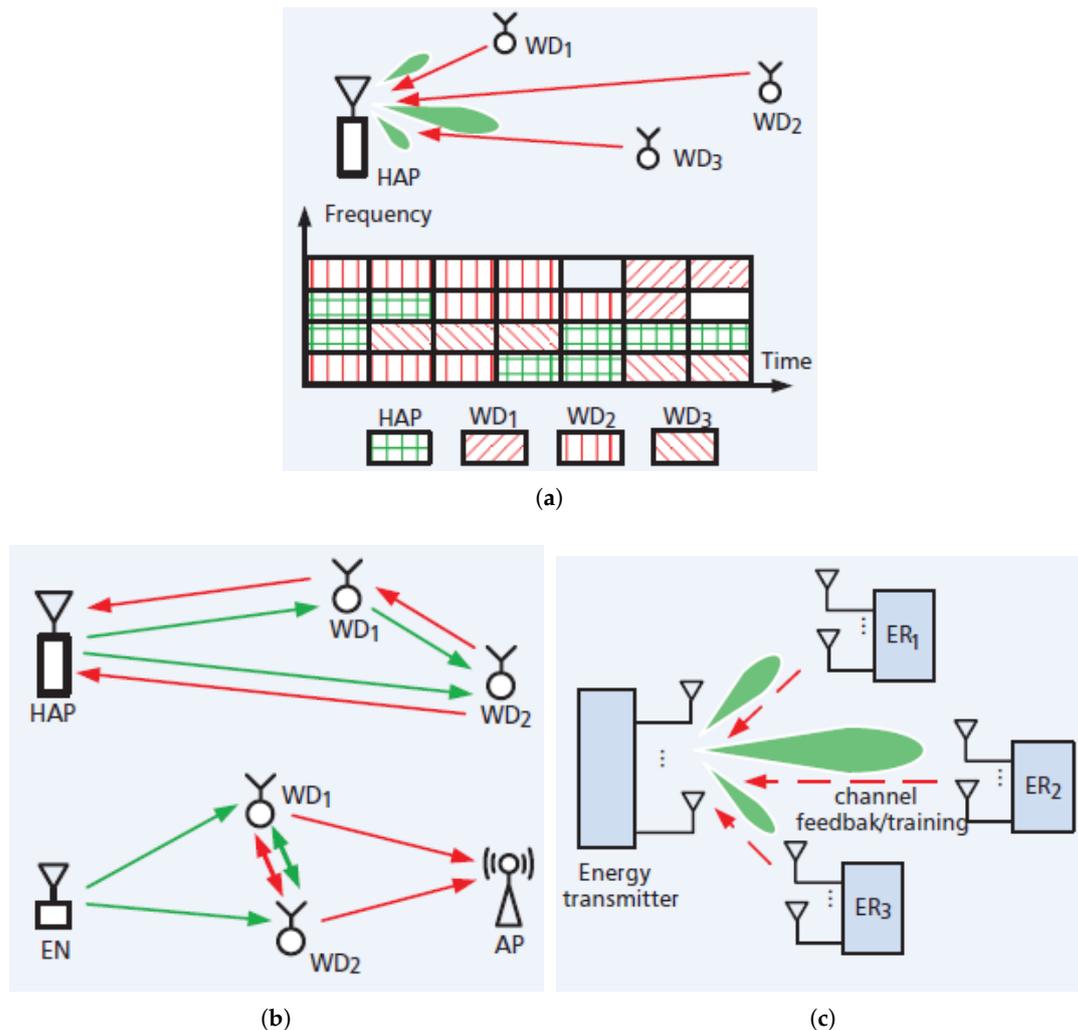
Figure 3. Major performance improving mechanisms for WPCNs; energy transfer is denoted by green lines and information by red lines: (**a**) wireless powered cooperative communication, (**b**) wireless powered cooperative communication joint scheduling for communication and energy transfer and (**c**) energy beamforming.

2.2.2. Joint Communication and Energy Scheduling

In WPCN, communication and energy transmission are dependent on each other. EN makes energy requirements from WDs to transmit downlink energy as per demand of WDs. Similarly, the uplink information transmitted by WD is highly constrained by available energy from WPT energy harvesting. Given this interdependence of E&I transmission, there is a need of combined scheduling to prevent co-channel interference for an efficient system. As shown in Figure 3a, there are multiple frequency-time resource blocks available to WPCN, which can be scheduled dynamically to HAP (for energy transmission) or WDs (for information transmission). Multiple factors are considered for the scheduling such as communication requests, channel conditions, battery conditions and fairness among WDs. For example, because WD_2 separated from HAP at large distance, more resources can be allocated to WD_2 than other WDs to ensure fairness (Figure 3a). This resource allocation method can also be used for WPCN with separate EN and AP. Although it seems effective, dynamic scheduling is very challenging to implement because of temporal dependence of wireless channels and cause–effect relation between WPT and future wireless communication techniques [61].

2.2.3. Wireless Powered Cooperative Communication

Wireless powered cooperative communication is a collaborative mechanism where users, i.e., WDs, share their resources with other WDs. The resources could be energy, time and collaboration with neighboring APs. In Figure 3b, user close to HAP, WD_1, shares its energy and time to transmit by relaying data transmission for distant user WD_2. The relay protocol can be designed with three time slots: one for downlink transmission from HAP to WD_1, a second one for WD_2 sending data to WD_1, and a third one for W_1 sending a message with its own and WD_2 data to HAP. In this way, a long-distant node can overcome the disadvantage of having short-range. To ensure fairness, WD_1 can be compensated by allowing more time to transmit because cooperation enables HAP to devote more time to communication than WPT [62]. This cooperation can be extended from communication to energy, i.e., WD_1 transmitting available excess energy to WD_2. This cooperation mechanism makes the WPCN a low-cost and efficient system for communication and energy harvesting [63].

