Wireless Power Transfer Technologies, Applications, and Future Trends: A Review

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***Abstract*—Wireless Power Transfer (WPT) is a disruptive technology that allows wireless energy provisioning for energy-limited IoT devices, thus decreasing the over-reliance on batteries and wires. WPT could replace conventional energy provisioning (e.g., energy harvesting) and expand for deployment in many of our daily-life applications, including but not limited to healthcare, transportation, automation, and smart cities. As a new rising technology, WPT has attracted many researchers from academia and industry in terms of technologies and charging scheduling within a plethora of services and applications. Thus, in this paper, we review the most recent studies related to WPT, including the classifications, advantages, disadvantages, and main application domains. Furthermore, we review the recently designed wireless charging scheduling algorithms and schemesfor wireless sensor networks. Our study provides a detailed survey of wireless charging scheduling schemes covering the main scheme classifications, evaluation metrics, application domains, advantages, and disadvantages of each charging scheme. We further summarize trends and opportunities for applying WPT at some intersections.**

***Index Terms*—wireless power transfer, wireless sensor networks, smart homes, healthcare, industrial, and charging schemes.**

I. Introduction

Sixth Generation (6G) wireless networks seek to enhance the dependability, speed, and bandwidth of their forerunners, the 5G networks, in order to meet the expanding demands of the Internet of Everything (IoE) applications and accommodate cutting-edge technological trends like decentralized and pervasive artificial intelligence (AI). Energy efficiency and power provisioning are critical problems in future wireless networking, including Wireless Sensor Networks (WSN), IoE, Beyond 5G (B5G), and 6G [70], [144].

Many power-saving (energy conservation) solutions are used to improve the power usage in wireless communications, such as in [44], dynamic routing techniques [80], [146], [145], efficient construction of multi-cast trees [27], [25], mobile data collection, low power hardware architecture [61, 33], and resource allocation. Despite the fact that these solutions

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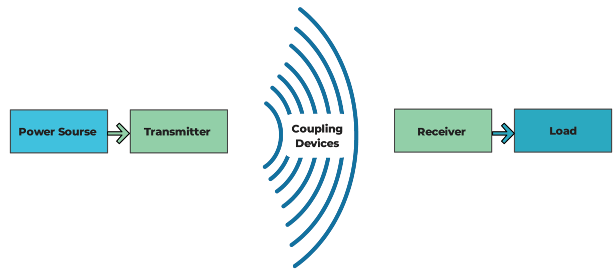


Fig. 1: A block diagram of the WPT system

can extend the network's operational lifespan, they failed to guarantee perpetual operations without downtime.

WPT facilitates the development of ultra-low power communication technologies such as IoE by providing a stable and reliable power source [139], enabling numerous novel applications and services. Therefore, WPT is expected to play a crucial role in powering and connecting a diverse range of devices and services in the 6G-enabled world. WPT technologies are vital in advancing the capabilities of 6G networks. By eliminating the need for cords and cables, WPT allows for more seamless and convenient charging of devices [17]. This enhances the mobility of devices, which is crucial for the growth of IoE applications [5]. WPT technologies offer improved energy efficiency, reducing waste generated by traditional charging methods.

Implementing WPT in 6G networks increase the popularity of wearable technology, such as smartwatches, fitness trackers, and IoT devices, which require constant power [120]. The integration of WPT with 6G networks provides a more convenient and efficient solution for charging these devices, ultimately leading to the growth of technology and the advancement of the IoE [74]. WPT modes of operation include power-sharing and time switching concerning the WPT receiver structure [55]. Power transfer and data transmission are designed to employ the same High Frequency (HF) band in different time slots, allowing the nodes to hold a single HF chain and reducing hardware costs. Planning the TIP and data collection to extend node battery life and minimize packet loss [55] is essential. WPT techniques are settled to manage the power limitation in Wireless Sensor Networks (WSNs) [96, 33]. As exemplified in Fig.1, the WPT technique implicates three primary components: the transmitter, receiver, and coupling devices [86].

WPT technology enables the transfer of electric energy without physical connections, offering a convenient and efficient solution for powering electronic devices [105]. The technologies used for WPT vary in terms of operating principles and efficiency, but all share the goal of delivering energy wirelessly [10]. The most commonly used WPT technologies are inductive coupling, resonant magnetic induction, radio frequency (RF), microwave, and solar wireless power transfer [119]. Inductive coupling uses magnetic induction to transfer energy from a transmitting coil to a receiving coil. Resonant magnetic induction operates at a resonant frequency, allowing for greater efficiency and longer distances. RF wireless power transfer uses radio waves to transfer energy, similar to Wi-Fi. Microwave WPT uses high-frequency microwaves and can transfer energy over longer distances than RF WPT [126]. Solar WPT uses photovoltaic panels to convert sunlight into electrical energy that can be transferred wirelessly [109]. The choice of technology depends on the specific requirements of the device being powered, including its distance from the power source, energy amount, and operating environment [101].

The applications of WPT are numerous and continue to grow, ranging from consumer electronics to industrial automation, and medical devices [50]. The widespread adoption of WPT has allowed for greater mobility, improved energy efficiency, and reduced waste generated from traditional charging methods [98]. Furthermore, the integration of WPT into everyday devices has made charging more straightforward and accessible, with new applications being discovered constantly [104]. Overall, WPT can be applied in various applications. The frequency of operation for different methods of power transfer over a wide range such as healthcare [1], [148] and [12], smart homes[121], [102] and [111], industrial and smart grid [84], [13], [8], [123], [122], and [53].

A. Related surveys

We listed the most recent related surveys with the comparisons in terms of main factors in Table I. Wong et al. [127] suggested an innovative retinal ingrained device using WPT. It substituted a conventional primary power supply with a photo-sensing circuit, assuming a phototransistor and a ring oscillator for stable power for wireless telemetry and power transfer. The authors in [84] proposed a new method for charging and discharging electric vehicles, which involves bidirectional WPT. They evaluated its practicality for use in traffic signals and called it a quasi-dynamic WPT (QDWPT). They suggested installing a sequence of coils beneath the road surface to provide both grid-to-vehicle and vehicle-to-grid (V2G) services to battery electric vehicles (BEVs) when stationary. The paper concludes that using QDWPT at traffic signals can significantly increase the range and operational duration of BEVs in urban driving conditions, especially at high charging levels. In [49], the authors applied the electromagnetic reciprocity theorem to retrodirective WPT system in reverberating room in the context of wireless power transmission was applied. Simulation results showed significant and considerable enhancement in the power transmission system efficiency achieved when applying the reciprocity theorem in the presence of reflecting walls.

Although many technical works have been done in WPT domains, few comprehensive surveys have been conducted, such as [148], [106], [18]. In [148], the authors provided an overview of near-field WPT technologies in a medical device, mainly focusing on those applied in medical applications. Additionally, the publication referenced as [106] discussed the current developments in WPT technology, including energy harvesting, millimeter-wave/THz rectennas, multiple input, multiple outputs (MIMO)-WPT, and advancements in near-field WPT applications. However, it should be noted that not all emerging technologies are covered in this paper. In [18], the authors concluded with a summarized synopsis of specific dynamic and static wireless charging technologies for electric vehicles.

