Pervasive and Mobile Computing 93 (2023) 101820

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

journal homepage: www.elsevier.com/locate/pmc

Review

Wireless power transfer with unmanned aerial vehicles: State of the art and open challenges

Tamoghna Ojha [a,b,*], Theofanis P. Raptis [a], Andrea Passarella [a], Marco Conti [a]

[a] Institute for Informatics and Telematics (IIT), National Research Council (CNR), Pisa, Italy
[b] Department of Computer Science and Engineering, SRM University-AP, Andhra Pradesh, India

ARTICLE INFO

Article history:
Received 24 December 2022
Received in revised form 3 May 2023
Accepted 3 July 2023
Available online 5 July 2023

Keywords:
Unmanned aerial vehicle
Wireless power transfer
Simultaneous wireless information and power transfer

ABSTRACT

Wireless power transfer (WPT) techniques are emerging as a fundamental component of next-generation energy management in mobile networks. In this context, the use of UAVs opens many possibilities, either using them as mobile energy storage devices to recharge IoT nodes, or to prolong their operation time via smart charging themselves at ground stations. This paper surveys the recent literature on WPT as it applies to UAVs and identifies several open research challenges for the future. As a first step, we tessellate the related research corpus in four fundamental categories (architectures, power and communications enabling technologies, optimization with respect to spatial concepts, optimization of operational aspects). Second, for each category, we provide a critical review of the recent WPT UAV approaches with respect to the way they specialize the general concept of WPT and the extent of their applicability. The survey presents the latest advances in WPT UAV methodologies and related energy-centric services, spanning all the way from the communications aspects deep in the small- and large-scale deployments, up to the operational and applications aspects. Finally, motivated by the rich conclusions of this critical analysis, we identify open challenges for future research. Our approach is horizontal, as the selected publications were drawn from across all vertical areas of research on UAVs. This paper can help the readers to deeply understand how WPT is currently applied to UAVs, and select interesting open research opportunities to pursue.

Contents

* Corresponding author.
E-mail addresses: tamoghna.ojha@iit.cnr.it (T. Ojha), theofanis.raptis@iit.cnr.it (T.P. Raptis), andrea.passarella@iit.cnr.it (A. Passarella), marco.conti@iit.cnr.it (M. Conti).

https://doi.org/10.1016/j.pmcj.2023.101820
1574-1192/

1. Introduction

1.1. Motivation and reference scenario

With the explosive growth of cyber and physical data, unmanned aerial vehicles (UAV) have been considered a promising enabler for future wireless networked infrastructure. Both communication and energy efficiency can be improved in settings where the mobility of UAVs as well as their cooperative communication are well managed. In fact, UAVs have been used in various applications, such as coverage [1], localization [2], surveillance [3] and data collection [4]. To fully exploit the cooperative and autonomous UAV-enabled operational functions, it is of utmost importance to investigate and optimize the energy-related aspects [5]. UAVs may have a dual role from an energy management perspective. On the one hand, being battery-powered, they need to adopt energy-saving mechanisms to prolong their operational lifetime. On the other hand, because they can be equipped with significant loads, they could also be used as mobile charging stations, to replenish batteries of more constrained devices even located in not easily accessible places, such as small-size IoT devices. These specificities make energy management for UAVs particularly challenging.

Because of this dual nature, not only energy *conservation* algorithms should be used for UAVs, but also mechanisms should be devised, to support flexible *recharging* of UAV batteries. Both approaches need to be employed. For example, solutions limiting to a smart management of the battery capacity via, e.g., battery replacement or battery ageing mitigation [6], can be an immediate remedy but it is costly and may not be practical. To manage recharging of UAVs during their operation, energy harvesting solutions have been proposed, exploiting, e.g., solar, wind or vibration energy sources. However, those approaches suffer from limited practical applicability due to the predictability constraints and bounded energy supplies that can be harvested over time [7].

Wireless power transfer (WPT) is considered a more viable alternative with respect to energy harvesting, and has recently gained prominence in the literature. WPT implements the energy recharging process in a cordless way [8]. This novel technological enabler has changed the traditional energy management patterns in numerous applications [9], including UAVs. Owing to its adjustable parameters of flexibility, positioning and mobility, the WPT solutions are considered as a viable enabler for energizing electric-driven devices [10], therefore contributing to UAV use cases of interest.

In Fig. 1, we depict a simple WPT framework for recharging of the UAVs. The recharging process of the UAVs are aided by a charging platform at the ground. The UAV can detect the charging platform using different means such as wireless communication or image processing, and aligns its WPT receiver with the WPT transmitter embedded in the charging platform. On the other hand, the charging platform can also employ sensor-based systems to better align the WPT transmitter and receiver for better efficiency of the recharging process. Depending on the application and requirements, there can be multiple UAVs employed in operation and multiple charging platforms deployed at the ground for facilitating the WPT. Fig. 2 shows an example scenario consisting of multiple UAVs and charging platforms. In this figure, we also highlight the multiple possible roles of the UAVs in a UAV-WPT scenario — *UAVs as charge provider*, *UAVs as charge receiver*, *UAVs providing/receiving charge* as well as *UAVs acting as data mule*. Additionally, the figure points out the possibility of multi-UAV collaboration for data collection, coverage, and trajectory planning.

The focus of this survey is to provide a comprehensive presentation and critical analysis of the state of the art in the area of UAV-assisted WPT. Specifically, we analyze the literature across multiple technological aspects, and across many verticals, aiming at providing a unique reference points for researchers interested in the topic across the many verticals where UAV-assisted WPT can be applied, and in the specific technological components that are required to realize an efficient UAV-assisted WPT system.

1.2. Sketch of application areas

WPT in presence of UAVs has been envisioned for a number of application areas, already. Possible verticals are many, including agriculture, disaster recovery, industrial, electrical, and transport. Notable examples, among many, include UAV-based delivery scheduling [11], railway safety in high-speed train communication [12], Internet of MIMO things [13], empowering ocean surface drifting buoy system [14].

In this section we briefly point to some relevant such use cases. While a detailed discussion of use case is not the main focus of this paper, these pointers allow the reader to frame the technical solutions presented hereafter in a more comprehensive way.

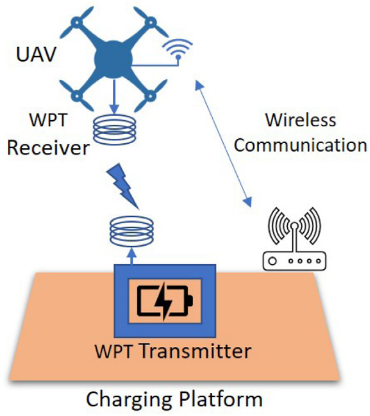

Fig. 1. UAV-WPT overview with single UAV.

