WIRELESS POWER TRANSFER AND ENERGY HARVESTING: CURRENT STATUS AND FUTURE PROSPECTS

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ABSTRACT

The rechargeable battery is the conventional power source for mobile devices. However, limited battery capacity and frequent recharging requires further research to find new ways to deliver power without the hassle of connecting cables. Novel wireless power supply methods, such as energy harvesting and wireless power transfer, are currently receiving considerable attention. In this article, an overview of recent advances in wireless power supply is provided, and several promising applications are presented to show the future trends. In addition, to efficiently schedule the harvested energy, an energy scheduling scheme in the EH-powered D2D relay network is proposed as a case study. To be specific, we first formulate an optimization problem for energy scheduling, and then propose a modified two stage directional water filling algorithm to resolve it.

INTRODUCTION

A stationary power supply via wires would never be the best option for mobile devices. The rechargeable battery is a conventional power source for the majority of portable devices. However, the batteries need to be frequently charged by connecting to the power grid due to the limited battery capacity. To save the inconvenience of connecting cables, an unprecedented amount of attention has been focused on finding ways to deliver power wirelessly. Transmitting energy into free space and converting the wireless energy to usable direct current power was proposed by a great visionary, Nikola Tesla. This vision has led to the development of novel power supply methods that include Energy Harvesting (EH) and Wireless Power Transfer (WPT). Unlimited wireless power will lead to fast processors, bright screens, and good connectivities.

Energy harvesting intends to scavenge wasted energy from the ambient environment. Renewable energy sources, including solar power, indoor illumination, heat, sound, motion, vibration, wind and electromagnetic radiation, can be utilized to power low-power devices in an eco-friendly manner. EH is a promising solution to power sensors, wearables, biomedical implants, RFIDs, and so on. However, people used to believe that harvested energy is insufficient to complete computation-intensive tasks. With the rapid development of silicon technology, even a tiny amount of energy ia able to do plenty of work.

With energy harvesting, batteryless systems can be developed to reduce the detrimental environmental hazards of manufacturing and disposing of batteries. For example, in a large-scale wireless sensors network (WSN), the expenditures to recharge such a vast number of batteries is notably high [1]. Solar energy harvesting using photovoltaic cells forms the batteryless WSNs, where the system life is no longer limited by the battery capacity, and the operational expenditures are reduced. Kinetic motion is another interesting source. The movement of pressing a switch can be utilized by an electro-mechanical energy converter to broadcast a telegram to control a light. Ambient RF radiation is a ubiquitous power source in urban areas because of the dense deployment of WiFi access points and cellular base stations.

Nevertheless, compared with traditional grid/battery powered systems, the ambient energy sources utilized are highly unreliable due to their variability and dependency on climate parameters, as well as human factors. This severely affects the EH process. For instance, weather conditions would hinder the utilization of solar power, and the density of ambient RF radiation entirely depends on human activity. In addition, these ambient sources are also scarce, which makes EH unsuitable for energy-hungry applications.

Typical power consumption by sensors ranges from 100 μW to 100 mW, which is much less than that of other consumer electronics, such as smartphones, the power consumption of which is in the orders of 20 mW to 1.3 W [2]. To provide a reliable wireless power supply for energy-hungry devices, WPT is proposed to deliver sufficient energy.

Instead of passively harvesting energy, WPT technology is designed to provide a stable and controllable wireless power supply by deploying a dedicated power beacon. In WPT, the energy is carried in various forms. One typical application is wireless charging technology, which is capable of charging smartphones or even electric vehicles (EVs) through a wireless charging pad. A similar technology is applied to charge biomedical implants in a non-invasive manner. Replacing these implant batteries is both costly and invasive. Another novel application, known as simultaneous wireless information and power transfer (SWIPT),

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Digital Object Identifier:
10.1109/MWC.2019.1800378