Because the field of WPT is still rapidly evolving, with new technologies and applications emerging frequently, WPT continues to mature. Hence, conducting surveys that provide a comprehensive overview of the field may become more feasible, which would be valuable for researchers and industry practitioners. Therefore, we comprehensively survey WPT technologies and applications, highlighting future trends. Such surveys would offer insights into the latest developments and help guide the development and deployment of WPT technologies and applications.

B. Motivations and Contributions

WPT can offer a stable power reserve for power-limited devices such as sensors, Internet of Everything (IoE) devices, IoT devices, ITS road-traffic sensors, and sustainable smart cities in a manageable manner. It realizes the energy migration wirelessly to the target low-life devices. Power-limited devices in future networks can benefit from WPT technology by designing an efficient charge scheduling scheme and optimizing the charging paths to improve the system's scalability and increase the charge efficiency for each charge run. Taking Wireless Rechargeable Sensor Networks (WRSNs) as a case study, the nodes were recharged by utilizing one or more additional MCs before they run out of energy. In this way, the network can ideally function perpetually [93].

Furthermore, WPT techniques such as inductive coupling have been applied in multiple biomedical applications such as hospital-electric vehicles (EVs), Implantable Medical Devices (IMDs), wearable and implantable biomedical devices such as cardiac pacemakers or implantable ECG recorders [103]. Recently, few studies on wireless charging scheduling schemes have been proposed aiming to enhance the performance of power-limited devices by optimizing charging scheduling schemes and load scheduling. Recent surveys did not holistically cover WPT, which encourages writing these articles. The emergence of WPT charging techniques and charging scheduling schemes with many applications covering many trends of our daily life are the main motivations for this article. However, many studies that covered this topic did not cover the classifications of charging sachems and charging technologies. Furthermore, they did not cover the challenges and the open issues related to this topic.

The major contributions of this article are:

TABLE I: Related surveys comparison with existing work

Ref	Year	MCs Classification	Application	Techniques	Future Trend	Objectives
[142]	2018		✓	✓		They provided an overview of WPT techniques emphasizing working mechanisms, technical challenges, metamaterials, and classical applications. In particular, it is noted that the main research topics in this article were WPT systems and discussed, and based on their particular focus, future developments.
[35]	2019		✓		✓	In their article, the authors provided a comprehensive overview of the recent developments in wireless power supply and highlighted various potential applications of this technology. They discussed the implications of these advances and made projections for future trends while also identifying the energy scheduling problem as a major challenge in the field of WPT.
[29]	2020		✓		✓	The essence of this work is to examine the essential works in this area and provide a perspective on other WPT approaches for biomedical applications.
[50]	2020			✓	✓	This article reviews several WPT platforms that have been utilized for biomedical implantable devices and have been previously discussed in the existing literature. These platforms include capacitive coupling, inductive coupling, magnetic resonance coupling, and newer techniques such as acoustic and optical powering methods.
[40]	2022			✓		The objective of this research is to conduct a comprehensive investigation of WPT methods that can enable sensor devices to acquire energy, thereby minimizing instances of node failures. The study begins with an introduction to Wirelessly powered sensor networks (WPSNs), followed by an examination of three distinct wireless power transfer models, and a discussion of the associated techniques based on existing literature. The research concludes by addressing various challenges and potential future directions to encourage further exploration of WPSNs.
Our work	2023	✓	✓	✓	✓	We identified key issues in Wireless Power Transfer and highlighted its applications in various fields. WPT technologies were classified as radiative and non-radiative, with their characteristics explained. We also discussed classifying Mobile Chargers (MCs) delivery according to various factors, including advantages and disadvantages. Lastly, we summarized potential research trends in WPT.

1) A review of other surveys on WPT and related topics, with the aim of highlighting their strengths and limitations. Then, we present the potential application of WPT, such as home appliances, smart homes, healthcare, industrial, automotive, and smart grids, that can become the driving force of the development of WPT shortly.
2) We classify the wireless power transfer technologies into radiative and non-radiative charging methods. These technologies are categorized according to the primary instrument, power transmission, and transmission path.
3) The study classifies the mobile charging schemes based on different criteria such as charging time (full or partial), MCs numbers (single or multiple), charging cycle (periodic or on-demand), charging model (point–to point or point–to-multiple), and route-control (centralized or distributed). We explained the advantages and disadvantages of each scheme. Furthermore, we pointed out some evaluation metrics that have been recently employed to evaluate the implementation of the designed charging system.
4) This survey describes the most desirable sub-topics of Wireless Rechargeable Sensor Networks (WRSN), such as route planning, trajectory prediction, and charging methods. We then place a great deal of emphasis on the available technologies, opportunities, open issues, challenges, and future trends of WPT.

C. Paper Scope and Organization

This paper is arranged as follows: the technologies for WPT are provided in Section II, while the applications are reviewed in Section III. The charging scheduling schemes for WRSNs are reviewed in Section IV, including the classification of charging schemes, advantages, and disadvantages. Trends are reviewed in Section V. Finally, Section VI concludes this paper.

II. Technologies

Electrical energy can be transferred from a power source to an electrical load without using interconnecting wires by using electromagnetic fields to transfer energy from a transmitter to a receiver. This section will provide several methods of WPT, covering the advantages and disadvantages of each.

WPT technologies can be classified into two primary types: radiative and non-radiative. It is classified based on mechanism, power transmission, and transmission route. Radiative-based employs electromagnetic waves as a medium to transmit energy over longer distances. In contrast, non-radiative methods use inductive and resonant coupling to smoothly transmit the power over short distances to various electronic devices [41]. The classification of these technologies is depicted in Fig.2, additionally explained in the subsequent two subsections.

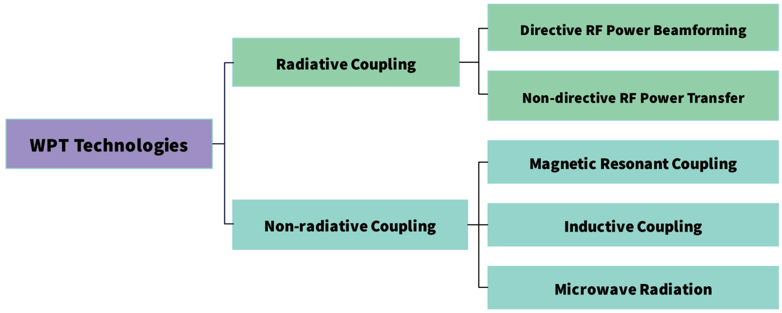


Fig. 2: Classifications of WPT technologies.

A. *Non-radiative Coupling-based (NC)*

Non-Radiative energy transmission, or near-field energy transmission, offers excellent energy transmission efficiency. But it is subject to some constraints, such as small range, where the space from the receiver is less than the signal's wavelength; it is broadly categorized into three methods: Magnetic Resonant Coupling (MRC), Inductive Coupling (IC), and Microwave Radiation (MR). According to the reference [3], MRC and IC have been considered the most dependable methods for transferring power. This is because with capacitive coupling, the amount of transferred power is directly proportional to the capacitance between the capacitor containers, which can be limiting. These three methods for energy transmission are further explained in [76].