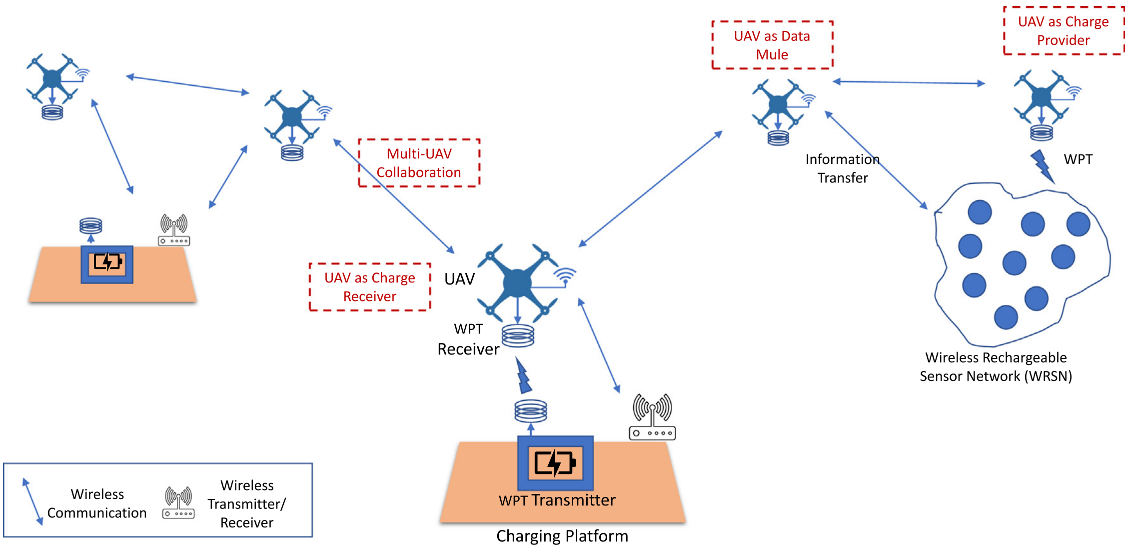

Fig. 2. UAV-WPT overview with multiple UAVs.

- *UAV-assisted sustainable precision agriculture*: Precision agriculture is an area which can be benefited by the application of UAV in terms of data collection as well as enhancing the lifetime of the deployed sensor nodes. In [15], the mobility and flexibility of the UAV is leveraged to recharge the deployed sensor nodes as well as collect their data in a precision agriculture scenario. This ensures the proper functioning of the system based on the sensed data about the environment and continued decision making based on the collected information. [16] proposed an idea of a battery-less agricultural sensor system. The authors focused on planning the navigation of the UAV such that the deployed nodes are recharged with the limited available battery capacity of the UAV.
- *Disaster recovery and rescue missions*: In disaster and rescue operations, the mobility and flexibility of the UAVs helps in rapid setup of the communication network for the mission. However, the issue of powering the UAVs for longer missions and the collaboration among themselves are important issues to consider. [17] discussed the methods for optimal UAV placement in formation of an ad-hoc network to provide communication coverage for the mission area. In [18], discussed the problem for collaborative trajectory and charging schedule planning while minimizing the total mission duration by multiple UAVs. A UAV-assisted and WPT-empowered public safety network is another application for providing resilient communication in disaster recovery scenarios [19].
- *Belt Conveyor inspection system in the mining industry*: The belt conveyor system used in the mining industry requires periodic inspection and maintenance. In this regard, the UAVs provide a low-cost and secure solution for monitoring the belt conveyors. Ribeiro et al. [20] proposed a UAV routing and charging schedule planning method for such scenarios.
- *Inspection of overhead power lines*: [21] proposed to leverage the UAVs for inspection of the overhead power lines while also recharging themselves. Using this method, multiple UAVs can be engaged for efficiently inspecting the

Table 1
Classification of non-WPT, UAV surveys.

Focus of the study	References
General issues and applications	[23–26]
Computer Vision models for UAVs	[27,28]
Communication channel modeling	[29,30]
Optimization approaches for civil applications	[31]
Computational intelligence and path planning	[32–35]
Collaborative UAV-WSN systems	[36]
5G mmWave communications for UAV-assisted networks	[37,38]
Multi-UAV Cyber-Physical Systems	[39,40]
Integration of UAVs and cellular networks	[41,42]
Communication and networking issues	[43]
UAV flight control methods	[44–46]
Load transportation using UAVs	[47]
UAV communications for civil applications	[48]

power lines by collaborating among themselves to optimize the inspection time and accuracy. The energy harvesting facility along with the inspection will help in prolonging the flight time.

- *Road patrol*: In the area of transportation and traffic management, a fleet of UAVs can reduce the cost of road patrols and improve the efficiency. [22] proposed a model for task assignment and recharging in a multi-UAV road patrol scenario.

2. Related surveys

We would like to emphasize that there is no comprehensive survey up to date on a *holistic examination of UAV-WPT techs, systems, architectures, algorithms, problems, etc*. It is important to note that the incorporation of WPT technology in a UAV-based scenario changes the problem perspective and solution approach. Therefore, with the presence of WPT facility, it is necessary to revisit the typical issues (such as coverage, trajectory planning, energy management, placement, scheduling) of UAV-based systems.

The existing survey articles are mostly focused on either solely (a) UAV or (b) WPT specific issues, and only a few articles are focused on (c) UAV-WPT. In the following Sections 2.1–2.3, we list the articles in these three categories, and point out the specifically surveyed topic in each of the articles. The survey articles focused on UAVs do not considered the presence of WPT. On the other hand, the survey articles focused on WPT are outdated as they have been published years ago and they have either (i) *tech-focus* on various charging techniques, (ii) *extremely broad focus* on general WPT aspects which makes it difficult to understand the WPT added value for UAV, (iii) *extremely narrow focus* on specific WPT-UAV aspects which makes it difficult to understand the full picture.

2.1. Surveys on UAV Standalone

There is a significant body of work focusing on UAV-related issues without considering WPT aspects *(non-WPT, UAV)*. Table 1 shows the works in this category according to their main surveyed topic, such as computer vision models for UAVs, communication channel modeling or optimization approaches. It is important to note that the presence of WPT in this background is important, as the energy resources available at devices may change the design and optimization of the technologies considered in those surveys.

2.2. Surveys on WPT Standalone

In this section, we list the articles focused on the WPT issues, without considering the presence of UAVs (*non-UAV, WPT works*). They focus on issues specific to WPT technologies, such as, charging techniques. However, these works do not feature the presence of UAVs while performing WPT. Table 2 shows these works. Again, including UAVs in the picture may bring to significant design changes in the WPT schemes.

To be specific, the surveys articles in [49–54] were published at least 5 years ago up to *2018*, do *not focus on UAV*. The survey work on [55] specifically focused on the mobile charging techniques for Wireless Rechargeable Sensor Networks (WRSNs), and very limited coverage of the UAV-WPT aspects in a holistic way.