1536-1284/19/$25.00

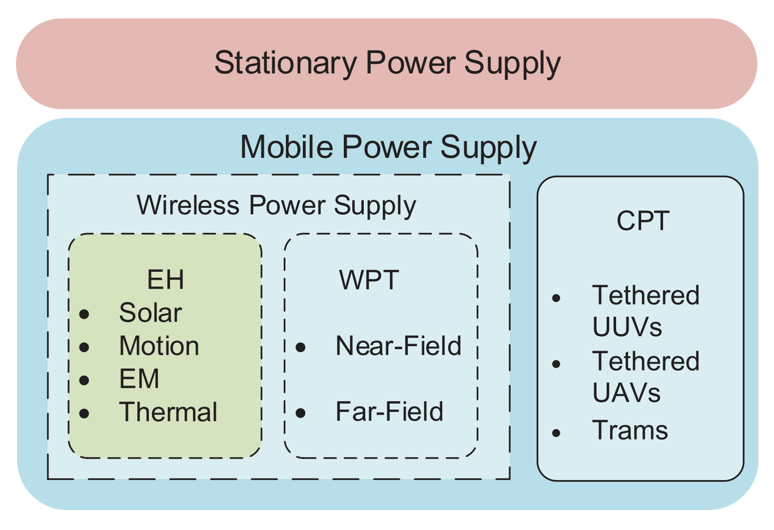

FIGURE 1. Classification of current power supply method.

is based on the idea of using the RF signal to carry both information and power [3].

The other form of WPT is to transmit power over a long distance through RF waves, microwaves, laser beams or even ultrasonic waves. It has various applications, including RFID tags, wireless sensors, Internet of Things (IoT) devices, and even laser-powered unmanned aerial vehicles (UAVs). Generally, far-field methods have lower efficiencies where their end-to-end performances depend on DC-to-RF conversion efficiency, RF-to-RF transmission efficiency, and RF-to-DC power conversion efficiency [4]. To improve end-to-end efficiency, much effort has been made to design efficient circuits, antennas and rectifiers and develop updated techniques like waveform optimization.

Conductive power transfer (CPT) is also an effective way to charge mobile devices. One typical application is railway usage such as tram and bullet trains that can gain power through a detachable pantograph. Other applications include tethered UAVs and unmanned underwater vehicles (UUVs). A company named PowerLight can transmit power and information over optical fibers toward UAVs and UUVs. It should be noted that CPT is not a wireless solution. A reasonable classification of power transfer methods is demonstrated in Fig. 1, in which CPT is a wired power supply method for mobile applications.

Although some literature consider WPT as a special case of EH, we argue that these two concepts are distinct from each other. The power provided by WPT originally comes from the grid, while EH utilizes renewable energy harvested from ambient sources.

Much progress has been made recently, but there are still many major issues remaining to be resolved. In this article, we aim to summarize these advances and their future prospects, and introduce the energy scheduling problem as one of the major challenges of WPT.

Recent Advances in Energy Harvesting

In this section, recent advances in energy harvesting are summarized. Three selected power sources, that is, indoor light, mechanical motion, and electromagnetic (EM) radiation are discussed, and their applications are presented.

Indoor Light

Compared with solar power, indoor light is much dimmer. The power density of solar energy can reach 10000 W/m^2 during the daytime, while the power density of indoor light typically ranges from 0.1 W/m^2 to 1 W/m^2. Indoor-light spectrum is very different from sunlight. In need of compact design, small photovoltaic cells are preferred under most circumstances. Amorphous silicon (a-Si) can be utilized for indoor solar cells to meet these needs. Different from conventional crystal silicon, amorphous silicon has irregular atomic arrangements, absorbing more light and work well in a dim environment. It also makes the solar cells ultra thin like films. Generally, cells with larger size and higher weight have higher efficiency. One of the Amorton products from Panasonic, AM-1816, can provide 94.0 μA at 4.9 V under 200 lux.

Mechanical Motion

Technical issues and recent advances in the utilization of kinetic motions are comprehensively summarized in [5]. Mechanical energy harvesting can be used for monitoring and home automation purposes. For instance, a self-powered wireless switch consisting of a kinetic converter and a wireless communication module uses the power of button-push actions to transmit wireless signals to control household appliances. A typical self-powered wireless switch manufactured by EnOcean, PTM 210, can transmit an RF telegram (868 MHz), including a 32-bit ID powered by an actuating force about 9 N over a travel of 1.8 mm, and its communication range reaches about 300 m under the ideal free space and 30 m under a realistic indoor environment.

Ambient Electromagnetic Radiation

In crowded urban areas, there are various types of EM radiation sources, including WLAN access points (APs), cellular base stations, TV broadcasting stations and AM/FM radio stations. Such ambient EM radiation can be harvested to power low-power devices, known as RF energy harvesting. RF energy harvesting is an intriguing topic that has drawn enormous attention recently, but it is also facing some issues. Most importantly, the density of ambient EM radiation is highly stochastic, scarce and uncontrollable. The amount of harvested energy can be as low as −40dBm. In addition, proper circuit design is needed to improve RF-to-DC efficiency and keep the harvester small in size. To address these issues, scientists and engineers are working to design efficient RF energy harvesters.