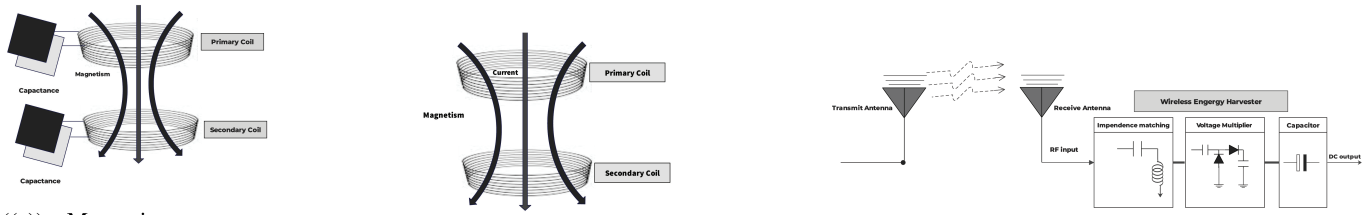
1) Magnetic Resonant Coupling (MRC): As shown in Fig.3(a), MRC comprises passing wave lovemaking that supplies electrical power between two resounding coils by oscillating or irregular magnetic waves. Since the resonant coils operate at the identical resonance frequency, heightened energy transfer efficiency may reduce leakage to non-resonant external aspects. MRC can operate with sufficient efficiency in mid-range applications. Magnetic resonance coupling approaches generally operate in RF bands. In magnetic resonance coupling methods, a high-efficiency level can achieve a more significant length between the transmitting and receiving antenna if their resonance frequencies are the same. It has an average efficiency of 40% to 60%. The high-quality benefits mitigate the sharp decline in the coupling coefficient; thus, the charging efficiency increases with increasing the charging distance. Hence, it is possible to develop the transmission distance. In 2007, researchers proposed a medium-range, high-efficiency wireless power transmission technology using MRC [54]. They declared that wireless power transmission could burn a 60W lightbulb from over 2m away with a transmission efficiency of about 40%. With a transmission length of 1m, the efficiency increases to up to 60%. Nevertheless, MRC isn't straight for decreasing the Witricity length [1] receiver, and for operating, it requires a distributed capacitive coil [76]. It is a significant challenge to implement Witricity technology in portable devices. MRC can charge numerous instruments concurrently by adjusting associated resonators of multiple acquiring coils. It shows that enhancing the power transfer efficiency performs a result. Nevertheless, mutual coupling of the receiving waves can produce interference, so proper tuning is demanded.

[1] An American wireless charging technology company based in Watertown, Massachusetts.

2) Inductive Coupling (IC): IC only operates efficiently over a short distance while it can be developed to a longer length through robust coupled. Fig.3(b) illustrates the authority instance. The appearance of Inductive Power Transfer (IPT) is when an energy transmitter's primary coil generates a primary magnetic field across the secondary coil of the power receiver within the space, typically smaller than the wavelength. IC can be classified into two classes based on the direction of flux flow relative to the road surface: horizontal and vertical focus. The type that generates the limit of charging length to tens of centimeters at diminished efficiency with mysterious power in the microwatt scope is called Inductively coupled Radio Frequency Identification (RFID). However, with the finite transmission capability, the sufficient charging capacity can be very high. The benefits of electromagnetic coupling have the comfort of performance, convenient operation, high efficiency over short spaces, and protection. Hence, it is suitable for portable machines [76].

3) Microwave Radiation (MR): It operates microwaves as a medium to bring radiant power. Microwaves multiply over distance at the rate of sunshine, generally in line of sight. Fig.3 represents the architecture of a microwave energy transmission procedure. Through a magnetron at the transmitter side, power transmission starts with the AC-to-DC conversion, observed by a DC-to-RF transformation. AC-to-DC conversion refers to the process of converting electrical power from an alternating current (AC) source to a direct current (DC) load. This conversion is necessary because many electronic devices require DC voltage to operate, while the standard for power transmission in electrical grids is AC voltage. And DC-to-RF conversion is a process that is commonly used in electronic devices that require wireless communication or transmission, such as radios, televisions, cell phones, and satellite systems. The process involves the conversion of direct current (DC) electrical power into radio frequency (RF) energy.

In the line of sight, it employs microwaves as a medium



((a)) Magnetic resonance coupling. ((b)) Inductive coupling. ((c)) Far-field wireless charging.

Fig. 3: Classifications of Non-radiative Coupling-based technology in WPT.

to bring radiant power—propagation microwaves over height at the rate of light. Microwave energy can be emitted in an isotropic manner or directed via beamforming, with the former being more suitable for streaming applications. On the other hand, beamforming is used for point-to-point communication and involves the transfer of electromagnetic waves, known as power beamforming. This is achieved using an array of antennas or aperture antennas. The sensitivity of the energy beamforming is used to improve the number of transmitting antennas. Employing massive antenna arrays can improve sensitivity. Current growth has also obtained commercial products to the market [76].

B. *Radiative Coupling-based (RC)*

Far-field wireless energy transfer method is called radiative processes. It transfers energy by manipulating the Principle of Electromagnetic Radiation (EMR)[87]. Because of their ability to reach greater distances, this technique is better suited for WSNs and IoT chargers, RFID, and wireless UAVs.

Today, the directive method of radiative wireless power transmission has been used to operate electric cars of electrified vehicles from a remote charge [81]. During the wireless power transmission system design, electromagnetic compatibility should be considered. Relying upon the design and infrastructure, commercializing this technique is costly. High-frequency microwave power (60 GHz) is used for mobile power devices on mobile networks [139]. Radiative WPT systems permit a power transmitter to assign multiple remote devices, named power receivers. Elements direct the energy to the power receivers and equip them with various antennas. The power transmits by transmitting modulated RF signals to energy receptors wireless media [138]. It classifies into Directive RF Power Beamforming (DRPB) and Non-directive RF Power Transfer (NRPT). DRPB and NRPT are two different methods of wireless power transfer. DRPB is a method of wireless power transfer that uses directional antennas to focus the energy in a specific direction. The antenna array is designed to create a beam of energy that is directed toward the receiving device. This method is often used for long-range wireless power transfer applications [77]. NRPT, on the other hand, is a method of wireless power transfer that does not use directional antennas. Instead, the energy is transmitted in all directions using an omnidirectional antenna. This method is often used for short-range wireless power transfer applications. Both DRPB and NRPT have their own advantages and disadvantages depending on the application. DRPB is more efficient for long-range power transfer but requires a more complex antenna system. NRPT is simpler to implement but is less efficient and has a shorter range [78]. In [6], M. Alsharif presented a comprehensive review covering the above two techniques (DRPB and NRPT). Wireless charging is commonly achieved through three alternative methods, namely, magnetic inductive coupling, magnetic resonance coupling, and non-directive RF radiation. This is due to the apparent limitations of the DRPB and NRPT techniques.

III. Applications

WPT can be used in a plethora of applications across a wide range of industrial domains. This section will focus on the most common applications such as smart homes, healthcare, industrial, and automotive. In summary, the existing applications are shown in Fig.4.

A. *Smart homes*

WPT can be used to charge a wide range of home appliances deployed in smart home applications, including home devices, home entertainment systems, and LED lighting. It has the potential to simplify the way we use home appliances by eliminating the need for cords and making it easier to power these devices. Recently, WPT has been deployed in short-range offices and houses to charge multiple devices such as kitchen appliances (i.e., coffee makers, toasters, and microwave ovens), smart home devices(i.e., such as sensors, security cameras, and thermostats), home entertainment systems (charging remotes, game controllers, and other accessories), and other devices such smartphone, tablet. Besides, in the context of home appliances, WPT eliminates the need for electrical outlets and liberates these devices from the sockets-outlets [121]. Furthermore, WPT brings new trends for LED light manufacturers, such that the LED can be powered wirelessly, eliminating the need for cords and, thus, enabling easier replacement and installation. Such WPT systems can offer several operational merits, such as being dustproof, waterproof, and maintenance-free, making LED installation much safer and more convenient [97].