2.2.4. Future Research Considerations

In addition to the above methods, there are other important areas in WPCN, which can be further studied for improvement of the overall system. Some of those are discussed below:

Green WPCN [55,64]: In WPCN, EN draws their energy from fixed aboveground energy sources. There is a potential to improve WPCN significantly by combining WPT-based energy harvesting methods with green and sustainable energy sources. Figure 4a shows the architecture of green WPCN. It can be seen that energy harvesting methods can be implemented at EN and WD. WDs can harvest energy from renewable energy sources and store them in rechargeable batteries. When there is enough renewable energy at WDs, ENs can stop transmitting energy because of battery constraint. On the contrary, WPT methods can be used when energy is not enough at WDs. With hybrid energy sources, i.e., fixed and renewable energy sources, the challenge is to change operation modes and using less amount of fixed energy source without degradation in communication performance. An optimal green WPCN depends on many factors: intensity of renewable energy, wireless channel and battery state.

Cognitive WPCN [55]: In practical implementations, WPCNs are expected to co-exist with various communication networks, which can lead to co-interference when they are simultaneously operating in same frequency bands. For example, in Figure 4b, there are two networks: a traditional communication network and a WPCN. WPCN can cause interference at WD_3, and similarly AP, can cause interference at HAP in WPCN, while decoding information. Note that in case of interference from AP to HAP, HAP harvests energy from AP for the use of WD_1 and WD_2. Therefore, with limited available spectrum of frequencies, WPCN must be able to cognitively share the spectrum with other networks. A cognitive WPCN can be cooperative or non-cooperative. A cooperative cognitive WPCN and existing network can work similarly as a traditional primary/secondary setup of cognitive radio network where cognitive WPCN (secondary network) operates in the most optimal way possible while not affecting the operation of the existing network (primary network) [59,65]. A non-cooperative cognitive WPCN works in a similar way, except that it prioritizes its own well-being and gives secondary consideration to minimizing its effect on the primary network [66].

Transmission Range: Transmission range of devices is one of the important issues in WPT. It is evident from the fact that a maximum of 50% energy efficiency is achieved in a far field region [67–69]. Some systems can achieve up to 90% of efficiency using the high antennas and microwave signals; however, they are constrained by transmitter-receiver alignment, which requires both of them to be in Line-of-Sight (LoS). Therefore, there is a need to design omni-directional antenna for WPT systems. Moreover, WPT range in far field regions also needs to be investigated to enhance directivity and efficiency of energy transmission.
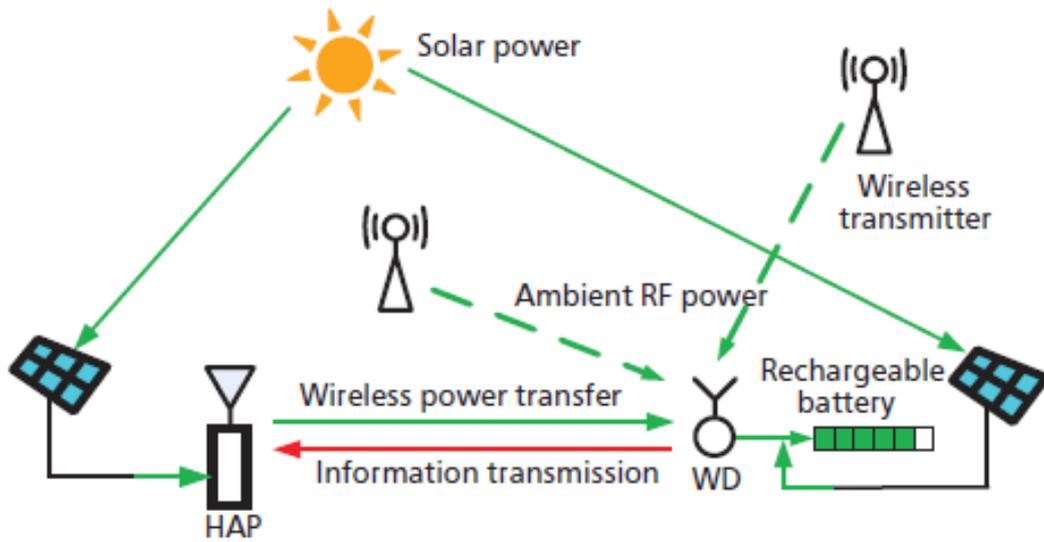
(a)
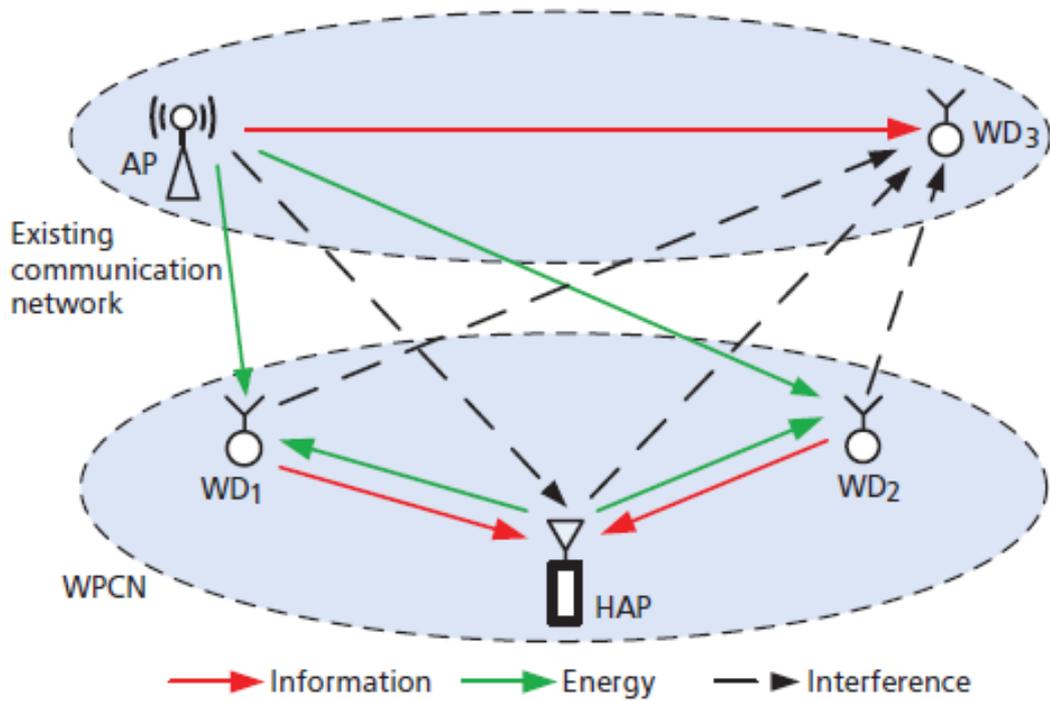
(b)

Figure 4. (**a**) WPCN implementation using hybrid energy sources, (**b**) WPCN using cognitive radio to efficiently use frequency spectrum.