There are some commercial products available falling into the above category. For instance, P2110B is one of the RF energy harvesters produced by PowerCast[1], and it can harvest RF energy (850 ∼ 950 MHz) with input power down to −11 dBm. Its RF-to-DC efficiency can reach 55 percent under a specific circumstance. However, this harvester works only if the RF input power is above −11 dBm, which is pretty high compared to the minimum sensitivity of WLAN ranging from −88 dBm to −65 dBm. Hence, the RF energy harvester has to be placed in the vicinity of an RF energy

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[1] Certain commercial equipment, instruments, or materials are identified in this article to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

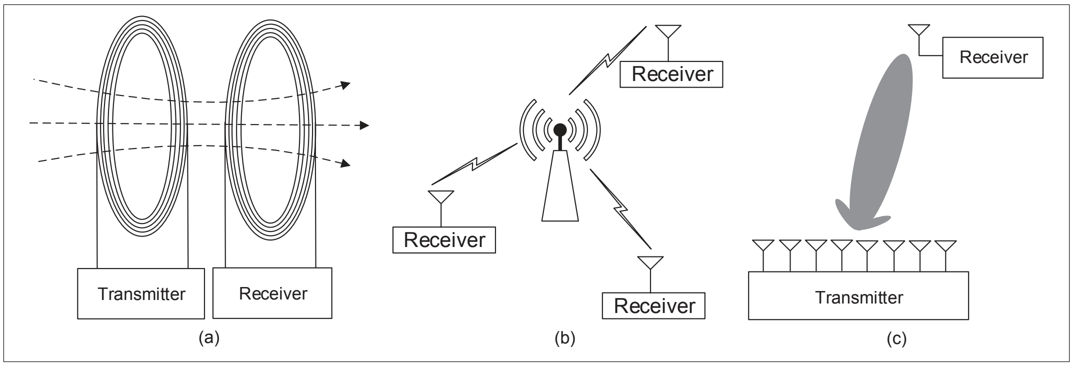

FIGURE 2. Different types of WPT systems: a) WPT with coils; b) WPT with omnidirectional transmitter; c) WPT with antenna array.

Based on the operating distance, WPT technologies can be divided into two categories, that is, near-field WPT (non-radiative WPT) and far-field WPT (radiative WPT). Near-field WPT systems transmit power via coils, while far-field systems use antennae to radiate and receive power.

source, which dramatically hinders the application of RF energy harvesting.

THE STATUS QUO

The leading industry consortium is the EnOcean Alliance, which is formed by companies including EnOcean, Texas Instruments, IBM, and MK Electric. The EnOcean Alliance focuses on developing EH standards that are dedicated to innovative solutions for home automation and IoT. A wide range of product categories, such as self-powered wireless switches and sensors, are developed for sustainable buildings using the EnOcean wireless standard. However, ambient energy sources are scare and unreliable in general, and are not able to power high-power applications. For example, ambient RF energy harvesting generally does not provide enough energy for cellphones.

RECENT ADVANCES IN WIRELESS POWER TRANSFER

Based on the operating distance, WPT technologies can be divided into two categories, that is, near-field WPT (non-radiative WPT) and far-field WPT (radiative WPT). As shown in Fig. 2, near-field WPT systems transmit power via coils, while far-field systems use antennae to radiate and receive power. In this section, the recent advances in near-field WPT and far-field WPT are introduced.

NEAR-FIELD WPT

The near-field WPT utilizes two aligned coils and inductive coupling among coils to transfer energy over very short distances (tens of millimeters). Nowadays, many consumer electronics like phones and electric toothbrushes adopt wireless charging by using a charging pad or a mat. Since Apple Inc. announced their products can be charged wirelessly by using Qi technology, wireless charging has gained tremendous popularity. Numerous cellphone manufacturers have adopted wireless charging. The latest version of the Qi specification (v1.2) enables 5W to 15W power transfer over a distance of 5mm using 140kHz frequency. Other applications include powering wearables, implants, peripherals, and tablets. There is also great interest in integrating wireless charging in furniture and vehicles, so that smartphones can be charged even in cars or sofas.