2.3. UAV-WPT technological surveys

In the third category, we list the UAV-assisted/included WPT works (charging *by the UAV* or *for the UAV*) as shown in Table 3. These works ([56–59]) focused on WPT *technology*, which is not the main focus of our paper; rather a small step for explaining the tech capabilities for the rest of the paper. To be specific, these works focused on wireless charging techniques for UAVs [56,57], various WPT techniques for UAV [56,58], and UAV-enabled WPT scenarios [59]. However, the

Table 2
Classification of non-UAV, WPT surveys.

Focus of the study	References
Technology and roadmap	[49–51]
Compensation technologies	[52]
Techniques, standards, scheduling strategies	[53]
Wireless Rechargeable Sensor Networks (WRSNs)	[54,55]

Table 3
Classification of UAV-WPT surveys.

Focus of the study	References
Near-field WPT for UAVs	[58]
Wireless charging for UAVs	[56,57]
UAV-enabled WPT	[59]

authors in [59] followed a tutorial approach, rather than a survey approach, and specifically focused on maximizing the energy transferred to the ground deployed devices in different scenarios such as single/multi-UAV WPT, Wireless Powered Communication Networks (WPCNs), wireless powered Mobile Edge Computing (MEC). Further, the authors highlighted few relevant issues on trajectory design, swarming in each such scenarios, and also proposed few solutions for those problems. However, these existing works did not include various important aspects (especially the spatial and operational aspects) of both UAV and WPT perspectives. Also, the detailed analysis of the approaches including implementation and objective-based problem solving are missing in the existing literature.

2.4. Novelty in our work

In contrast to the above mentioned works, in this paper, to the best of our knowledge, for the first time in the state of the art, we provide an exhaustive survey of Wireless Power Transfer with UAVs (UAV-WPT), and we highlight the related intrinsic design and application challenges in a comprehensive manner. Our survey includes scenarios where UAV assists the charging process as well as UAV is assisted for charging. We also discuss different dimensions of works including single- and multi-UAV scenarios, UAV-assisted Wireless Powered Communication Network (WPCN) and UAV networks, different levels of mobility in the network. We provide a broader classification (and sub-classifications) of the existing works in terms of different aspects compared to the exiting surveys. For each such category, we again structure the works into various sub-categories based on their main focus and consideration. We also present comparison of the existing works with respect to different parameters and highlight methods using images.

3. Taxonomy and organization of the survey

In Fig. 3, we provide an organizational roadmap of the paper contents. We classify the existing works in the literature into four distinct aspects. First, in the *architectural aspects*, we discuss the number and types of WPT sources and receivers, and their mobility. This section is needed primarily to set the scene, and present the different variations of our reference scenario, depicted in Fig. 2, which have been considered in the literature.

Sections 5 and 6 include approaches to design or optimize specific technical or performance aspects of a UAV-WPT system. Specifically, for *power and communication aspects*, we categorize the existing UAV-WPT works according to their focus on demonstration platforms, issues such as power efficiency, communication, throughput maximization, resource allocation and Simultaneous Wireless Information and Power Transfer (SWIPT). The papers presented in this section deal, therefore, with specific technological components related to power management (during a WPT process), as well as coupling between communication and WPT operations.

On the other hand, in the *spatial aspects* category, we discuss the issues such as coverage, navigation, surveillance and trajectory and how these issues impact UAV-aided WPT applications. These papers do not deal with technological components of the WPT process, but rather optimize the management of the *spatial operations* WPT system, in presence of UAVs.

Section 7 broadens the spectrum of optimization, and considers works aimed at optimizing UAV-WPT at an overall system level during its operation. We discuss the *operational aspects* which include important issues such as energy management, data collection, operating utility, placement, scheduling and security.

Finally, after presenting the state of the art along the taxonomy of Fig. 3, we discuss key open research challenges in Section 8.

In Table 4, we list the abbreviations used in this paper.

4. Architectural aspects

In the following, we discuss the different types of WPT sources and receivers, the numbers and mobility of such WPT provider/consumer elements. For each types of architecture model, we also discuss the effect on UAV-WPT with respect to different scenarios.

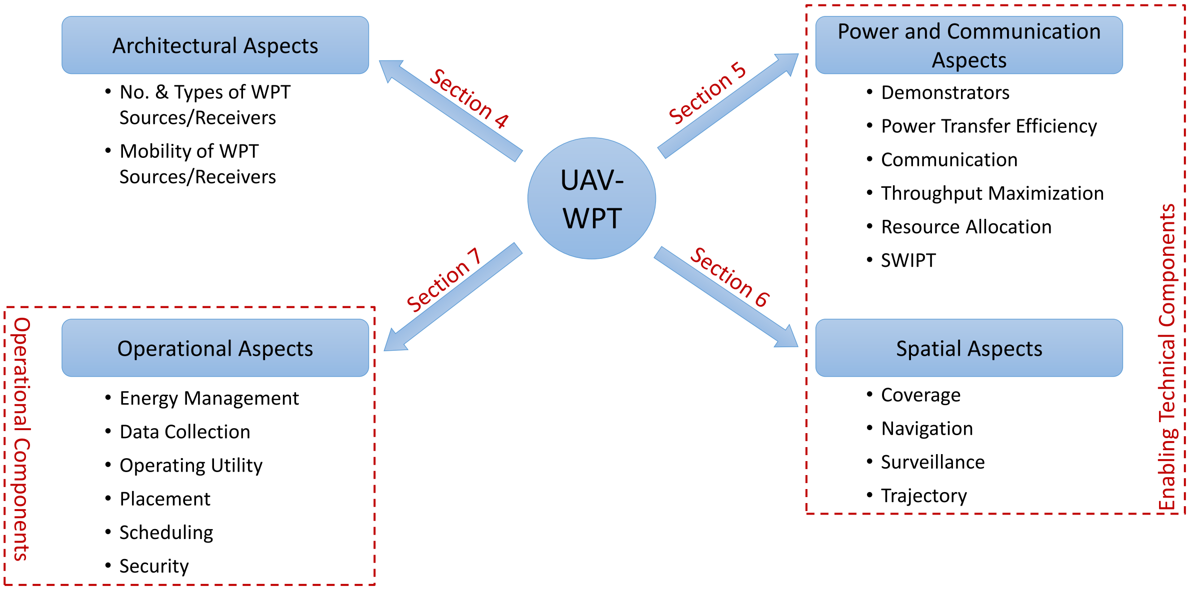

Fig. 3. Organizational roadmap of the paper.

Table 4
List of abbreviations.