2.3. SWIPT

SWIPT was first studied by [70] as a technology that stems out of various WPT technologies [71]. It allows simultaneous transmission of information and power (Figure 5) by exploiting the EM waves emitted in WPT. There are three basic advantages of SWIPT [72]: (1) WDs in SWIPT are able to harvest energy while receiving data, thus extending their lifetime; (2) it improves the transmission efficiency from traditional Time Division Multiplexing Access (TDMA) methodology where information and power are transmitted separately and finally, (3) SWIPT gives a controlled communication interference, which is beneficial for EH.

Reference [70] uses an ideal receiver to for EH and Information Retrieval (IR). Reference [73] extended [70] by implementing SWIPT in for frequency selective channels with Additive White Gaussian Noise (AWGN). In [74] author uses two separate antenna circuits, i.e., one each for EH and IR, and [75] uses asmart antenna and the concept of relaying in SWIPT Multiple Inputs Multiple Outputs (MIMO). In [76], authors evaluate SWIPT EH capabilities in presence of multiple users. EH with cognitive radios is studied in [77] where secondary radios harvest energy for primary users. Reference [78] uses energy constrained relay nodes to perform communication between two devices. However, practical SWIPT systems do not perform EH and IR using the same signal because of the possibility of information loss from the same RF signal performing EH. Therefore, SWIPT either divides the received signal into two separate parts (i.e., energy and information) or uses two different antennas for both tasks [74].

An efficient SWIPT system warrants some changes in a wireless communication system. Along with the traditional performance metrics (i.e., reception reliability and data rate) of a wireless communication network, trade-off between harvested power energy and received information data is an important factor to consider while evaluating SWIPT performance [70]. There are two major types of SWIPT architectures (Figure 6): (1) Time Switching [75] and (2) Power Splitting [79]. In time switching (Figure 6a), antenna at receiving node switches periodically between energy and information receiving modes. In power splitting (Figure 6b), signal at receiver is separated into two separate streams of information and energy.
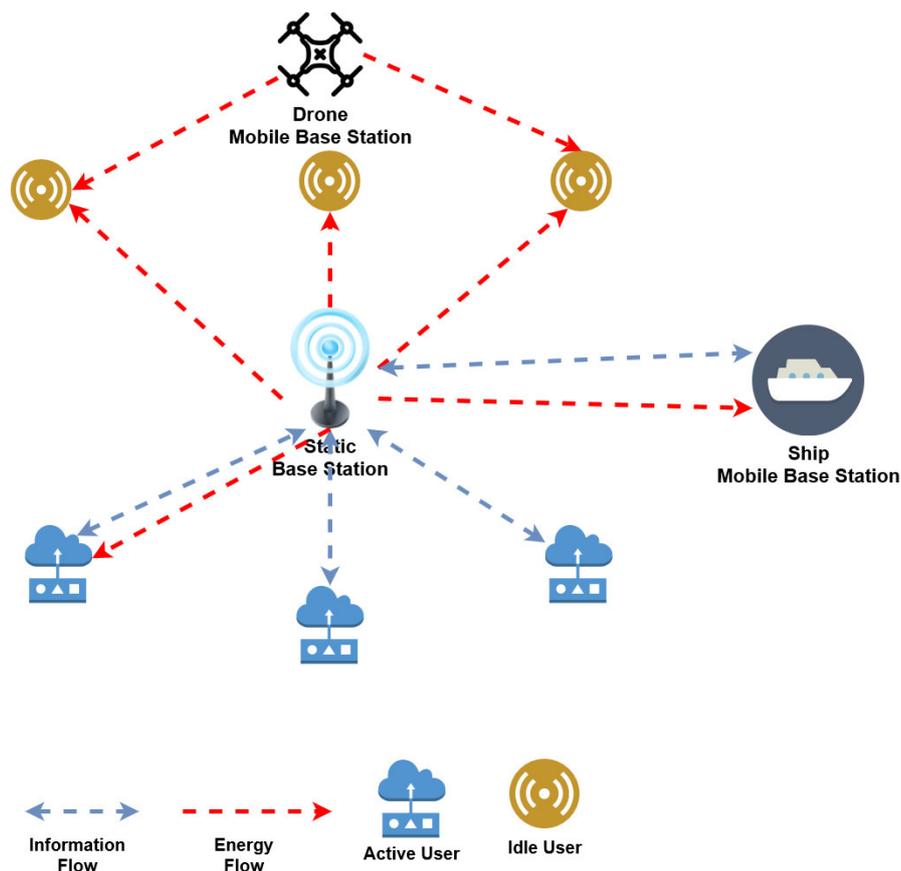