Near-field WPT can also be applied to charge EVs and plug-in hybrid electric vehicles (PHEVs). Using resonant inductive coupling technology, a firm named WiTricity attempts to charge EVs and PHEVs efficiently via a charging pad with charging rates ranging from 3.6kW to 11kW. Resonant coupling was first proposed in 2007, and simple resonant circuits were used to make coils resonate, enabling power transfer over mid-length distances at frequencies over 1 MHz. WiTricity claims to have the ability to charge vehicles over 10–25 cm with the maximum misalignment of 10 cm.

WiTricity has been involved in the development of an international standard, SAE J2954. For autonomous EVs, charging without plugs is of great significance, because there could be no driver plugging in the vehicle. However, these near-field WPT technologies are highly efficient, but can only be used to charge devices within a very limited range. Major standards and technologies in wireless charging are summarized in Table 1.

FAR-FIELD WPT

Far-field WPT uses EM radiation to transfer energy over long distances. Longer operating distances makes far-field WPT more flexible and particularly suitable for power multi-casting, allowing the transmitter/receiver to move around, even under a Non-Line-of-Sight (NLoS) environment [4]. Hence, far-field WPT has numerous applications in charging low-power devices such as RFID tags, IoT sensors, and smartphones, and even high-power applications such as powering UAVs.

However, long distance also brings huge path loss, resulting in poor transmission efficiency. To address this issue, EM radiation needs to be concentrated on the direction toward the energy receiver by using a directional antenna or an antenna array to implement energy beamforming, as shown in Fig. 2c. An alternative solution to concentrate energy is using laser beams.

Back in 1975, a milestone experiment known as the Goldstone demonstration was conducted. In this demonstration, more than 30 kW power was transferred over a distance of 1.54 km using a microwave beam at 2.388 GHz utilizing a 26m-diameter dish transmit antenna and a 7.3 × 3.5 m^2 receiving antenna array. The result prompted NASA and the DoD to look into the feasibility of solar power satellites (SPS). The main motivation of SPS was to harvest solar power by geostationary satellites and then transmit the power back to the earth using microwave-based WPT. These attempts to build an SPS system significantly promoted the development of far-field WPT. Similarly, but on a smaller scale, such a system is expected to be applied to power in-air unmanned aerial vehicles.

Standard	Org.	Method	Power	Distance	Application	Issue date	Remark
Qi v1.2.3	WPC	Inductive	5 ~ 15W	5 mm (typical)	Smartphones, smart watches, headsets, cameras, shavers	2017-2	Qi is the dominating wireless charging standard working at 87 to 205 kHz. There are over 700 Qi certified products, and most of them are smartphones.
Rezence (Air-Fuel Resonant BSS 4.0)	AFA	Resonant	≤ 70W	Tens of millimeters	Headsets, smartphones, tablets and laptops	2017-5	This standard is still under development. The Bluetooth LE is applied for control purposes. It provides more spacial freedom and easier support toward multi-device charging than Qi, using 6.78 MHz.
SAE J2954 RP	SAE	Resonant	≤ 11kW	Vehicle ground clearance ≤ 250 mm within a misalignment tolerance of 100 mm	Stationary EVs	2017-11	This Recommended Practice is planned to be standardized very soon. Dynamic charging may be considered in the future.

TABLE 1. Major standards and technologies in wireless charging.

It is proven that large and fixed-wing UAVs are likely to be powered by solar energy and WPT. Infinitely long durations will make UAVs cost-efficient to replace satellites in applications such as conducting surveillance and relaying communications. Far-field WPT can also be utilized to power UAVs. Companies including Global Energy Transmission and PowerLight (formerly known as LaserMotive) envisage the possibility of powering in-air UAVs using far-field WPT, which will make UAVs fly restlessly without landing and taking off frequently to refuel or recharge. Similar to parked EVs and PHEVs, landed UAVs can also be charged by near-field WPT. Some researchers believe that it is challenging to power multirotor UAVs wirelessly, because they are smaller, but more power-hungry than fixed-wing UAVs.