More details about deploying WPT for home appliances can be found in [102]. The authors explain wireless solutions for small home appliances and designs. They illustrated that conventional batteries based appliances are disadvantageous

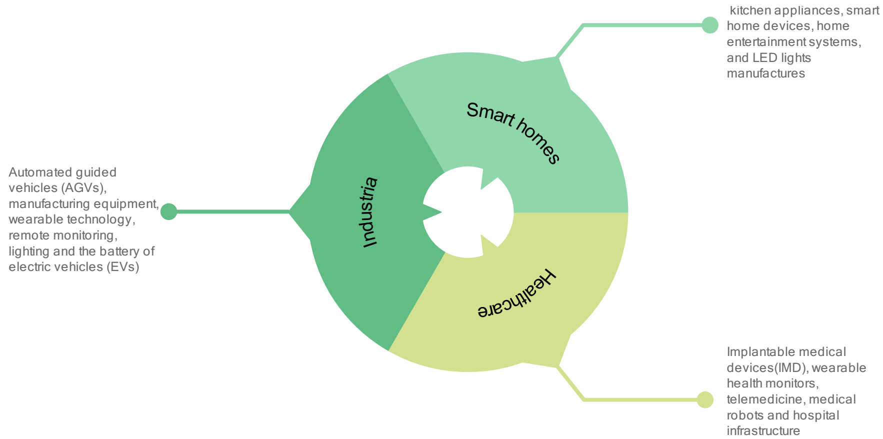


Fig. 4: Applications of WPT.

regarding safety, weight, and life. Solutions that reduce cable complexity are recommended for specific small home appliances in battery-free designs. The users can manipulate the outcomes in a mobile way, thus, enhancing the device's functionality and spread. WPT has been widely used to enable smart home devices such as security cameras, lighting systems, and smart locks to be powered by new solutions that can be used for automating and controlling the home environment.

In [89], the authors discussed a method of integrating security camera functions onto glass windows using wireless power transmission technologies. The proposed method uses a transparent conductive film on the glass surface to enable wireless power transfer and data communication. The camera module is attached to the conductive film, allowing it to capture images and transmit data wirelessly. The authors conducted experiments to evaluate the performance of the proposed method, and the results showed that it was able to transmit both power and data effectively. The paper concludes that this approach could be a promising solution for integrating security cameras into building designs without the need for visible wiring or bulky camera mounts.

B. Healthcare

WPT can play a critical role in healthcare applications by liberating the patients from the constraints and the need to undergo surgeries to replace the batteries of medical devices such as pacemakers, hearing aids, and insulin pumps. In addition, WPT will revolutionize the healthcare industry by facilitating a more convenient, efficient, and cost-effective means of powering medical devices and infrastructure, having the potential to be involved in many healthcare applications, as explained in [115], [75], [12], [14], and [22]. The healthcare applications are given in the form of some examples:

1) Implantable Medical Devices(IMD): IMD such as biomedical implants, pacemakers, and defibrillators require a constant supply of energy for operation. Magnetic resonance coupling-based loading for biomedical implants [135], [2] has a more vital penetrating ability. WPT can be used to transfer power wirelessly to these devices, avoiding the need for battery replacement surgery and reducing the risk of infection.
2) Wearable Health Monitors: Wearable health monitors such as fitness trackers and smartwatches are also well-suited to benefit from WPT. In the case of these devices, the charging time is often very frequent, which may be greatly inconvenient for the users. The wireless charging of these devices with WPT provides convenience and ease of use for these devices.
3) Telemedicine: WPT can be used for powering remote healthcare devices, such as telemedicine carts and monitoring equipment. These devices can be easily moved between patients without bulky power cords, thus improving efficiency and cost-effectiveness in healthcare.
4) Medical Robots: It is increasingly being used in healthcare settings for tasks such as surgery and patient monitoring. WPT can be used to power these robots wirelessly, increasing their mobility and versatility.
5) Hospital Infrastructure: WPT can also be applied for powering hospital infrastructure, such as lighting and heating, ventilation, and air conditioning (HVAC) systems, thus, reducing energy costs and increasing efficiency.

C. Industrial

WPT is able to significantly improve efficiency and productivity in the industrial sector by eliminating physical constraints along with the need for physical cables and enabling more flexible and mobile operations. WPT has a significant impact on companies to reduce costs and increase competitiveness by reducing downtime and increasing mobility. WPT offers several potential applications, including:

1) Automated Guided Vehicles (AGVs) [122]: These vehicles are used in manufacturing and logistics to transport materials and products. WPT can be used to wirelessly charge the batteries of these vehicles, avoiding manual charging and enhancing productivity; thus reducing the need for charging cables and making the charging process more convenient. EVs Show many advantages over fuel-powered IC engines, such as eliminating the fuel

combustion process and reducing emissions. It is a very efficient and quiet operation.

2) Manufacturing Equipment [9]: The manufacturing equipment, such as robotic arms and conveyors, also benefit from WPT. The increase in wireless power enables these machines to be repositioned more easily, thus reducing downtime and increasing efficiency.
3) Wearable Technology [45]: In the industrial environment, wearable technology, such as smart helmets and safety vests, can enhance worker safety and efficiency. The wireless charging of these devices, with WPT, eliminates the need for cumbersome battery packs and increases mobility.
4) Remote Monitoring: WPT can also be used for powering remote monitoring systems, which are used in a wide range of industrial settings to monitor equipment and processes. These systems can be placed in remote, highly accessible areas and can be powered wirelessly, simplifying equipment monitoring and maintenance.
5) Lighting [28]: Lighting plays an important role in the operations of many industrial settings. By using WPT, the wireless powering of lighting can be realized, reducing the need for cables and enabling the repositioning of lighting fixtures.
6) The battery of Electric Vehicles (EVs) [69]: It is a widely used application of high-energy charging to maintain Plug-in Hybrid Electric Vehicles (PHEVs). Inductive coupling for demanding electric vehicles emerged in the 1990s. Inductive chargers have been developed for both unidirectional, and bidirectional charging [69], [83], and [53]. It is possible to supply vehicles with electricity from the grid.

IV. Charging Schemes Computing

Current WPT advancements have generated a novel network called WRSNs. It has quickly received general scrutiny from numerous researchers in terms of high-capacity rechargeable batteries, low-power devices, and scheduling policies design. It shows a simple structural sample of a deploying WRSNs in a two-dimensional plane including three main components: 1) numerous homogeneous sensor nodes with batteries of rechargeable, 2) mobile Wireless Charging Vehicles (WCVs), and 3) a base station (BS) or a service station (SS), located in the center of the network. The BS and sensor nodes form a reliable sensor network for collecting, sending, storing, and processing data. The WCVs (i.e., mobile chargers) can be primarily responsible for the power supply of the sensor network. In each charge trip (round or cycle), MCs start each from the BS, moving around the network and charging the nodes which asked for power(i.e., to be recharged). After charging all/some of the requesting nodes, the mobile charger returns to the BS to refill itself. Multiple mobile chargers can be used; this raises three research questions in this context. How many mobile chargers should we use? Which node should be assigned to which charger? As multiple nodes will be assigned to one charger, which node will be charged first? These three research questions form a new computing problem named as charging scheduling problem. Many efforts have been made in academia to solve this problem by proposing a charging scheme. This section gives a review in this context, providing a classification of the charging scheme based on different criteria that directly influence the scheme performance in terms of charging cost and resource-friendly. In summary, the existing charging schemes are classified as depicted in Fig.5 and listed in Table II.