Figure 5. Simultaneous Wireless Information and Power Transfer (SWIPT) using static and mobile base stations where arrow heads represent the direction of information and power flow. Idle users only harvest energy from base stations. Active users transmit and receive energy and information.
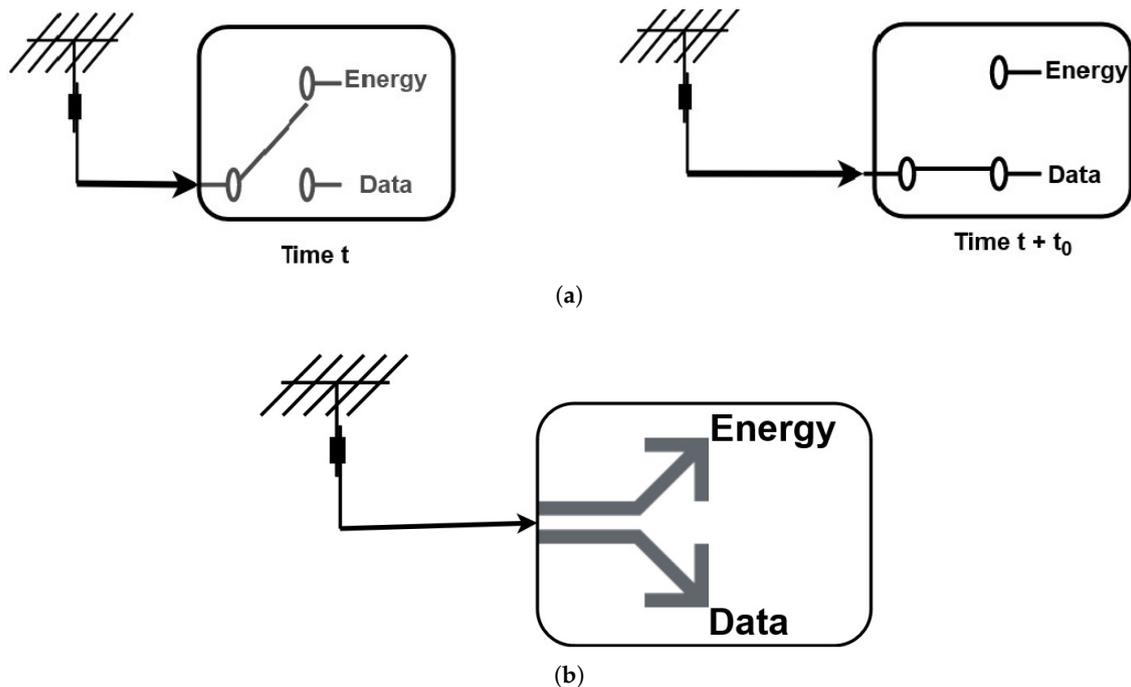
Figure 6. SWIPT Architecture: (**a**) Time Switching, (**b**) Power Splitting.

2.3.1. SWIPT-Enabled Wireless Systems

This section classifies SWIPT enabled wireless networks into the following types:

A　WSN: In WUSNs or IOUTs, the underlying buried sensors are connected via some WSN. The sensors have limited battery life. In some cases this network is huge, and it is almost impossible or very difficult to replace the batteries [80]. SWIPT is an enabling technology that can improve the WUSN/IOUT paradigm by prolonging the life of underlying WSN. The simultaneous exchange of energy and information can increase the performance of systems where sensors are frequently communicating with each other.

B　Relayed Networks: Relay networks use intermediate nodes to transmit signal or data in cooperative way. This improves performance by reducing fading and signal attenuation. SWIPT can be applied to a relayed network to power up the relay nodes in an effort to compensate them for helping in data transmission [81]. There are two types of scenarios in relayed networks for energy harvesting: SWIPT-based and Multihop-based. In the former, both relay nodes and source nodes harvest energy from each other whereas in the latter relay nodes are used to transfer energy to remote nodes [72]. The SWIPT relays are also studied in the context of physical, data and network layer where issues like relay operation, relay selection and power allocation, are addressed.

C　Cognitive Radio Networks: Cognitive network is a spectrum sharing network where high priority users (primary users-PUs) share their underutilized spectrum with secondary users (SUs) such that the SUs do not cause interference to the transmission of PUs. It aims to solve spectrum scarcity [82]. SWIPT-based cognitive network [83–85] can increase the spectrum sharing and EH efficiency. Extra energy from SUs can be utilized to transfer energy between PUs.

D　Collaborative Mobile Clouds (CMC): CMC is a cooperative way of sharing multimedia content in mobile computing in peer-to-peer manner [86]. In contrast to traditional cloud computing, CMC consist of mobile terminals that collaborate and cooperate to complete a task in a distributed manner. SWIPT can introduce energy efficiency to current CMC paradigm by allowing mobile terminals to receive information and harvest energy simultaneously. Moreover, as transmitting data consumes a large amount of energy, users may become selfish and do not join the network.

SWIPT can be used as an incentive for the users to motivate them to join the CMC network, hence, improving the overall performance of the network.

2.3.2. SWIPT Technologies

Implementation of SWIPT in wireless systems requires integration of multiple technologies. This section discusses some of these state of the art technologies below:

A Multi-antenna Transmission: Limited communication is one of the major challenges in SWIP-based wireless systems. To that end, multiple antennas can be used to increase the antenna aperture and gain [72] higher communication frequency with multiple antenna arrangement in small devices. One of the challenges in multiple antenna design is the co-channel interference due to the presence of multiple users. Reference [74] attempts to solve this problem by block diagonalization precoding. This technique selectively transmits data to receivers with no interference only and energy to all other users.

B Resource Allocation: SWIPT resource allocation is the optimal allocation of the resources available to the system. The resources for wireless systems include energy, time, bandwidth and space. The dual function of a transmitted signal needs an optimum method of scheduling and power allocation mechanisms. To that end, opportunistic power control uses the channel fading feature to improve energy and information transmission. Moreover, higher gain users, which are not transmitting the data, can be used to transfer power. Moreover, SWIPT systems can use the interference signals to their favor by directing it towards power hungry nodes. In [87], authors proposed resource allocation for SWIPT-based multi-user Orthogonal Frequency Division Multiplexing (OFDM) systems, which maximizes the total information rate under the constraint of minimum harvested energy. Reference [88] extends [87] by implementing a sub-optimal resource allocation technique for OFDM to balance the downlink and uplink communication rate. A SWIPT protocol is given in [89] for a massive MIMO antenna array system, which performs the scheduling of sensor nodes on the basis of beam-domain channel distributions to increase the transmission rate and decrease interference between the sensors.

C Signal Processing: Another concern for the SWIPT is the signal attenuation due to path loss when distance is increased. Beamforming signal processing solutions [90–92] are presented as one of the viable methods to solve this problem. In [92], a SWIPT-MIMO system uses multi-antenna APs to collaboratively transmit a beam to multi-antenna active users. Reference [91] gives a hybrid approach of SWIPT-beamforming combining both analogue and digital beamforming for efficient energy harvesting. Moreover, received power over a SWIPT wireless system varies over time; however, the goal is to keep the received signal power below some threshold. To that end, energy modulation scheme can be used. In energy modulation, information can be encoded in the energy signal to ensure continuous information transmission. Reference [93] presents a modulation scheme, which uses multiple-antenna architecture to transfer an information encoded energy signal.