The above efforts focused on long-distance and high-power applications. Recently, there has been an urgent need to autonomously charge small low-power devices, such as sensors and smartphones, over a short distance (1 mm to 10 m). Companies, including Ossia, PowerCast, Energous, TechNovator and Wi-charge, attempt to build wireless power systems to meet these requirements. PowerCast claims its omnidirectional transmitter can broadcast 3 W power and enable 12-meter power transfer toward multiple low-power devices such as RFID tags and wearables. However, the overall efficiency is limited due to its isotropic nature. PowerCast and Energous are the only two companies that have received FCC approval to deploy their far-field WPT transmitters so far. To improve efficiency, multiple antennas and beamforming are adopted in Energous' Mid Field Wattup technology, which concentrates the power in one direction as shown in Fig 2c. This technology can transmit power over 60 cm to 90 cm to power a mouse, a keyboard or wearables. Another company named Ossia claims that its Cota technology can even "trickle" recharge a cellphone within 3 meters. In some cases, RF EH and far-field WPT may share the same energy receivers, while in other cases, far-field WPT receivers are required to interact with power transmitters.

Standardization

For the near-field wireless charging technology, there are several competing organizations trying to develop international standards. The leading ones are Wireless Power Consortium and AirFuel Alliance (AFA). Wireless Power Consortium developed the Qi standard, and AFA issued Rezence standards, which enables 70 W power transfer within tens of millimeters. It is believed that a unified standard will be formed and led by Qi. In the area of far-field WPT, one major issue is safety, since too much EM radiation is considered harmful to the human body. Hence, the FCC has so far only approved power transmitters of two companies, that is, Energous's Mid Field Wattup transmitters and PowerCast's PowerSpot transmitters. Numerous startups are waiting in line to get FCC approval.

Future Prospects

EH and WPT are considered game changers in many areas. In this section, several killer applications are highlighted, including active implantable medical devices, solar powered pseudo-satellites, and roadway powered electric vehicles.

Active Implantable Medical Devices (AIMDs)

AIMDs are a kind of active medical device intended to be totally or partially introduced into the human body by surgery or by medical intervention into a natural orifice. AIMDs can be used to monitor indicators or deliver electrical signals to organs. AIMDs include cardiac pacemakers, implantable cardioverter defibrillators, implantable nerve simulators and implantable active drug administration devices. With WPT, AIMDs with no batteries become possible, and surgeries to replace the battery can be avoided.

As a conventional neural recording method, electrocorticography is conducted by deploying a wired electrode array on the cortex surgically, which can reduce the patient's mobility and shorten the monitoring time. The life-long implantation of such a wired system is impossible. Hence, one significant application of WPT-powered AIMD is to eliminate all the wires of neural activity recording systems to build an implantable wireless neural recording system. Such a wireless powered system is of great significance in numerous applications, including building brain-machine interfaces, reconstructing lost brain functions, and exploring the intricate mechanisms behind neurological disorders.

One of the applications is the wireless floating microelectrode array (WFMA) reported by Troyk *et al.* [6]. As shown in Fig. 3a, WFMA devices are comprised of 18 microelectrodes, an ASIC, and

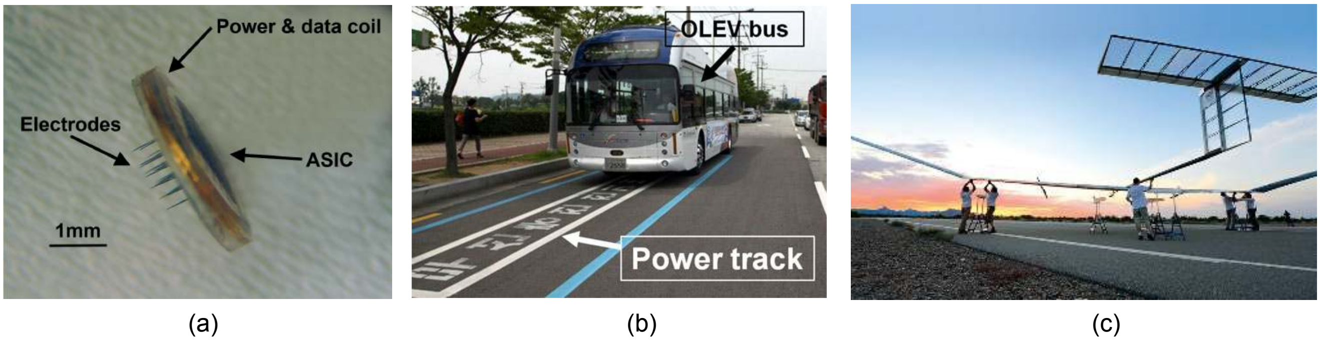

FIGURE 3. Wireless powered applications: a) WFMA devices [6]; b) OLEV [8]; c) Airbus Zephyr 7.

a coil. This coil is responsible for both data and power transfer. The WFMA system is designed to restore vision to blind people.