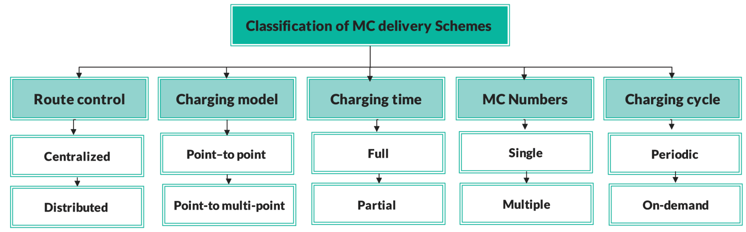


Fig. 5: Classification of charging schemes.

A. Route Control

The categorization of charging scheduling schemes can be based on route control and divided into two types: centralized and distributed. The classification is determined by the location where charging requests are gathered and the place where charging schedules are calculated. Without loss of generality, charging requests are collected by a central entity (i.e., sink or base station) or distributed by mobile chargers [39]. Table III listed some examples to show the differences between the centralized and distributed schemes. Table IV shows the classification of charging schemes based on route control.

1) The Centralized Approach: The charging requests are collected at the base station or the sink. The charging schedules, tasks, and tour planes are computed centrally at the sink and delivered to each mobile charger. The mobile charger completes the charging task and charging tour as given by the sink/base station. Most work in this area has the planning of Cluster Members (CMs) as its sole objective and uses centralized mechanisms to coordinate CMs. Sensor nodes transmit their recharging demands to the BS, and the BS transmits the mobile chargers to the end nodes. Various centralized schemes [32], [31], [133] and [140], have been developed based on heuristic algorithms to increase coverage utility and provide quality of monitoring. Examples of centralized schemes are studied in [133], [95], [100], [58] and [56]. The advantage of this approach is having global knowledge of the network, which leads to more optimized charging schedules. While the main disadvantage is the big communication overhead incurred due to collecting the networking information for building global knowledge.

2) The Distributed Approach: The recharging requests are collected by mobile chargers. Usually, the network is partitioned into multiple sub-regions so that each sub-region is assigned one or multiple chargers. The nodes in the subregion send the recharging requests to the specified charger of that region rather than to the sink. The mobile charger schedules

TABLE II: Classification of charging scheme computing.

Criteria	Charging scheme	Definition
Route control	Centralized	The charging requests are collected at the base station. The charging schedules, tasks, and tour planes are centrally computed at the sink and dispatched to each mobile charger.
	Distributed	The mobile chargers collect the recharging requests. The nodes in the network sub-region send the recharging requests to the specified charger of that region.
Charging model	Point–to point	It employs a traditional charging paradigm in which the mobile charger transfers the energy to one node within its charging range.
	Point-to multi-point	The nodes within the charging range of the mobile charger are simultaneously charged through appropriately tuning operation frequencies of both the mobile charger and node coils.
Charging time	Full	The mobile charger is scheduled to recharge the nodes to their full energy capacity. It is appropriate for the network with multiple mobile chargers.
	Partial	The mobile charger is scheduled to recharge the critical nodes in each charging tour partially. These schemes are more efficient for the network with a single charger.
MCs number	Single	The network employs one charger to recharge the sensor nodes. It is appropriate for small networks with easy network typologies.
	Multiple	Large-scale networks employed multiple mobile chargers to recharge the sensor nodes. It is appropriate for large-scale networks with complicated network typologies. Many MCs work together to charge SNs.
Charging cycle	Periodic	A periodic charging planning specifications have the following marks. The time of each charging and charging path of a mobile device are identical.
	On-demand	An on-demand charging planning transforms the mobile device's traveling path according to the energy consumption of each sensor node in the existing networks and the distance factor.

TABLE III: Protocol phase details of Route control

s. Protocol	Coordination	Charging
Distributed Coordination Protocol (DC)	Distributed	No knowledge.
Distributed Coordination Local Knowledge (DCLK)		Local knowledge
Centralized Coordination (CC)	Centralized	No knowledge
Centralized Coordination Reactive Knowledge (CCRK)		Reactive knowledge
Centralized Coordination Global Knowledge (CCGK)		Global knowledge

TABLE IV: The route control of WCVs.

Ref/Year	Control	Charging	Objectives
[4]/ 2020	Distributed	Full	Multiple
[47]/2022		Partial	Multiple
[95]/ 2021	Centralized	Partial	Multiple
[100]/ 2019		Full	Single
[58]/ 2019		Full	Single
[30]/ 2019		Full	Single
[56]/ 2016		Full	Single

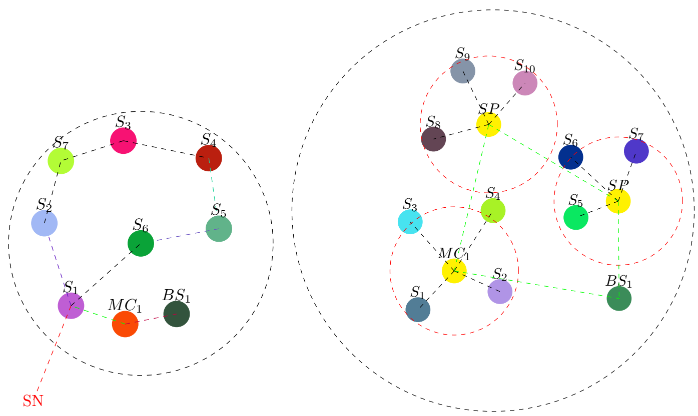
the request and charging tour based on specified criteria. No centralized entity exists in the distributed network to assign the charging commands. With distributed control, the dependability of the sensor network is enhanced compared to the centralized one; Based on local information, mobile chargers receive recharge requests directly from nearby sensor nodes. Furthermore, this approach works agreeably on clustered networks and allows for faster charging decisions. Examples of distributed schemes are studied in [4], [47] and [48]. This approach is more energy efficient for large-scale networks because a mobile charger needs to gather information from its specific subregion rather than the entire network, compared to the centralized architecture [113]. However, an additional burden on the charger is introduced in distributed schemes, such as collecting info and computing the scheduling schemes.

B. The Charging Model of WCVs

The charging model refers to the ability to charge multiple/single nodes at a given time or location by one or multiple mobile chargers. Based on this feature, the schemes can be classified into Point-to-Point (PTP) [36], [62], [134], [60] and [82] and Point-to-Multipoint (PTM) [19], [71], [63] and [107] explained in the following subsections. More details and examples are listed in Table V. In Fig.6, we classified the charging model into PTP and PTM charge.

TABLE V: The Charging model of WCVs.