2.3.3. Future Research Considerations

In an effort to improve a complex SWIPT technology, this section presents some of the areas that are worth exploring in the context of SWIPT.

Mobility: Mobility is one of the desired features of SWIPT systems. The information transfer, energy harvesting and status of the network is time-dependent. Therefore, mobility affects the wireless channel, and it is not easy to obtain the channel information in a SWIPT system with mobility. To that end, it is important to device efficient beam formers to solve the mobility issue.

Security: Increase in energy of transmitted signal is desirable because it enhances the energy transfer from one source to destination. However, it also exposes various eavesdroppers stealing the information and causing a serious security breach. Therefore, it is important to devise SWIPT systems

that adapt their performance to the channel state by decreasing the signal power on the legitimate channel while decreasing on a wiretap channel.

Multi-hop Networks: There is a trade-off between information transmission and energy harvesting in relay networks [72], i.e., a relay node which is suitable for information transfer may not be good for energy transfer. Therefore, optimal selection of relay node is an important issue in SWIPT. Network coding allows increased data transmission for multiple receivers. It would be interesting to explore the combination of SWIPT, network coding and multi-hop networks.

3. Energy Harvesting

Wireless methods have been studied for mobile and aboveground applications. However, one of the challenges in this method is that an aboveground energy source must be available to provide adequate energy when needed. For this purpose, either a separate facility can be build aboveground or a flying object, e.g., Unmanned Aerial Vehicle (UAV), can be used as an energy carrier at site on the regular basis. Moreover, efficiency of transferring power wirelessly is yet to be understood completely. On the contrary, energy harvesting is a promising solution as an energy harvester can be deployed underground. This energy harvester can use existing vibration sources, e.g., agricultural machinery and vehicles on road); hence, it requires no separate and dedicated aboveground facility [60,94].

As per the International Energy Agency (IEA), the energy demands of the world are mainly fulfilled by non-renewable fossil fuels. With the world's energy demand incessantly increasing, these non-renewable resources are also being depleted and expected to exhaust in few years [95, 96]. Besides the environmental drawbacks of using fossil fuels, such as pollution, being harmful to human health, greenhouse gas emissions are also an important issue to consider while using these resources [97]. Therefore, it is important to shift the energy supply from fossil fuels to renewable and sustainable energy resources [98]. To that end, this section reviews the energy harvesting methods from renewable and sustainable energy resources.

WUSN's research mainly focuses on achieving advance functionalities within constrained energy and battery capacities. It is important to distinguish between energy sources and harvesting techniques in order to understand the energy harvesting paradigm completely. Energy sources are the natural and environmental phenomenon that one can use to harvest energy, e.g., radiant energy sources, kinetic energy sources. Next, we discuss some of the important energy sources that can be used to extract energy in WUSN [99,100].

3.1. Energy Harvesting Sources

3.1.1. Kinetic Energy Sources

Kinetic energy is the energy generated from motion. It is the work required for moving an object of a certain mass from rest to a certain speed. Kinetic energy may take number of forms such as vibrations and air or water flows. Some of these are discussed below:

Vibrations: Different manufacturing machines, mechanical stress and sound wave machines produce vibrations when used in various applications. The vibrations produce high-density energy, and devices used for producing energy are readily available off-the-shelf. The methods using these sources are majorly based on piezoelectric, electrostatic and electromagnetic effect [101,102]. These solutions use vibrations to generate electrical energy through two sub-systems: (1) a mass-spring system that transforms vibration into motion between two elements, and (2) a mechanical-to-electrical converter that changes the motion to electrical energy using any of the above mentioned effects. Vehicle vibrations are used as source of kinetic energy [103] and may also power on-board sensors [46,104]. For example, in [105], the authors propose a prototype design for energy harvesting in roadway pavements using the vibration produced by vehicles passing from speed bumps. Kinetic energy from human, e.g., energy from heart-beats [106], is also used to generate energy.

Air or Water Flows: One of the oldest methods to extract energy from natural resources such as air and water is by using windmills and hydroelectric turbines. Turbines transform a regular flow to rotational movement that powers the electromagnetic generator. Physical properties of turbine (e.g., number of blades, type of blades and axis of rotation) affect the amount of energy harvested. For example, for high-speed flows, few short blades work well, and for low-speed flows, a large number of long and wide blades serve the purpose. Due to low robustness and high maintenance costs, they are limited to specific applications. A system for self sustained fire-monitoring in the forest was designed by [107]. It uses a microwind turbine generator for energy harvesting. The output of wind turbine used by [107] depends upon the area, cube of wind speed and air density. The contact area of the wind turbine was 28.3 cm and the radius of its blade was 3 cm. They were able to harvest a power of 7.7 mW for the lowest wind speed of $3\,\mathrm{m\,s^{-1}}$. A vertical-axis water turbine is used by [9,108] for energizing IOUT nodes in the application of water pipe monitoring.

3.1.2. Radiant Energy Sources

Radiant energy is the energy of electromagnetic waves. The most common radiant energy example is solar energy. Solar energy is an abundant, clean and readily available energy source. Photovoltaic cells, also known as solar cells, are used to extract energy from the EM radiations below the infrared spectrum. These cells work on the principle of photoelectric effect. Photoelectric effect is the phenomenon in which EM radiations, after hitting the material, emit electrons. The cell's material (e.g., Monocrystalline, Polycrystalline and Amorphous) plays an important role in efficiency, form actor and cost. Efficiency also depends on the load and operating temperature of the cell. For example, a cell generates maximum power with a load of $10.000\,\Omega$. under office lightning and $1000\,\Omega$. under PowerLED torch. A solar cell incorporates Maximum Power Point Tracking (MPPT) module to take advantage of this phenomenon. MPPT keeps a record of output power and applies the required load to optimize the performance. Radiant energy harvesting sources are popular because of their off-shelf availability and low cost. However, their performance relies heavily on duration and intensity of light. Some of the examples of energy harvesting using radiant sources for IOUT are given in [109], which designs an automated irrigation system using solar cells.