Abbreviation	Definition
AF	Amplify-and-Forward
AoI	Age of Information
ConvNTM	Convolution Neural Turing Machine
DF	Decode-and-Forward
DRL	Deep Reinforcement Learning
H-AP	Hybrid Access Point
LoS	Line-of-Sight
MEC	Mobile Edge Computing
NLoS	Non Line-of-Sight
NOMA	Non Orthogonal Multiple Access
OLoS	Obstructed Line-of-Sight
OMA	Orthogonal Multiple Access
PLoS	Probabilistic Line-of-Sight
SDN	Software Defined Network
SWIPT	Simultaneous Wireless Information and Power Transfer
UAV	Unmanned Aerial Vehicle
WPCN	Wireless Powered Communication Network
WPT	Wireless Power Transfer
WRSNs	Wireless Rechargeable Sensor Networks

4.1. Number and types of WPT sources and receivers

Based on the number and types of WPT sources and receivers, we have three different architectural settings for UAV-WPT.

- *Single UAV or Ground Station*: In this case, only a single UAV is employed to work as WPT source for the deployed nodes or a single ground station is providing charging facility to the UAVs. For example, in [60–63], a UAV provides WPT services to the deployed nodes. In such scenario, the challenge is to plan the UAV trajectory for achieving multiple different objectives depending on the application requirement. For example, when the UAV is acting as a charge provider, one objective can be planning the UAV trajectory to maximize the energy harvested throughout the network, or prioritizing the energy requirements of the deployed nodes with the available battery energy of the single UAV. We discuss more on this types of issues in Sections 6.4 and 7.1. Whereas, in case the UAV is acting as a charge receiver, one objective may be to maximize the data collection efficiency with the limited onboard battery power. We further our discussion on this direction in Section 7.2.

- *Multiple UAV or Ground Station*: Here, multiple UAVs or multiple ground stations are acting as charge providers to the deployed nodes or the UAVs. For example, in [64,65], the UAV receives WPT services from the ground-based stationary/mobile charging stations. In case of multiple UAVs, the WPT focus is more on the collaboration of the UAVs — in terms of coverage and planning of the trajectories of different UAVs. More discussion on these issues are presented in Sections 6.1 and 6.4. On the other hand, in the presence of multiple ground charging stations, the issues of UAV positioning and scheduling of the charging tasks are important. We extend the discuss on these issues in Sections 7.4 and 7.5.
- *Hybrid*: In this setting, both UAVs and ground stations are employed for acting as WPT sources for deployed sensor nodes as well as UAVs. Also, there can be one or more number of UAVs and ground stations. One such example is mid-air charge replenishment [66] where UAVs transmit power to other UAVs that are working as hotspot for ground deployed nodes. With the availability of multiple types of energy sources (UAVs as well as ground stations), the earlier discussed issues of trajectory planning, UAV placement and charging scheduling needs to be reviewed. Additionally, in case of heterogeneous types of these energy sources, issues of task scheduling among these sources (UAVs or ground stations) need to be looked into. Further discussions on these directions are presented in Sections 6.4 and 7.5.

4.2. Mobility of WPT sources and receivers

Based on the mobility of the WPT sources and receivers, we can classify the architectures considered in the existing literature in three types.

- *Stationary*: In this case, the deployed nodes (WPT receivers) and UAVs or ground stations (WPT sources) are stationary [67,68]. In such stationary scenarios, UAV's positioning, charging duration and power allocation directly impacts the energy received by the deployed nodes. In Section 5.5, we discuss the impact of power and time allocation in UAV-WPT.
- *Mobile*: In this case, there can be two possible scenarios. First, the UAV as well as the ground-based charging stations are mobile [64,66] and second, the UAV as well as nodes are mobile [69–71]. Here, in addition to the issues of UAV's source allocation, impact of UAV trajectory as well as other objectives such as data collection, utility maximization, are relevant. Subsequently, the number of such resources is also another important design parameter. We extend these discussions on Sections 6.4, 7.2, and 7.3.
- *Hybrid*: In this setting, the ground-based charging stations can be stationary or mobile (for example: placed on ground-vehicles) [65]. In this scenarios, the issues of dynamic trajectory planning and UAV scheduling are important. We present these issues in Sections 6.4 and 7.5.

5. Power and communication related aspects

In this section, we analyze the power and communication related aspects of the UAV-based WPT schemes. Specifically, we put emphasis on various demonstrating platforms, techniques for enhancing power and communication efficiency, allocation of resources, and information and power transfer.

5.1. Demonstrators

In the following, we discuss about different platforms that demonstrated wireless power transfer for UAVs and sensor nodes. In one such early work, Simic et al. [72] presented the prospect of applying WPT for charging UAVs, and thereby extending their lifetime as well as capabilities. We discuss several other WPT-based solutions for UAVs in detail.

5.1.1. Automated wireless charging station

An automated charging station was designed by Choi et al. [73] to enable wireless charging for the UAVs without manual intervention. The designed station provides a landing platform for the UAV, and using distance sensing, the platform automatically aligns the transmitter charging coil with the receiving charging coil placed at the UAV. Therefore, the platform provides flexibility to the UAV in terms of positioning, and automates the charging process of the UAV.

The proposed platform leverages various sensors to automate the whole task — the ultrasonic sensor is used to detect the presence of the UAV, binary distance laser sensors to precisely locate the UAV, and stepper motor to move the transmitter coil below the UAV. The WPT between the platform and UAV was performed using magnetic induction, with coils of 43 mm diameter. However, the required wireless charging time is nearly 50% more than it requires in wired cases, and the achieved charging efficiency is approximately 65%. Additionally, the detection of the UAV's precise position takes nearly 7% of the charging time.

5.1.2. DSENSE

A mobile wireless charging and sensing platform named DSENSE was proposed by Chen et al. [74]. The system enables wireless information collection as well as charging of deployed sensor nodes in remote locations. This system was implemented for applications comprising sensors deployed in multi-storied buildings and large agricultural fields.

In this system, instead of magnetic induction, electromagnetic radiation harvesting technology was used to leverage the flexibility and longer range of the far-field wireless charging. First, the UAV transmits 915 MHz electromagnetic waves, which is converted to DC voltage in the deployed sensor nodes. Then, these nodes use ZigBee protocol to transmit their data to the UAV, which forwards the data to the cloud. The UAV can navigate using the pre-loaded trajectory file or can follow the trajectory by manual control using 433 MHz MavLink.

5.1.3. Autonomous charging system

Khonji et al. [75] developed an autonomous wireless charging station for UAVs. The authors consider the arbitrary shapes and landing positions of the UAVs, and uses 2D Lidar sensor to localize the UAV such that the system can properly function in adverse external and lighting conditions where traditional computer vision based techniques fail. The autonomous charging station is equipped with a robotic arm to dynamically adjust the inductive charging panel for achieving maximum charging rate.

The charging station is equipped with a solar panel and the energy is stored in a battery to power the rover and charge the UAVs. To charge the UAV, the robotic arm is moved to a preset position over the UAV, and then, the arm adjusts the charging panel to maximize the charging rate. The panel is equipped with 6 coils each capable of a current output of 700 mA. The adjustment of the coil is performed based on the current readings from the coils.