ROADWAY POWERED ELECTRIC VEHICLES (RPEVS)

RPEVs are designed to acquire wireless power provided by roadside infrastructure while in motion. Different from stationary charging, wireless power delivery toward RPEVs can power moving vehicles. Inductive power transfer (IPT) systems have been considered as a solution for RPEVs. Unlike traditional EVs, RPEVs do not rely on high capacity batteries. Such batteries bring problems like long charging time, low energy density, deteriorated lifetime after rapid recharging, and high pollution [7].

The first RPEV system, known as the online electrical vehicle (OLEV), was built by Korea Advanced Institute of Science and Technology in 2013, as shown in Fig. 3b. A 2.4-kilometer roadway was built with cables and coils under the road surface and two RPEVs were used in this system. Innovative coil designs adopted by OLEV made it possible to achieve a power delivery efficiency up to 83 percent at an output power of 60 kW, with an air gap up to 20 cm and a fairly good lateral tolerance of 24 cm [8]. Some companies, for example, Elect-Reon also attempt to build RPEV systems. One of the major challenges is that the initial investment of road infrastructure that enables RPEVs to be astronomical.

SOLAR POWERED PSEUDO-SATELLITES

Many projects, such as Solar Impulse and NASA's Pathfinder, have successfully built solar powered aircrafts with both manned and unmanned patterns that are capable of flying for days. After sunset, these aircraft, equipped with ultra-lightweight photovoltaic cells, can use stored solar power that is harvested during the daytime, which gives aircraft the potential to fly forever.

Two collaborative companies, Prismatic and BAE Systems, claim that they are building a new solar powered UAV, named PHASA-35, that can operate at high altitudes for one year without any maintenance. Solar powered High Altitude, Long Endurance (HALE) UAVs are considered as atmospheric satellites or pseudo-satellites that can provide similar functions as conventional artificial satellites in earth orbit. The HALE UAVs are useful in intelligence, surveillance, and reconnaissance. By deploying pseudo-satellites, the cost of launching satellites can be saved.

Facebook's Aquila project plans to build solar powered HALE UAVs as relay stations for extending Internet access to remote areas. This project is intended to operate at 18,000 m to 27,000 m and uses laser beams to communicate. Similarly, project Loon aims to achieve the same objective by deploying solar powered balloons in the stratosphere. Airbus also has an ambitious program named High Altitude Pseudo-Satellite (HAPS). As shown in Fig. 3c, Airbus's solar powered HALE UAV, Zephyr 7, holds the official endurance record of 336 hours and 22 minutes. HALE UAVs are facing challenges to reduce weight, find a good aerodynamic design, accurately predict energy usage, and optimize the battery and solar harvesting system design.

SUMMARY

Fulfilling the demand for powering mobile devices like phones, wearables, and implants wirelessly is merely the beginning of a wireless power era. With the popularization of EVs, the need for stationary charging EVs and dynamic charging EVs will be enhanced. Hopefully, wireless powered personal air vehicles will become a reality. The wireless powered applications introduced in this section can become the driving force of the development of WPT and EH in the near future.

ENERGY SCHEDULING IN THE D2D RELAY NETWORK

Device-to-device (D2D) communication will play an important role in future cellular communication systems. D2D communication enables direct communications for mobile devices in proximity, which is applicable to local service provisioning and emergency scenarios [9, 10]. More recently, 3GPP released a report about enhancing D2D communication to better relay data for IoT and wearables [11]. The main idea behind this is to combine D2D with IoT by adopting a D2D relay network. Taking Fig. 4 as an example, a D2D relay network has multiple energy-limited IoT devices and a relay node. Through such a relay, IoT devices are no longer required to send data to the distant base station directly. In this way, short-range D2D communication can improve energy efficiency, which is very important for IoT devices. In this article, the energy-limited devices are considered being able to harvest energy from ambient energy sources, for example, two EH nodes in Fig. 4, and the corresponding energy scheduling problem is formulated. Unlike the previous work [12], our proposed scheduling mechanism focuses on addressing the total throughput maximization problem in D2D-enabled wireless networks.