	Charging Model		
Ref/Year	PTP	PTM	Purpose
[36]/2022	✓		It minimized the battery capacity planning model by taking into account multiple chargers and the path of energy consumption.
[62]/2021	✓		It maximized the charged energy for sensors provided by the UAV, which has energy restrictions.
[16]/2021	✓		It maximized the diversity of populations and improved the charging efficiency.
[134]/2020	✓		It minimized the most extended charge time between multiple runs with mobile chargers instead of a single charge a single mobile charger.
[60]/2019	✓		It maximized the energy efficiency of UAVs and suggested two heuristic scheduling systems to offset energy expenses.
[82]/2018	✓		A novel charging utility maximization problem was formulated to minimize the sensor power depletion time.
[19]/2021		✓	It minimized the mobile charger's power consumption on the road and the portable charger's driving distance.
[71]/2020		✓	It optimized the numeral of dead nodes.
[63]/2019		✓	It maximized charged energy within power restrictions.
[107]/2018		✓	A novel maximization problem for charging utility was developed to minimize the time for sensor power to come to a halt.



((a)) Point–to Point charge. ((b)) Point–to Multi charge.

Fig. 6: Classification of The Charging Model: a) Point–to Point charge b) Point–to Multi charge.

1) Point–to Point (PTP) Charging Scheme : In PTP charging schemes, a mobile charger can charge a node at a given position (one charger per node), even if multiple nodes are within its charging range [60]. The chargers are usually moved closer to the nodes to achieve higher loading efficiency. Trajectories are usually modeled as travel path optimization problems that can convert into Traveling Salesman Problem (TSP), which is an NP-hard issue [64], to discover the shortest Hamiltonian cycle. PTP charging schemes are largely based on magnetic resonance coupling. However, complicated charging route planning and little scalability reduced the excellent feasibility and increased charging efficiency in low-density WRSNs. The Advantages of PTP charging schemes can be summarized as: (1) Suitable for sparse networks, (2) Reduce the charging frequency and enhance its efficiency, (3) Minimize the total power consumption of the sensor network, and the charging method, (4) Maximize the vacation time ratio of the WCVs in each cycle time, and (5) Maximize the travel route, the charging period in each node and discharge guidance techniques, and the optimal travel path of WCVs rotated out to be the quickest Hamiltonian cycle passing via all sensor nodes [21]. On the other hand, the main disadvantage of such schemes is lowering the charging scalability and inefficiency, especially in dense networks. Examples of PTP charging schemes are provided in [36], [62], [134], [60] and [82].

2) Point-to Multi-points (PTM) Charging Scheme : In the PTM charging scheme, one mobile charger simultaneously charges multiple sensor nodes, theoretically the nodes which are located within its charging range. The path optimization problem is converted into a charge coverage case (where WCVs can pause to charge more additional nodes at once). The advantages of such schemes are as follows. It is appropriate for sensor networks, wide or clustered nodes, or ultra-low energy sensor networks. It can shorten the charging time, reduce energy consumption during WCVs motion, and enhance the scalability of charging planning. Otherwise, the disadvantage is as follows. The schemes required a larger charger range, while nowadays, WPT supports power transfer within a range from 0.75m to 2.25m. Examples of PTM schemes are provided in [19], [71], [63] and [107].

C. Charging Time

Based on the amount of energy transmitted to each sensor per charging tour, charging schemes can be classified into partial and full schemes. Table VI outlines the advantages and disadvantages of such schemes. Various examples of these schemes are reported and summarized in Table VII. In Fig.7, we categorized the charging time schemes as full and partial charges.

1) Full Charge Schemes: The mobile charger is scheduled to recharge the nodes to their full energy capacity, which may take half to one hour to recharge a commercial off-the-shelf battery fully (e.g., Lithium battery). Full charging schemes are appropriate for the network with multiple mobile chargers, while partial charging schemes are more efficient for the network with a single charger. Table VI lists the benefits and drawbacks of these approaches. Examples of full charge schemes are studied and explained in [45], [66], and [118].

2) Partial Charge Schemes: In such a scheme, the mobile charger is arranged to recharge the vital nodes during each charging tour partially. Thus, multiple recharging tours may require recharging the node to full capacity. Such a scheme is much preferable when a single charger is employed in offline schedules because the lifetime of the node battery lasts for several months while the charging tour may take a few days, assuming the network contains less than five hundred nodes. In [73], the author focused on controlling the number of stop locations and the charging duration at each stop location so that the nodes can be charged partially at each tour. More critical nodes require a lesser number of stops and a smaller charging duration. The same idea is employed in [132], where the authors optimized the charging duration and reduced the problem to a matching problem between the sensors and time slots. Examples of partial charge schemes are studied and explained in [125], [124], and [51]. The advantages and disadvantages of the partial charging schemes are listed in Table VI.

D. Number of Mobile Chargers

Based on network size, the charging schemes can employ one or multiple chargers. The advantages and disadvantages of such charging schemes are listed in Table VI.

1) Single Charger Schemes: The small network employs one charger to recharge the sensor nodes. This approach is beneficial for small-size networks and cost-effective to deploy one charger for energy provisioning. While for large-scale networks, one charger is unable to recharge all life energy-critical nodes. To maximize the sum of sensor survival times, Xu et al. [132] considered how to schedule MCs to charge sensors multiple times in one charging cycle. Examples of single charging schemes are studied and explained in [124, 128, 90].

2) Multiple Chargers Schemes: Large-scale networks employ multiple mobile chargers to recharge the sensor nodes. This approach is suitable for large-scale networks and can provide a larger network lifetime. But it is more expensive to deploy more than one charger. Examples of multiple charging schemes are studied and explained in [92, 61, 59]. The advantages and disadvantages of multiple charging schemes are listed in Table VI.

E. The Charging Cycle of WCVs

Based on trajectory accessibility (i.e., Charging Cycle), the charging schemes can be classified into On-demand (i.e., online [116], [47], [88]) and Periodic (i.e., offline [137], [20], [24], [147]). Trajectory accessibility or Charging Cycle means how the trajectories of the chargers are defined for each charging tour. Various examples of these schemes are summarized in Table VIII. The advantages and disadvantages of the online (on-demand) and offline (periodic) schemes are listed in Table IX. In Fig.8, we Classified the Charging Cycle into periodic charge and On-demand charge.

1) Periodic Charge Scheme : For periodic schemes, the trajectories (i.e., paths) are fixed and predefined by the sink for all tours. Thus, the chargers are periodically delivered to recharge all the nodes. Periodic schemes assume that nodes' charging period, traveling direction, and charging sequence are fixed in each round tour. These scheduling schemes suit networks with uniform power usage and minimal data transmission requirements. They are straightforward to implement and have a slightly positive impact on operational efficiency. However, such schemes are designed offline without considering the instance situation of the node's energy rate. This may lead to a longer traveling distance which defiantly increases the kinetic energy consumption of the mobile chargers [21]. Examples of periodic (i.e., offline) charge schemes are studied and explained in [137], [20], [24] and [147].

2) On-demand Charging Scheme: In On-demand schemes, the trajectories are computed online and are not fixed or predefined paths. Energy-critical nodes report their energy status to the sink, and then the sink computes the trajectories based on the location of the energy-critical nodes. Due to the online decisions of the On-demand scheme, the length of the traveling path is decreased, the charging efficiency is increased, and the system's robustness is guaranteed. Examples of on-demand (i.e., online) schemes are studied and explained in [116], [47] and [88].

V. Trends and Opportunities

The WPT paradigm has grown exponentially, with several trends driving its growth and development. This section provides the recent research trends, including rising interest in IoT, increased interest in sustainability, increased adoption of EVs, development of new WPT standards, and advancements in WPT technology.