In another work, Sang-Won et al. [76] proposed the idea to use two receiving coils to extend the charging area. The authors analyzed the optimum receiver structure for cases where the size of the receiving coil is very less compared to the transmitting coil. The dual receiver structure proved to be better compared to the single receiver cases with wider charging area and better charging efficiency. Ohira et al. [77] presented a capacitive coupling based WPT for UAV systems. The use of capacitive coupling helps in reducing the weight of the coils significantly, thereby enhancing UAV's flight time indirectly.

5.1.4. Autonomic landing and charging platform

Two systems to enable autonomous landing and wireless charging of UAVs were proposed by Woo et al. [78] and Aboumrad et al. [79]. Woo et al. designed the system such that the UAV can autonomously land on the platform using image processing techniques. In the UAV, two systems are present — *flight controller* for controlling basic flight related operations and anther *heavy task processing unit*, which uses Raspberry Pi, camera and WiFi module to locate the landing platform and accordingly commands the flight controller for movements using predefined APIs. On the other hand, the autonomous landing system proposed by Aboumrad et al. was equipped with a computer vision-based system to assist landing of UAVs. The charging platform is associated with a single board computer (RaspberryPi 3B+), which commands the UAV using 2.4 GHz radio to properly position it over the charging platform. The orientation of the UAV is determined using the computer vision-based system. Then, the current coordinates of the UAV are compared with the desired target coordinates. The UAV adjusts its position until the positional error in x- and y-coordinates are in allowable range, the UAV is instructed to lower its height over the Qi charging pad. The Qi 1.2 charging deck [80] can supply 1 A current at 5 V.

In Table 5, we present a comparison of the different demonstration platforms with respect to various features, and highlight their pros and cons.

5.1.5. Discussions and open issues

In the existing works, the main studied problem was to enable autonomous landing of UAVs in the charging platform. The existing platforms use sensor-based alignment [73,75], charging area extension [76], and computer vision-based techniques [78,79] to enhance the WPT experience of the UAVs. The recent computer vision-based techniques have improved the autonomous landing, although, other approaches remain important for specific application scenarios. In this regard, improved localization of the ground station is necessary for efficient charging of the UAV. Subsequently, the charging station design should also be suitable for different sized UAVs.

5.2. Power transfer efficiency

In the following, we present the different couplings and coils used for enhancing the power efficiency of the WPT system. Here, our focus is on the specific technology enabling the point-to-point WPT.

In the existing literature, RF-powered WPT systems proposed inductive/magnetic coupling and capacitive couplings. The inductive coupling systems are challenged by the alignment of the charging coils [81,82], design of compensation circuit [82], problem of magnetic field [83] and electromagnetic interference [84,85]. The capacitive coupling-based systems focus on minimizing the weight of the receiver circuitry [77,86] and increase of energy efficiency [87]. Apart from RF-powered WPT systems, another type of WPT systems, powered by laser beams, were proposed to enhance the charging energy amount and distance [88,89].

Table 5
Comparison of the demonstration platforms.

System	Type	Target device	Detection technique	Detection range	Pros	Cons
Automated wireless charging station [73]	Inductive charging	UAV	Distance sensing	30–40 cm	Precise landing of UAV	Longer UAV sensing time, less efficiency
DSENSE [74]	Electromagnetic radiation	Sensor nodes	Pre-loaded trajectory/ manual control	Long[a]	Powers embedded sensors, high range and flexibility	No autonomous detection of nodes
Autonomous charging system [75]	Inductive charging	UAV	Lidar	30 m	Supports long-range detection, unaffected by lighting conditions, adjustable charging	No support for different shapes of UAVs
Autonomous landing and charging [79]	Inductive charging	UAV	Computer vision	1.83–3.08 m	Computation efficient for UAV	Small range, higher landing time, affected by lighting conditions

[a]Not specifically mentioned.

5.2.1. Inductive/magnetic coupling

In this type of coupling, power is transferred by induction of a magnetic field from the primary (transmitter) to secondary (receiver) coil.

Griffin et al. [81] presented a demonstration of wirelessly powering the sensor nodes by the UAV using magnetic resonant coupling. The coupling coil-based WPT generates low power efficiency mainly due to the incorrect alignment of the primary and secondary coils. To solve the alignment problem of charging coils, Yan et al. [82] proposes a magnetic coupling-based WPT system. This system was able to minimize the change in power transfer efficiency even in case of misalignment of the charging coils. The authors proposed an *independent array coil design* to reduce the air gap between the coils using a controller to open the charging area after detecting the Bluetooth signal from the UAV. Also, the coil array design helps in enhancing the uniformity of the magnetic field and coil quality. Next, the coupling coil was wound by copper to reduce the losses due to skin effect and proximity effect. To model the relevant parameters such as coupling resonance, charging distance, power, the authors used the equivalent circuit theory. Subsequently, four different basic resonant compensation circuits, Series–Series (S–S), Series–Parallel (S–P), Parallel–Series (P–S), and Parallel–Parallel (P–P), named according to their mode of connection with capacitors, were analyzed. Among these, the S–S mode of compensation circuit is better suited for WPT systems due to their invulnerability against varying load and coupling coefficient. The WPT system adopted a low weight spiral coil which is suitable for UAV. Also, the use of higher resonance frequency increases the effective transmission distance as well as efficiency of the WPT system. We discuss more about the issues affecting the power efficiency of WPT system in Section 5.2.4.

The magnetic coupling based WPT systems with high frequency magnetic field might affect the UAV's internal equipments. To solve this problem, Cai et al. [83] proposed a cross-type magnetic coupler. The output power of the WPT system depends on two important factors — magnetic coupler's coupling coefficient (k) and inductance of the primary coil (L_p).

Few other prototypes of WPT systems were developed by [84,85,90–92]. [84] proposed a charging system which is able to reduce the electromagnetic interference problem in WPT systems. Zhou et al. [85] presented non-linear parity-time (PT) based system with a series–series topology and a self-oscillation controlled inverter which outperforms a system with parallel–parallel topology and amplifier. In a recent work, [93] proposed a design to mitigate the magnetic saturation effect and maximize the harvested power for a UAV charging station near high voltage power line.

5.2.2. Capacitive coupling

The capacitive coupling based WPT systems use electric fields, in contrast to magnetic field in inductive/magnetic coupling, to transfer power between the coils. Typically, capacitive coupling based WPT is used in low power applications compared to inductive coupling based WPT.

In UAV-WPT, due to the size and weight constrain, the design of the output filter of the secondary circuit is an important issue. Carloni et al. [86] presented a simulation analysis using LTSpice showing the trade-off between the power delivered to the battery and the capacitor size. The authors show that by leveraging the intrinsic inductance of the Li-poly battery, the output filter design can be reduced to a single capacitor. Subsequently, the secondary on-board circuitry can be minimized and the related weight can also be reduced. The simulation analysis present the output power as a function of the capacitance value.