Solar energy harvesting is most suitable for outdoor implementations; however, some indoor implementations for hospitals and stadiums, etc., are also presented in [110]. For outdoor settings, Reference [111] extends the life of agricultural sensor nodes using the combination of wireless technology and solar energy. The achieved significant performance increases by combining solar energy and wireless communication technology. Similarly, Reference [112] also uses solar energy harvesting to propose an efficient energy management technique. They achieved minimum network delay and optimal throughput through this management technique.

Many solar EH implementations differ on the basis of solar cells and battery type. Some of the platforms include Batteryless Solar Harvester (BLSH) [113], Long-Term Solar Powered Node (LTSN) [114] and Micro-Scale Indoor Light (MSIL) energy harvesting system [115]. Reference [116] reviews solar energy based harvesting solutions. The wide availability of solar energy makes it an ideal option to be used in WSNs [117,118]. Many of the approaches are adaptive in nature and change their transmission range [119], routing [120], MAC [121] and scheduling [122] in order to adapt to solar energy harvesting. There are many other approaches [123,124], which ensure energy optimization and prolonged life of the network.

3.1.3. Energy from RF Transmission

RF energy harvesters are reliable, controllable, predictable and are available in both indoor and outdoor environments, which makes them more suitable than a solar energy harvester for some applications [125]. However, they have relatively low power density, i.e., $0.2\,\mathrm{nW\,cm^{-1}}\,-\,1\,\mathrm{\mu W\,cm^{-1}}$ [126] and harvest a very low amount of energy, which makes them unsuitable for applications with a large number of nodes expecting low energy consumption [127].

There has been widespread use of cellular stations, WiFi networks and FM radios in recent years. This motivated the energy extraction from available RF transmissions [128]. The major component of RF-energy harvesting is the use of *rectenna*. Rectenna is a special type of antenna that converts the energy from electromagnetic waves into electrical energy [129]. Historically, the first microwave rectenna was introduced by Raytheon in 1964 [130], and it was first used to convert solar power to electrical power in 1972 [131]. Rectennas have been used for transmission of microwave power [132] and satellite power to analyze the performance of a rectenna array [133]. It consists of an antenna for capturing waves in the from of AC current, and a rectifying circuit to perform AC-DC conversion [134, 135]. Multiple antenna types and rectifying circuits have been used in order to design an efficient antenna. Multiband and broadband rectennas have been discussed in [136]. Lack of mechanical process in conversion of RF transmissions into electrical current make it a highly robust technique.

RF energy harvesting is gaining momentum [137]. Some of the studies are very encouraging [125,138,139] while some are pessimistic [140–142]. A single frequency GSM base station provides the power density of $0.1\,\mathrm{mW\,m^{-1}}$ to $1\,\mathrm{mW\,m^{-1}}$ to users in its proximity [142]. For a total GSM downlink frequency band, it increases the power density up to the factor of 1 to 3 [143]. However, for WLAN, lower power densities were observed (i.e., one order of magnitude lower) [140]. It shows that both, WLAN and GSM, fail to provide enough energy unless a large antenna is being used. This can be complicated in routing and scheduling decisions [137]. However, improvements are possible and more energy can be harvested using beam steering approaches at transmitter and efficient antenna design at the receiver [140]. Moreover, use of rectenna can provide stable DC electricity for the electric field ranging from $0.5\,\mathrm{V\,m^{-1}}$ to $1\,\mathrm{V\,m^{-1}}$.

3.1.4. Thermal Energy Sources

Internal energy of an object under thermodynamic equilibrium is known as thermal energy. Thermal energy can be harvested using Thermo Electric Generators (TEG). TEG work on the principle of Seebeck's effect given by Thomas Seebeck. Seebeck effect is the phenomenon that generates a voltage difference from the temperature difference between conductors/semi-conductors. Basically, a connection point of two metal elements (connected in series) is brought into contact with a hot spot to generate electrical energy as voltage. An important issue with the Seebeck effect is that it produces very low output voltage. Most of the electrical circuits are unable to operate at that voltage. To that end, more metal elements are connected in series to increase the output power [144].

Although the Seebeck effect is a very old technique (more than a decade), researchers have started investigating solutions based on this technique because devices, circuits, processors and system-on-chips (SoC) have a low power consumption [145,146]. Therefore, thermoelectric harvesters found their application as voltage sources [60,147]. The temperature of pyroelectric harvesters continuously changes; therefore, they use the material with ability to generate temporary voltage. Absence of mechanical motion makes these thermal harvesters robust and prolongs their lifetime without any maintenance. References [108,148] developed self-powered WUSN underground nodes, which harvest energy from the environment. Similarly, an underground health monitoring system for oil, gas and water pipes generates energy by leveraging thermal sources such as hot water and steam [149,150].

There have been efforts made to harvest energy from thermal sources. For example, the human body can generate power of around $30\,\mathrm{\mu W\,cm^{-1}}$ [151]. This energy can be used as an energy source for wearable devices in the healthcare sector. Thermal energy harvesting is being used in many fall detection systems for elderly people [144]. Some hybrid energy harvesting approaches combining thermal and energy sources are reported in [152–154]. Similarly, in [155], thermal and optical energy harvesting is combined by fabricating a micro-TEG (μ-TEG) and a solar cell on a single chip. Reference [156] propose a special antenna design, nanoantenna, to harvest thermal energy from an automobile exhaust system.

4. Energy Harvesting Techniques

4.1. EM-Based Approach

According to Faraday's Law of Electromagnetic (EM) Induction, an electric voltage is generated by any conductor that moves towards a magnetic field. EM-based approaches use Faraday's Law of EM induction [157]. Wireless power transfer (WPT) is being accomplished using RF over long-ranges. RF energy transfer enables wireless transfer of energy form power source to remote devices using electromagnetic waves as a medium [43,59]. Due to characteristics of EM waves, it has added advantage of energy transfer over long distance over other competing technologies [43,158]. EM harvesters are reliable, require no external voltage source and suffer from lower mechanical damping. However, they also suffer from rapid power dissipation as they travel in space resulting in very low end-to-end energy transfer, e.g., few watt of transmitted power will be received as few microwatt or milliwatt.