A. Growing interest in IoT

The Internet of Things (IoT) is a rapidly growing network of devices connected to the internet that can communicate with each other. This includes devices such as smart thermostats, wearables, and even vehicles. Wireless technologies play a critical role in the IoT ecosystem, enabling devices to communicate and operate seamlessly without wires. This includes Wi-Fi, Bluetooth, Zigbee, Z-Wave, LoRa, NB-IoT, and LTE-M [26].

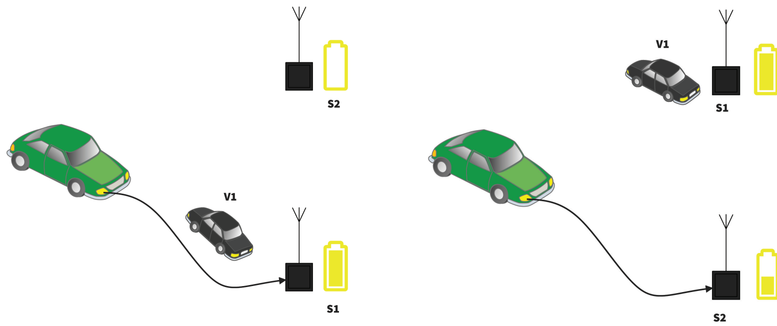
TABLE VI: Advantages and Disadvantages of Charging time and MCs Numbers.

Criteria	Charging scheme	Advantages	Disadvantages
Charging time	Full	-Lower service cost (i.e., the smaller traveling distance of mobile charger) compared with the partial ones since it requires fewer numbers of charging tours. -Battery friendly.	-Lower energy-distribution efficiency since power resource is not allocated based on demand.
	Partial	-Higher charging efficiency since the energy resource of each charger is fairly allocated in each charging tour. Hence there will be a more significant number of nodes to be charged.	-Not battery friendly; the number of times to recharge a rechargeable battery is limited, and more times means less battery capacity. -Higher service cost (i.e., the more considerable traveling distance of mobile charger). Because it partially charges the nodes, it requires more charging tours to recharge them fully.
MCs number	Single	-Cost-effective to deploy one charger for energy provisioning. -Appropriate for networks that are small in size.	-One charger cannot recharge all life energy-critical nodes for a large-scale network.
	Multiple	-Appropriate for networks that are large in scale. -Can provide a larger network lifetime.	-It is more expensive to deploy more than one charger.

TABLE VII: Charging time scheme and the number of WCVs.

Charging mode	Charging time	Ref	Variables	Objectives
Single node	Partial charging	[124]	Charging path	Max(the overall working time), Min(the required traveling cost) .
		[143]	Charging node, Charging time	Max(energy), Min(travel cost) .
		[90]	Charging time	Min(charging delay).
Single node	Fully charged	[128]	Charging path	Max(charging utility).
		[46]	Charging path	Max(the survival ratio).
		[57]	Charging time	Max(energy efficiency), Min(total sleep time).
		[136]	Charging time	Min(number of dead sensors).
		[23]	Charging time	Min(charging delay).
Multiple nodes	Fully charged	[61]	Charging time and charging path	Max (energy usage efficiency and survival rate).
		[43]	Charging point, charging time	Max (energy efficiency of MCs).
		[134]	Charging node. charging time	Max(charging utility), Min(charging delay)
		[92]	Charging node	Max(load benefits), Min(data loss).
		[129]	Charging time	Max(Ratio of the wireless charging vehicle)
Multiple nodes	Partial charged	[131]	Charging time	Min(the travel cost of the mobile charger).
		[130]	Charging time, routing path, charging path	Max(vacation time).
		[72]	Charging time, charging path	Max(charging duration), Min(number of dead sensors).
		[59]	Charging time and charging point	Max(charging utility).

As the IoT continues to evolve, there is an increasing need for advanced technologies such as edge computing, machine learning, and AI. To reduce latency and improve performance, edge computing involves processing data at the network's edge, closer to the devices themselves. Machine learning and AI are used to analyze the vast amounts of data generated by IoT devices and provide insights that can be used to improve efficiency and make better decisions. The Integration of WPT technology with IoT devices can provide several benefits, such as reducing the need for battery replacement or recharging,



((a)) Full charge. ((b)) Partial charge.

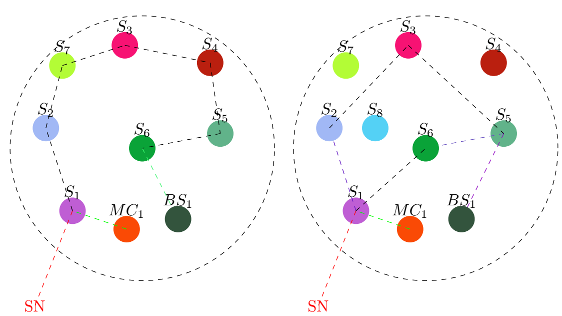
Fig. 7: Categories charging time scheme a) Full charge, and b) Partial charge.

TABLE VIII: The Charging Cycle of WCVs.

Ref/Year	Charging Cycle On-demand	Periodic	Purpose
[47]/2022	✓		It achieved the lowest charging delay and highest charging coverage.
[88]/2021	✓		It maximized the network lifetime.
[117]/2020	✓		It maximized performance by achieving both low average charging latency and high energy usage efficiency.
[67]/2018	✓		It minimized the number of dead nodes while increasing power efficiency.
[65]/2017	✓		It Enhanced charging efficiency.
[68]/2022		✓	It minimized the model control cost.
[137]/2021		✓	It Minimized the battery capacity required by each sensor.
[20]/2020		✓	It minimized the charging frequency and enhance its efficiency.
[34]/2018		✓	It Enhanced charging efficiency.
[147]/2017		✓	It minimized data transmission delay and power consumption.

TABLE IX: Advantages and Disadvantages of the Charging cycle.

Criteria	Charging scheme	Advantages	Disadvantages
Charging cycle	online(On-demand)	- Dynamic and recharge the nodes on-demand. -Lower service cost (i.e., visiting the energy-critical nodes only).	-Larger communication overhead (i.e., the critical nodes report their energy status).
	offline(Periodic)	-Simple scheduling for energy provision. - Zero communication overhead.	-Limited application range because it is unsuitable for variable energy consumption rates and dynamic environments.



((a)) Periodic charge. ((b)) On-demand charge.

Fig. 8: Classification of the Charging Cycle: a) Periodic charge, and b) On-demand charge.

improving device reliability, and enabling new use cases for IoT devices. For example, WPT technology can power remote sensors that are difficult to access or wearable devices that must be constantly charged.

B. Increased interest in sustainability

WPT solutions have become increasingly popular in recent years due to their potential to reduce carbon emissions and increase sustainability. The traditional method of transferring power through cables and wires often results in energy losses due to resistance, which wastes energy and generates heat, leading to further energy waste. WPT systems typically use electromagnetic fields to transfer energy between transmitting and receiving devices. This technology can reduce energy waste and increase energy efficiency, leading to a more sustainable and environmentally friendly future. WPT solutions are being adopted in various industries, including consumer electronics, automotive, and healthcare. For example, in the consumer electronics industry, WPT technology is being used to charge smartphones, laptops, and other portable devices wirelessly. In the automotive sector, WPT technology is being explored for electric vehicle charging, which could significantly reduce carbon emissions compared to traditional gasoline-powered cars. In the healthcare industry, WPT technology is used to power medical implants, such as pacemakers, requiring a reliable and long-lasting power source. As this WPT technology continues to advance and become more widely adopted, it has the potential to play a significant role in creating a more sustainable and environmentally friendly future [91].