Another capacitive coupling based WPT for UAV systems was proposed by Ohira et al. [77]. The introduction of capacitive coupling helps in reducing the weight of the coils significantly, and thus, indirectly extending the UAV's flight time. Gao et al. [87] also proposed another UAV-WPT system which also helps in reducing the heat sinks, and thereby increasing the fly time. To reduce the power loss, the authors proposed applying a buck converter between the rectifier circuitry and battery, and generate higher energy efficiency as well as lower weighted receiver.

5.2.3. Laser-powered WPT

In this type, electromagnetic radiation enables the power transfer using laser beams or microwave. Compared to inductive/capacitive coupling, in laser-powered WPT, the energy transfer distance is higher. However, the beam needs to be focused towards the receiver.

Ouyang et al. [88] described a system where the UAV is charged using a laser beam from the ground station. The advantages of using laser-powered WPT is that it can help the UAV to harvest large amount of energy while hovering at a longer distance compared to the RF-based WPT solutions. However, the efficiency of this system depends on the locations of the UAV and ground stations, and thus, the UAV needs to plan its trajectory for maximizing the energy harvested from the laser transmitters. In [89], the use of laser charging and battery level information were leveraged to extend the UAV's functional lifetime.

5.2.4. Discussions and open issues

In the following, we discuss few factors and open issues which affect the power transfer efficiency.

- *Coil Size*: Coils of smaller size and weight are suitable for UAVs. For example, plain spiral coil adopted in [82] provides these features in addition of being easy to assemble. Also, receiving coils' should be smaller than that of the transmitting coil to ease the coupling process after landing of UAV.
- *Resonance Frequency*: A higher resonance frequency increases the effective transmission distance of the WPT system, thereby enhancing the efficiency.
- *Alignment*: In case of magnetic coupling, an array of coils can be used in the transmitter to enhance the uniformity and intensity of the magnetic field as well as to reduce the complexity of accurate docking. Misalignment tolerance is an important requirement for magnetic coupler based WPT systems.
- *Skin Effect*: Winding the coupling coil using copper can help in reducing the skin and proximity effect.
- *Compensation Circuits*: According to the connection with the capacitor in the circuit, four different resonance compensation circuits, namely Series–Series (S–S), Series–Parallel (S–P), Parallel–Series (P–S), and Parallel–Parallel (P–P), are possible. Among these, the S–S type of circuit is most suitable in case of varying load and coupling coefficient.

5.3. Communication

The task of energy harvesting and communication are inter-related in a UAV-assisted WPT system. The joint problem of communication time allocation or transmission power allocation impacts the energy harvesting in WPT. In the following, we discuss the different relaying protocols and channel models investigated in the existing literature.

5.3.1. Relaying protocols

In the following, we first briefly introduce the different relaying protocols adopted in UAV-based WPT.

- **Decode-and-Forward** (*DF*): In this type of relaying, the received message is first decoded and then forwarded in the next time instance.
- **Amplify-and-Forward** (*AF*): In contrast to DF relaying, in AF relaying, the received message is just amplified and forwarded. Therefore, the AF systems can perform with less latency compared to DF-based systems.
- **Time-Switching Relaying** (*TSR*): In TSR, the total communication time-frame is divided into multiple slots using a *time factor* (τ) [94]. The receiver harvests energy during the reception of the message (in first few slots) and forwards the information using DF or AF protocols in the rest of the slots. The TSR-based communication method was adopted by various works [95–97].
- **Power Splitting-based Relaying** (*PSR*): As the name suggests, in PSR, a *power factor* (ρ) is used to split the signal power between energy harvesting and information processing [94]. For example, ρ part of the signal power was used for energy harvesting and $(1-\rho)$ part was used for processing of information by Hua et al. [98].

5.3.2. Channel models

In Table 6, we list the various channel models considered in the existing literature.

5.3.3. Discussions and open issues

In the existing literature, different relaying protocols are proposed. However, considering the requirements of the deployed nodes for energy harvesting, dynamic adjustments in TSR and PSR protocols can be made. Such dynamic adjustments of the power factor (ρ) and time factor (τ) can be done for fair energy harvesting at the receiver nodes, while also limited by the available energy at the UAV.

Table 6
Different channel models.

Channel type	References
Block-fading	[95]
Line-of-sight (LoS)	[95,99,100]
$\kappa - \mu$ fading	[96]
Rician fading	[101,102]
Non Line-of-sight (NLoS)	[99]
Obstructed Line-of-sight (OLoS)	[99]
Two ray fading	[103]
Fisher-Snedecoer $\mathcal{F}$ fading	[104]
Rayleigh fading	[102]

5.4. Throughput maximization

In this section, we study different throughout maximization approaches followed in the existing literature for UAV-based WPT. We classify and discuss the approaches, and then analyze the pros and cons of these architectures in achieving the goal of throughput maximization.

- *Throughput in relaying system*: Hua et al. [98] discussed the problem of throughput maximization from the perspectives of two distinct architectures — time switching architecture and power splitting architecture. In Section 5.6, we discuss these two architectures in detail. To maximize the network transmission rates, a joint optimization of UAV location, time switching ratio and power splitting ratio are considered, while the lifetime of the nodes are prolonged by harvesting the energy from the UAV. In contrast to the amplify-and-forward (AF) relaying-based UAV, Li et al. [105] considered the UAV as a decode-and-forward (DF) relay for the throughput maximization problem in a UAV-assisted WPCN. The use of DF relay brings an additional delay, the information processing delay, for the system and subsequently, the nodes and the UAV both face two different scenarios — delay-tolerant and delay-sensitive cases. In this problem, throughput maximization is achieved by joint optimization of downlink power allocation, uplink/downlink slot allocation and UAV's trajectory. In another work by Jia et al. [106], both AF and DF relaying systems were used in two different scenarios for maximizing the sum throughput.
- *Throughput and UAV placement/trajectory*: Xie et al. [107,108] proposed the idea to exploit the mobility of UAV to optimize the hovering position over the deployed nodes to aid the energy harvesting of the deployed nodes in the downlink. Subsequently, in the uplink, the nodes transmit their information to the UAV using the harvested energy. In addition to UAVs' hovering location optimization, [109] focused on optimizing the time slots for downlink and uplink sessions. A time-division duplex orthogonal-frequency-division multiple access (TDD-OFDMA) protocol was proposed to maximize the uplink throughput using a joint optimization of uplink/downlink time proportions, UAV-node association and UAVs' hovering positions. The idea of optimizing the UAV's trajectory and power allocation to maximize the minimum throughput of the nodes were investigated in subsequent works — specific task (WPT or data collection) allocated UAVs in WPCN [110], secure SWIPT system [111], cooperation between UAVs (with interference coordination and coordinated multi-point (CoMP)) for performing energy and information exchange with nodes in WPCNs [112], multi-UAV enabled millimeter wave WPCN [113]. A centralized approach for throughput maximization was proposed in [114], which leverages the joint optimization of the trajectory and transmission power. As the locations of the nodes are unknown to the UAV, a deep reinforcement learning (DRL)-based method was proposed to improve the performance.
- *Throughput and constrained navigation*: The concept of hover only energy harvesting is extended to hover-and-fly energy harvesting by Ye et al. [115]. The authors also incorporate simultaneous transfer of energy and information between the UAV and node using a two antenna UAV. Apart from these, the UAV's maximum speed constraint, flying time limit and energy causality constrain of the nodes are also considered. To maximize the sum throughput of the system, the authors established a relation between the hovering time and flying time — smaller hover time as well as maximum UAV speed while flying between nodes. In [116], a UAV-assisted cognitive network was studied, where the UAV periodically flies over the deployed nodes in a circular region and subsequently, harvests energy from the RF signal of the nodes.