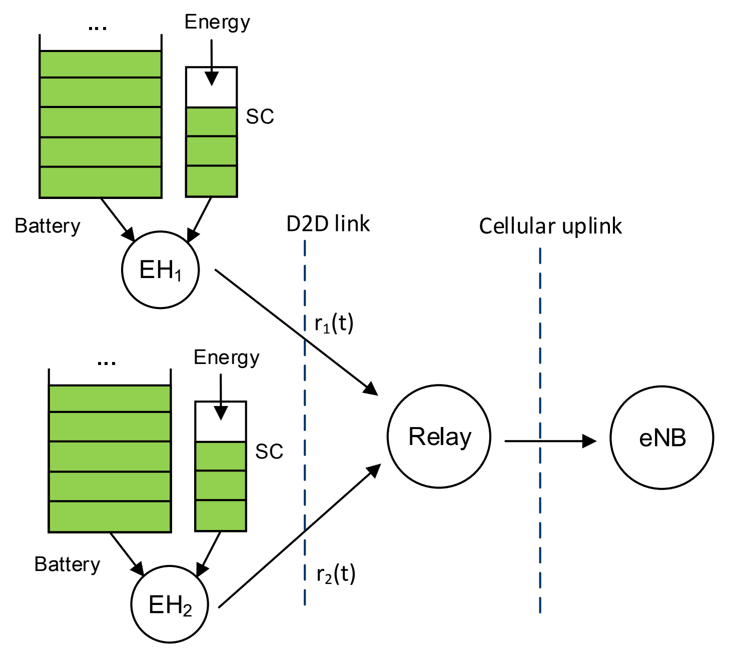

FIGURE 4. D2D relay network with two EH nodes and one relay node.

It is known that frequent recharge and discharge can compromise the performance of a rechargeable battery in terms of life span and capacity. An alternative solution is to adopt hybrid energy storage, consisting of a super capacitor (SC) and a battery [13]. As shown in Fig. 4, each EH node has an SC and a battery. The SC is to store the harvested energy, and the battery with infinite energy storage is used to provide stable energy.

In our model, the harvested energy is used to transmit data to the relay node. It is assumed that the relay node has sufficient energy as well as any other necessary resources. Thus, the bottleneck of such a network is the limited throughput between EH nodes and the relay node. In order to find an efficient way to spend the harvested energy, an energy scheduling problem is formulated to allocate the harvested energy. The harvested energy arrives in the form of discrete energy packets. The energy arrival profiles at the two EH nodes are assumed to be known non-causally, that is, their arrival time and volumes are known in advance [12, 13]. This assumption turns our problem into an offline energy scheduling problem, which evaluates the best possible performance of the D2D relay system [2]. Hence, the energy arrival profiles can be presented by $\{(t_i^1, E_i^1)\}_{i=0}^N$ and $\{(t_i^2, E_i^2)\}_{i=0}^M$ for two EH nodes.

To maximize the sum-throughput of EH nodes by a deadline T, based on the energy arrival profiles, the objective function can be presented by $\int_0^T (r_1(t) + r_2(t))dt$, where $r_1(t)$ and $r_2(t)$ are data rates of the two EH nodes. It should be noted that the two EH nodes and the relay node form a multiple access channel (MAC). According to the information theory, the objective function can be expressed by $\int_0^T \log(1 + p_1(t) + p_2(t))dt$, where $p_1(t)$ and $p_2(t)$ are the transmit powers of EH nodes [14].

The constraints on the two transmit powers, include the no-energy-overflow constraints and the energy-causality constraints [2]. The no-energy-overflow constraints ensure that the energy never overflows, while the energy-causality constraints guarantee that the harvested energy in the future can never be used in the past. The energy provided by the battery is limited by an upper bound.

With the objective function and the above constraints, an optimization problem is formulated. The aim is to maximize the sum throughput of the MAC by finding the optimal transmit powers under some constraints. The transmit powers, also known as power policies, indicate how to use the harvested energy over time. It can be proven that the optimal transmit power is a piecewise constant by using Jensen's inequality. Thus, the original problem can be reformed into a convex optimization problem.

To solve the problem, a modified two stage directional water filling algorithm is proposed. Intuitively, the optimal solution should allocate energy as evenly as possible, due to the concavity of the objective function. First, the harvested energy is allocated. Then the energy provided by the battery can be allocated by using the conventional water filling algorithm afterward. The first stage is the core of the algorithm where many constraints need to be considered.

In the first stage, due to the energy-causality constraints, the harvested energy should be allocated in a "backward" manner, which means that the last arriving energy packet should be allocated first. For example, the energy packet that arrives at time t can only be used after t. Because of the no-energy-overflow constraints, the proposed algorithm has to keep track of the energy stored in the two SCs. For each energy packet, the conventional water filling algorithm proposed in [12] is applied, provided there is no violation of the no-energy-overflow constraints. If the conventional water filling algorithm provides a solution that violates the no-energy-overflow constraints, two sub water filling processes are evoked to ensure that there is no energy overflow.