EM-based energy transfer method has been regarded as one of the possible ways of transferring energy for a very long time. However, it has recently been proved to be feasible because of reduction in power requirements of modern electronic devices, which according to Koomey's law [159], will further decrease in the future (by the factor of 10,000 over the next 20 years) [160,161]. This explosive decrease in power calls for rethinking and redesigning wireless networks.

In [158,162], authors have proposed an EM-based wireless powered sensor network (WPSN) that uses a power beacon to transfer energy to a sensor node. An efficient WPSN uses adaptive energy beamforming to change the direction of a microwave beam towards a sensor node in real-time. They proposed two algorithms: (1) a beamforming algorithm, which adapts to received power, and (2) an adaptive algorithm for controlling duty cycle. The purpose of the duty cycle algorithm is to prevent sensor nodes from depleting their energy. A testbed is created, which consists of one power beacon and one sensor node. WPSN protocol, beamforming and duty-cycle control algorithms are implemented in the testbed. The power beacon comprised six dipole antennas, six universal software radio peripherals (USRPs), an OctoClock, an Ethernet switch and a laptop. They conducted detailed experiments on the testbed and empirically evaluated the feasibility of multi-antenna WPSNs. The beamforming algorithm was able to receive 6 times more power than any random beamforming technique. The results also showed that the efficiency of the EM-based energy transfer (using RF), along with the applying beamforming, is directly proportional to the number of antennas used. This is because beamforming in large number of antennas makes the microwave beam sharper, resulting in better end-to-end efficiency. However, they considered only one sensor node for their experiments.

In [163], authors have developed EM harvesters, which have an energy conversion efficiency of 65 % and generate power of 22.5 µW at 10 Hz. Another study [157] developed a $4.5 \times 4.5 \times 1 \, \text{mm}^3$ EM harvester, which delivers 20.9 µV. Byung et al. [164] developed a self-powered system consisting of a permanent magnet, a planar spring and a copper coil. It was able to generate a power of 1.52 mW. Similarly, another self-powered EM harvesting system is developed in [165], which has the capability of generating 140 mW. This system was used in portable electronic devices. A bi-stable EM vibration energy harvester is developed by Podder et al., which generates a power of 22 µW at the frequency of 35 Hz [166].

In [167], a WPSN has been extended using multi-nodes multi-antenna. The system consists of multiple sensor nodes and a power beacon. The power beacon has multiple transmitting antennas, and each sensor node is equipped with a receiving antenna. The sensor uses this antenna to harvest energy from the power beacon. There is no other power source, except power beacon, for the sensor nodes. The beamforming algorithm enables the power beacon (connected to the power grid) to divide the microwave and direct them towards multiple sensor nodes for simultaneous charging. Two types of beamforming algorithms are used: (1) Time-sharing (TS) and (2) Beam-splitting (BS). For TS, the energy beam from the beacon is concentrated towards a single sensor for charging, and this beam is shared between all sensors in different time slots, hence maximizing the power of one

sensor node at a time. In BS, a single beam is shared between multiple sensor nodes to charge them simultaneously, achieving a Pareto optimal point in the region of received power. BS performs better than the TS. The technique aims to solve the problem of sending power to multiple nodes and prolonging their operation.

4.2. MI-Based Approach

MI-based WUSNs were introduced in [1,6], which uses magnetic antennas implemented as coils. Magnetic Induction (MI)-based communication systems have gained popularity in recent years. Battery life is an important issue in IOUT, and many nodes require to be charged wirelessly. Wireless Power Transfer (WPT) of traditional WSNs can be directly implemented in IOUT; however, few changes will be required because of difference in medium and transceiver design (as coils are used instead of antenna). Alignment of coils also plays an important role in transfer efficiency [61,168].

MI-based schemes are famous for Near-Field Communication (NFC) [169], WPT, and IOUT [7,46,47,63]. These works study the design of point-to-point MI-based information transmission. For example, [170] performs the channel characterization of point-to-point transmission. There have been many efforts to extend a point-to-point MI-based transmission system into multiple transmitters [63,171], receivers [172] and even relays [7,173]. MI-based networks involving multiple transceivers and relays have also been in analyzed in underground WSNs [174]. Various multiple-input multiple-output (MIMO) methods are used in different configurations of MI-based WPT and communication systems [58,175].

In [176], a MI-based SWIPT system with a three-coil transmitter and multiple single-coil receiver has been proposed. It divides the number of users into two groups: data receivers (DRs) and power receivers (PRs). From a pool of receiver devices, it randomly selects a device as a DR to receive information and uses the transmitter signal for WPT to PRs (remaining users). It further investigates two beamforming problems: (1) maximization of total power received for PRs (a max-sum problem) and (2) maximization of minimum power received among all PRs (max-min problem). High gains were observed in the received power as compared to the baseline technique, which validates the accuracy of proposed accuracy mechanism. However, there is a need of studying MI transmitter with more than three coils.

4.3. Vibration-Based Approach

Vibrations can be defined as the mechanical oscillation of an object whose equilibrium has been disturbed. These oscillations can be shown in any of the two functions of an object: (1) displacement and (2) frequency. Another method of energy harvesting uses the vibration sources from the environment. Vibration EHs are able to convert mechanical vibration into electricity to power up low-powered electrical equipment [177]. Vibration energy harvesters use energy sources such as sun [178], biomass[179] and wind[180] to harvest energy. Vibration energy harvesting has many advantages in WSNs. Some of these include: (1) no requirement of voltage source, (2) highly efficient power generation, (3) producing high power voltage, (4) suitable for using with resonant devices and (5) quick response time. Some of the studies [19,38,39] have considered vibration energy harvesting in the application of WUSNs. These solutions have been sought as promising alternatives to battery replacement [181,182].

This method is based on piezoelectric effect where vibrations due to stress are converted to electricity. The main challenge in this technology is to extract enough energy needed to fulfill the energy requirement of a certain application. Furthermore, piezoelectric is frequency dependent, therefore, to generate the desired power it should be set on a right frequency. Another challenge using vibration harvesting is having a wide range of frequency in the environment. It is difficult to get the right frequency, from this wide range, which can generate highest power. The amount of power generated by vibration energy harvesting method has been investigated by many studies [183–186].