5.4.1. Discussions and open issues

In UAV-WPT, the aspects of throughput maximization is studied with respect to the effects of uplink/downlink slot allocation, downlink power allocation, UAV trajectory and positioning. In the following, we point out few open issues that can impact the throughput maximization problem.

- *Fairness in throughput maximization*: In multi-UAV scenarios, the placement of the UAVs throughout the network needs to be aware of the different throughput requirements of the deployed nodes.
- *Heterogeneous WPCNs*: In heterogeneous WPCNs, to achieve throughput maximization, downlink power allocation and uplink/downlink slot allocation needs to consider the device heterogeneity of the deployed nodes.

5.5. Resource allocation

The problem of allocating resources is one of the most important and challenging issues of wireless network. In case of scenarios with presence of both UAV and WPT, the challenges of resource allocation have multiple dimensions. We discuss these different dimensions in the following. Wei et al. [117] presented an overview of resource allocation methods for SWIPT systems.

5.5.1. Power allocation

- *Power and sub-carrier splitting*: Unlike using the power splitter, here, the idea is to split the sub-carriers into two disjoint groups — energy signal group and information signal group. The energy signal group is applied to perform the energy harvesting and on the other hand, information decoding is performed by the information signal group. Based on this idea, [118] et al. developed a method where the UAV does not require the power-splitter, and instead uses the energy harvesting sub-carrier group for harvesting energy.
- *Power vs information*: [119] presents a scenario where the UAV supplies energy to two sets of nodes with two different energy requirements — one group with higher energy requirement and another with lower energy requirement. The UAV focuses on the power allocation for WPT whereas the nodes harvest energy required for information transmission. A dynamic game is proposed to decide on the optimal allocation for both UAV and nodes such that their objectives to minimize the required power level and energy price, respectively, are achieved.
- *Power and time*: Park et al. [120] proposed two different scenarios where the function of the UAVs are different. In one scenario, the UAV acts as a hybrid access point — employed for WPT source as well as information receptor. In the other scenario, two UAVs are employed — one each for WPT source and information reception. To maximize the minimum throughput of the deployed nodes, a joint consideration of UAV's power allocation, trajectory and time allocation for WPT and information transfer is proposed. In another work, the joint problem of downlink power allocation and wireless charging duration to maximize the downlink sum rate for single- and multi-UAV scenarios [121].
- *Energy and data collection*: One important challenge in optimizing energy consumption and data collection of the deployed nodes is managing the trade-off between node's battery level and data queue level. In such scenario, the WPT provider UAV might not have a prior knowledge of the node's battery level and data queue level. Considering this problem, Li et al. [122] proposed a resource management strategy based on the position of the UAV, channel condition, node's battery level and data queue level. Subsequently, the optimal nodes for data collection and power transfer are selected and a modulation scheme (transmit power) is allocated for each such node.

5.5.2. Time allocation

- *Time and trajectory*: In a multi-UAV scenario, the UAV needs to hover at an optimal position over the nodes as well as minimize the interference between the users, while avoiding collision between themselves. Therefore, it is important for the UAVs to manage their hovering time and trajectory jointly. Xie et al. [123] investigated this problem. In another work by Lu et al. [124], apart from trajectory optimization, the problem of interference at the receiver side is also considered. To solve this problem, a new time slot allocation scenario is employed and to maximize the minimum uplink throughput, joint consideration of UAV's trajectory, time allocation and node's power is applied. In this regard, the incorporation of cache placements along with high mobility of the UAVs can be exploited to improved the throughput [125]. Along with trajectory control and content caching, another problem is to consider the energy expense of the UAV, and dynamically deciding when the UAV should be returned back to the charging station [126]. In another work, a circular UAV trajectory is incorporated to mitigate the double near-far problem, and subsequently the trajectory radius is optimized for energy harvesting of the nodes [127]. Hu et al. [128,129] considered the optimization of UAV trajectory along with time and task allocation for maximizing the computation task output of the nodes.
- *TDMA-based workflow model*: Here, the idea is to create a TDMA-based workflow model for parallel transmissions and executions for different devices [130]. As a result, the UAV's hovering time and energy loss is minimized. Another resource allocation model [131,132] for UAV-based WPT in cellular network scenario considers both TDMA and FDMA-based resource allocation using the joint optimization of user association, resource allocation (in terms of downlink power allocation) and channel assignment. Here, the time-slots for WPT and downlink transmission are of equal length. In the first slot, UAVs are charged by the ground stations and then, in the next slot, the UAVs transmit to the ground users.

5.5.3. Computation management

Computation management refers to managing the computation loads of the deployed nodes, which typically have low computation power compared to the UAV.

- *Computation Offloading*: Zhou et al. [133] proposed a computation management framework for scenarios where the nodes are powered by the UAV using WPT. Based on the harvested energy from the UAV, the nodes decide to either perform the computations locally or offloading the computations to the UAV. Subsequently, a framework

Table 7
Comparison of different resource allocation methods.