C. Increased adoption of (EVs)

The increasing popularity of electric vehicles is creating a need for WPT technology, as these vehicles require charging solutions that are both convenient and efficient. As the number of EVs on the road grows, the demand for WPT solutions will also increase. The popularity of electric vehicles is on the rise as it decreases dependence on fossil fuels and minimizes greenhouse gas emissions. The use of dynamic wireless charging systems in electric vehicles is generally considered safe for transportation purposes [79]. However, significant obstacles still prevent the widespread adoption of electric vehicles. One obstacle hindering electric vehicle adoption is its limited driving range and extended charging times. However, WPT technology provides a viable solution to tackle these issues. WPT technology facilitates efficient wireless charging of electric vehicles, extending the driving range while reducing battery size and increasing convenience [114]. The U.S. Society of Automotive Engineers (SAE) J2954 has been updated to incorporate input from standardization organizations. SAE J2954 is a set of guidelines established by the Society of Automotive Engineers to regulate the wireless charging of EVs. The reference number ”J2954” identifies this particular set of guidelines. These standards are intended to facilitate the use of WPT technology to charge EVs by establishing performance and compatibility requirements that WPT systems must meet. The J2954 T/F (Wireless Charging Task Force) was established in October 2010 to formulate a standard specification and release it by 2014. One of the ongoing discussions within the task force is the frequency band to be utilized for WPT, and an out-of-band system is being considered, where the frequency utilized for management communication differs from that used for WPT, as stated in [15]. Additionally, the Inductive Wireless charging sub-working group (SWG) of the japan automobile research institute (JARI) is also discussing pertinent topics. The SWG of JARI is a research project similar to the PT61980 mentioned earlier and is the Japanese equivalent. The Wireless Charging System Technical Committee, which is part of Japan’s Society of Automotive Engineers, supports this SWG [108].

D. Development of new WPT standards

Several competing WPT standards exist, including Qi, AirFuel, and Power Matters Alliance (PMA). As the WPT industry grows, one or a few standards will likely emerge as the dominant, making it easier for manufacturers to develop and market WPT products. The current statuses of standardization organizations are included:

1) Qi: It is a term used to refer to the WPT standards developed by the Wireless Power Consortium (WPC). The name ”Qi” is derived from a Chinese word meaning ”life force” or ”energy flow.” The Qi WPT standard defines the technical specifications for wireless power transfer between a charging pad (transmitter) and a compatible device (receiver) [99].
   The WPC has developed multiple versions of the Qi standard, each with new features and capabilities. The most recent version of the Qi standard, version 1.3, includes the ability to fast charge, an extended range for transferring power wirelessly, and the capability for devices to send and receive power wirelessly in both directions [77].
2) The AirFuel Alliance: t is a group that creates standards for WPT, similar to WPC. The AirFuel Alliance also strives to establish a universal standard for wireless charging that is safe, dependable, and user-friendly. The AirFuel Alliance has created various WPT standards, such as the AirFuel Resonant standard, which uses resonant magnetic coupling for wireless power transfer, and the AirFuel Inductive standard, which uses magnetic induction purpose. These standards are intended to work with electronic devices like wearables, laptops, and smartphones. They have built-in safety measures to prevent potential hazards like overheating or overcharging [38, 37].
3) The Power Matters Alliance (PMA): It is a group that has established standards for WPT. Its objective is to develop a universal standard for wireless charging that is secure, effective, and works with various electronic devices. The PMA has created multiple standards for WPT technology, including the PMA Wireless Power standard that employs inductive charging for wireless power transfer and the PMA Extended Power standard that permits higher power transfer rates and more extended charging distances[94]. These standards are intended to be compatible with various devices, such as wearables, smartphones, and other portable electronics. They also incorporate safety features to prevent hazards such as overcharging or overheating. Ultimately, the

PMA's WPT standards offer a convenient and efficient method for charging electronic devices without requiring cables or connectors [42, 110].

E. Advancements in WPT technology

WPT technology is constantly improving, with new solutions being developed that can transfer energy over longer distances and with greater efficiency. Advances in WPT technology will make it possible to transfer energy to a wider range of devices and in more challenging environments. Some of the advancements in WPT technology that have been made in recent years include the following:

- Resonant WPT: This technology allows for power transfer over a greater distance and through objects, making it more efficient and convenient [52].
- Magnetic resonance coupling [11]: This type of resonant WPT uses magnetic fields to transfer power, making it more efficient and safer than other methods.
- Beamforming: This technology uses directional antennas to focus the power beam, reducing interference and increasing efficiency.
- High-power WPT [141]: Recent advancements in WPT technology have made it possible to transfer higher levels of power, enabling it to be used for larger devices such as electric cars.
- Standardization: The development of international standards for WPT has enabled interoperability between different devices and systems, making it easier for consumers to use WPT devices [7].
- Integration with IoT [112]: WPT can now be integrated with IoT devices, enabling the wireless powering of sensors and other low-power IoT devices.
- Efficiency improvements: Advances in power electronics and control algorithms have increased the efficiency of WPT, reducing energy loss and heat generation[85].

These advancements in WPT technology have made it more efficient, convenient, and cost-effective. As a result, WPT is increasingly being used in various applications such as smartphones, wearables, electric cars, and smart homes. WPT technology is expected to continue to improve in the coming years, enabling the wireless powering of larger devices and further reducing our reliance on cords and batteries.

VI. Conclusion

This paper places great emphasis on the emerging topic, namely, WPT and its future trends, covering its challenges and opportunities. This promising technology has significantly increased over the decades and has presented many user-friendly applications. Combining wireless charging with existing transmission networks develops unique opportunities and challenges for resource budgets. WPT technology is becoming increasingly popular for charging mobile devices and electric vehicles and has gained significant attention in recent years. Even though the fundamental concept of WPT was introduced over a century ago, there has been a surge in demand for this technology, particularly in the context of Industry 4.0, where it offers the potential for ubiquitous access to electricity. WPT can be integrated into the existing high-tech industry, similar to other technologies such as smartphones, and its applications have expanded from the chip scale to the spatial hierarchy.

We have pointed out the critical issues for wireless power transfer and provided an at-a-glance study table highlighting our contribution corresponding to the previous related survey works. The concept of the MCs delivery classifications according to charging time, MCs number, charging cycle, charging model, and route control have been explained here. We have presented the advantages and disadvantages of each item of this classification. In addition, we have highlighted the wireless power transfer applications such as home appliances, smart homes, healthcare, industrial, automotive, and its technologies, which will assist the investigators in understanding their principal characteristics and workflow. Finally, the research trends in WPT have been summarized.

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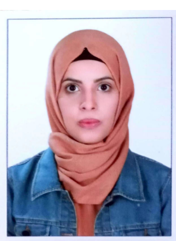

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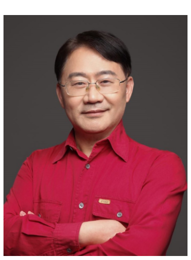

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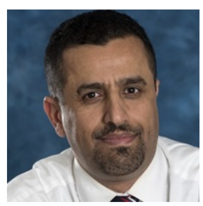

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