In WUSNs/IOUT, vibration energy can be generated from several sources. It depends upon the WUSN application. For example, for an agricultural IOUT, these sources can be seeders, harvesters, irrigation systems and other machinery. the vibration generated by this equipment, above the ground, should propagate underground reaching buriedpiezoelectric energy harvesters. The amount of power generated is then dependent upon the intensity of vibration reached at deployment depth. Therefore, it is very important to understand and study mechanisms of wave propagation from the soil and other underground mediums.

In [187,188], authors perform a three-step theoretical analysis and propose a mathematical model for estimating the amount of power generated by an underground vibration energy harvester, buried at some depth (d_h), in response to the amount of vibration generated by the above-ground vibrating object. First, they formulate the intensity of vibration generated. Second, they model how most of that vibration propagates to the soil. Finally, the amount of energy generated from this UG vibration and energy harvester is captured. Figure 7a illustrates the procedure. They tested their research on an agricultural setup by performing various experiments in South Central Agricultural Laboratory, one of the agricultural research divisions (ARD) near Clay Center, Nebraska. Figure 7b shows the schematic of the devices for the experiments. The intensity and frequency of vibration is measured for agricultural machinery. The agricultural machinery are the frequently used center pivot irrigation system and the four-wheeler used in farms. These vibrations were measured at varying depths to measure the feasibility of UG energy harvesting. Three DLP-TILT-G accelerometer sensors were used for the experiments (see Figure 7b). As a result of the experiments, a maximum output power of 17 mW was calculated. However, this power might not be achieved practically. For example, in one of the studies [183], the energy harvester achieved 3.5 mW. For the practical purpose of generating energy form a vibration harvester, high acceleration is required from the vibration sources (seeders, harvesters and sprayers). Furthermore, there is need of further advancement and investigation in vibration energy harvesting for studying environmental conditions, e.g., rain and temperature changes, and their impacts.
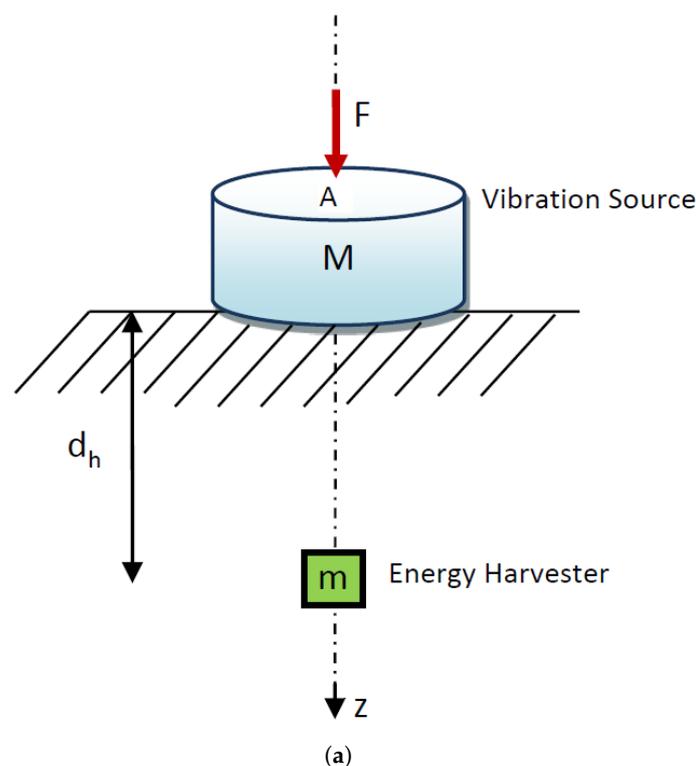

(a)

Figure 7. *Cont.*

(**b**)

Figure 7. Vibration energy harvester: (**a**) source for the vibration is on the surface with energy harvester deployed in the soil, (**b**) deployment in agriculture field.

Future Research Considerations

This section presents some of the areas that are worth exploring in the context of Energy Harvesting approaches.

Generic Harvester: Harvesting energy from multiple sources is a challenging task that needs more advanced power management techniques. To this end, it is important to develop a plug-n-play energy harvesting method, which uses multiple energy sources to harvest energy. Such generic harvesters may even eliminate the energy storage systems.

Efficient Networking Protocol: Research in WUSN has mostly been focused on efficient networking protocol [189]. A good EH approach can shift this focus from energy-efficient to information centric protocols.

Simulation Environment: To the best of our knowledge, there is no simulation environment for evaluating energy harvesting in WUSN. Such simulation environment would help in prediction performance of EH approaches in large-scale deployment of WUSNs.

Auxiliary Energy Storage: Large-scale WUSNs affect different parameters of batteries, e.g., charge cycles, self-discharge and environmental conditions. Therefore, it is important for researchers to analyze and improve the performance of rechargeable batteries. Moreover, battery-capacitor trade-off as a storage device is also an important area to improve.

Miniaturization: Large-scale WUSNs along-with heavy and bulky energy harvesting systems increase the deployment costs several times, which is not feasible when the budget is low. Therefore, it is important to develop mini energy harvesting systems. Such miniaturized harvesting systems can also be used to empower implants and for the monitoring of the human body.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

APs	Access Points
AWGN	Additive White Gaussian Noise
CSI	Channel State Information
EH	Energy Harvesting
EM	Electromagnetic
EN	Energy Nodes
ERs	Energy Receivers
ETs	Energy Transmitters
FCC	Federal Communication Commission
HAP	Hybrid APs
HBAN	Human Body Area Network
IOUT	Internet of Underground Things
LoS	Line-of-Sight
MI	Magnetic Induction
MIMO	Multiple Inputs Multiple Outputs
NFC	Near-Field Communication
OFDM	Orthogonal Frequency Division Multiplexing
RF	Radio Frequency
RFID	Radio Frequency Identification
SWIPT	Simultaneous Wireless Information and Power Transfer
TDMA	Time Division Multiplexing Access
UAV	Unmanned Aerial Vehicle
WD	Wireless Devices
WPCN	Wireless Powered Communication Network
WPT	Wireless Power Transfer
WSN	Wireless Sensor Network
WUSNs	Wireless Underground Sensor Networks

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