A simple example of the first stage is presented in Fig. 5. The two energy arrival profiles are presented in the first sub figure on the top, where red shows the energy packets arriving at the EH node 1, and blue shows the energy packets arriving at the EH node 2. The capacity of the SCs is 2 mJ. The last energy packet is 1 mJ arriving at time 70 ms, which is noted by (70 ms, 1 mJ). The second sub figure shows the optimal way to use this amount of energy. The third sub figure illustrates the water filling process over the last two epochs. Similarly, the fourth sub figure demonstrates how to allocate the harvested energy by using conventional water filling. The next sub figure illustrates the case where the conventional water filling algorithm provides a solution that violates the no-energy-overflow constraints. In this case, to avoid violation, the energy packet is divided into two parts, that is, 4 mJ is allocated over time interval [10, 30] ms while 2 mJ can be allocated over [30, 80] ms. Note that in this sub figure, the water level is uneven at 30 ms, which means the energy stored at the time 30 ms equals the maximum capacity, that is, 2 mJ. Similarly, in the last sub figure, due to the no-energy-overflow constraints, 3 mJ energy is allocated in [0, 20] ms, and 2 mJ energy is allocated in [30, 80] ms.

CONCLUSION

The state-of-the-art WPT and EH technologies are presented, and their corresponding prospects are summarized. Recently, many near-field WPT standards have been issued, and various far-field WPT technologies are under development. In the future, wireless powered systems including neural implants, RPEVs, and HALE UAVs will be viewed as promising applications. It is known that proper energy scheduling can improve the performance of the EH system. In addition, energy scheduling in D2D relay networks is analyzed, and a modified directional water filling algorithm is proposed.

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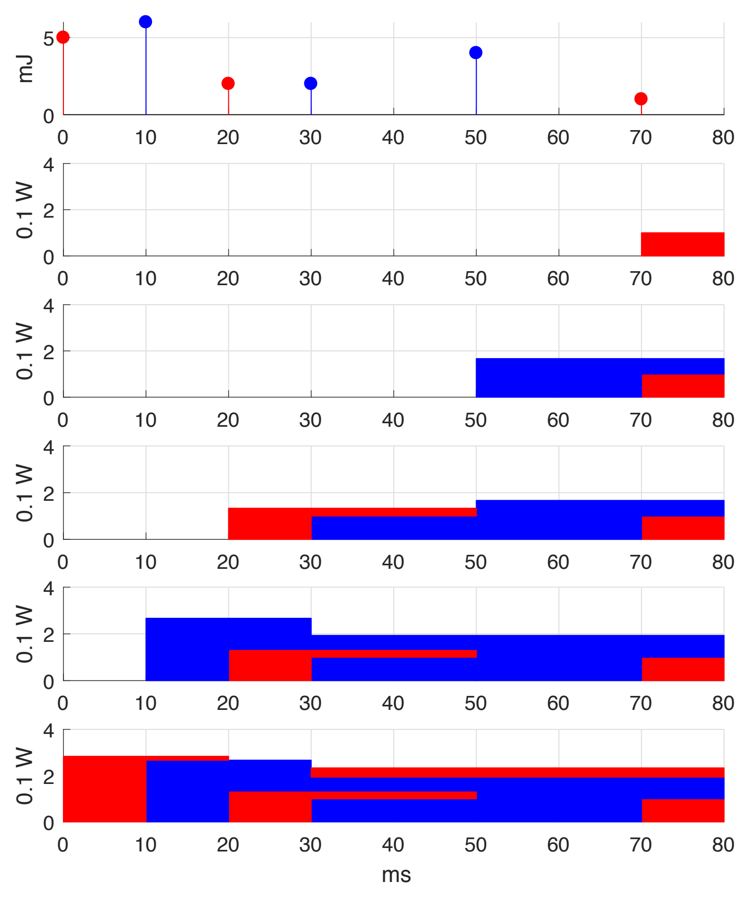

FIGURE 5. An example with energy profile (0, 5mJ), (20 ms, 2 mJ), (70 ms, 1 mJ) for EH node 1, and (10 ms, 6 mJ), (30 ms, 2 mJ), (50 ms, 4 mJ) for EH node 2. The capacity of the SCs is 2 mJ.

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