Method	Charge provider	No. of UAVs	Resource	Energy harvesting vs information transmission	Pros	Cons
[133]	UAV	One	Computation	Parallel	Dynamic decision of computation offloading	Performance limited by flight time, no. of UAVs
[123]	UAV	Two	Time	Slotted	Cooperation between UAVs	Limited scenarios considered
[118]	UAV	One	Power	Slotted	Subcarrier grouping reduces dependence of power-splitter	Specific scenario with single UAV
[130]	UAV	One	Time	Parallel	Leveraging workflow to reduce UAV's energy expense and increase mission duration	Required a priori knowledge about node's tasks
[131,132]	Ground station	Multiple	Time, power	Slotted	Throughput maximization in UAV-powered cellular networks	TDMA-based method less efficient
[119]	UAV	One	Power	Slotted	Dynamic power allocation, heterogeneous nodes	No use of multiple UAVs, no consideration of inter-node interference
[120]	UAV	One/two	Power, time	Parallel/ Slotted	Consideration of various scenarios, multiple UAVs and resources, linear/non-linear EH models	Differentiated QoS requirement of nodes not considered
[122]	UAV	One	Power	Slotted	Does not require knowledge of node's battery and data queue level	Only homogeneous nodes and specific scenarios considered
[124]	UAV	Two	Time	Slotted	Reduced receiver side interference	Only specific scenario with limited nodes, fixed altitude of UAVs
[121]	Ground station, UAVs	One, Multiple	Power, time	Slotted	Multiple scenarios considered, dynamic resource model	All UAVs hover at fixed altitude
[134]	UAV	One	Computation	Slotted	Minimizes energy expense of UAV, leverages idle nodes for computation offloading	Increased convergence time for higher number of idle nodes

for maximizing the computation rate was also proposed by jointly optimizing the transmit power, offload time, CPU frequencies, and UAV trajectory. In the method proposed by Liu et al. [134] the energy harvested nodes leverage both UAV and nearby idle nodes for computation offloading.

- *Computation rate*: Towards maximizing the computation rate, [135] proposed a hybrid beamforming and computation resource allocation optimization for a UAV-enables edge mobile edge computing (MEC) system where the deployed nodes are also powered wirelessly.

In Table 7, we compare the different resource allocation methods with respect to various parameters and highlight their pros and cons.

5.5.4. Discussions and open issues

In the following, we briefly point out few issues affecting the resource allocation methods.

- *Differentiated QoS requirement*: The deployed nodes can have different hardware configuration as well as different requirement based on various metrics. Therefore, the resource allocation methods also need to designed such that the dynamic requirements can be fulfilled.
- *UAV hovering altitude and multiple UAVs*: Based on the deployment and terrain, the UAVs may need to adjust the hovering altitude and hovering time to maximize the transferred energy. The resource allocation methods should be designed accordingly.

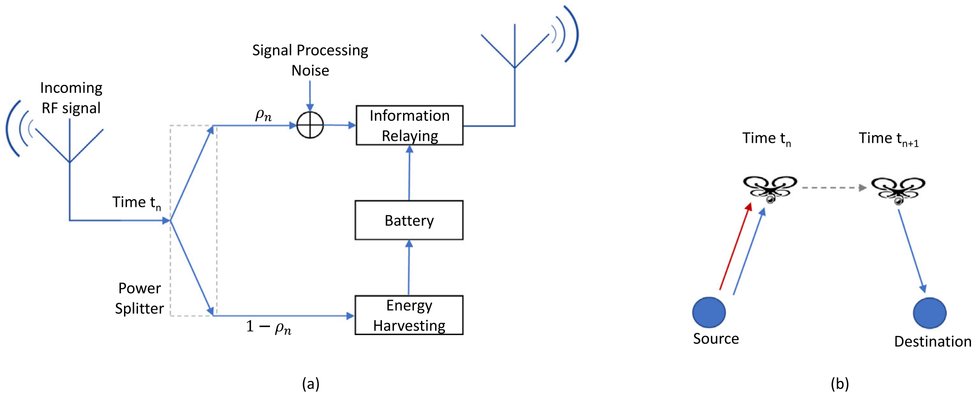

Fig. 4. Power-Splitting SWIPT — (a) receiver architecture (b) method overview.

5.6. Simultaneous Wireless Information and Power Transfer (SWIPT)

SWIPT is a promising technology which enables full utilization of RF energy by achieving energy transfer along with information transmission. Consequently, this feature provides an opportunity, especially for the smaller devices (which typically holds limited on-board energy) such as miniaturized UAVs, to replenish themselves wirelessly. Typically, the UAV's transmission activity is powered by the RF signal from the source, and a separate on-board battery is responsible for the UAV's maneuvering activities. Therefore, it is also beneficial for the larger UAVs which can recharge its battery while performing the transmission activities.

5.6.1. Architectures

In the following, we discuss the two types of SWIPT architectures, power-splitting and time-sharing, adopted in the existing literature.

- *Power-Splitting SWIPT*: In this type of SWIPT architecture, the received radio signal is divided into two power streams — one for energy harvesting and another for the information relaying. The power-splitting receiver structure is one of the most dominant SWIPT receiver structure [136]. In the existing literature, the power-splitting receiver is applied to both UAVs [137,138] as well as deployed sensor nodes [139–145]. Fig. 4 shows the (a) power-splitting receiver structure and (b) the overview of the method. A power-splitting unit aids the splitting process followed with a signal processing unit and an energy harvesting unit. Typically, as considered in [137,138], in any time iteration, the power-splitting process is performed first for information processing and energy harvesting. Subsequently, the received information is relayed using the harvested energy.
  The power-splitting profile depends on the power profile and the trajectory of the UAV (where the UAV is the SWIPT receiver) or on the energy harvesting requirements of the nodes (where the deployed sensor nodes are the SWIPT receiver). In scenarios where the UAV acts as the SWIPT receiver, the existing works mainly focus on the optimization of trajectory and power profiles. Yin et al. [137,138] focused on the joint optimization of the trajectory and power-splitting profile by applying alternate optimization of the two sub-problems – *power profile optimization with fixed trajectory* and *trajectory optimization with fixed power profile*. On the other hand, in scenarios where the nodes are the SWIPT receiver, the existing focus on maximizing energy harvested at the nodes while maintaining their minimum data rate requirement (or vice-versa such as in [141]) achieved with the power budget of the UAV. Mamaghani et al. [146] have used power-splitting SWIPT along with Cooperative Jamming [147] for performing secure communication in the presence of eavesdropper node. Here, while the source node transmits the information to the UAV, the destination node simultaneously transmits jamming signal (which also helps in energy harvesting at the UAV) to block the eavesdropper's wiretap channel. The proposed method can also determine the optimal power-splitting ratio and best location for the UAV to hover while maintaining secrecy with a given location for of the eavesdropper node. Few other works emphasizing secure communication in SWIPT systems are — secure communication in NOMA networks using artificial jamming [148], mmWave NOMA and OMA networks with improved secrecy performance [149].
  Power-splitting SWIPT (PS-SWIPT) was also implemented in various different application and network scenarios. Wang et al. [145] proposed the use of PS-SWIPT in the context of cellular IoT networks with LoS and NLoS path loss models for the UAV to nodes communication links. For a disaster management scenario, [150] proposed dynamic and flexible cluster formation and restructuring for improved SWIPT performance in terms of less outage. [151] also proposed to apply SWIPT for enabling emergency communication in a disaster scenario. Next, the authors designed a dynamic path planning method based on users' service requirement (charging or data transfer).

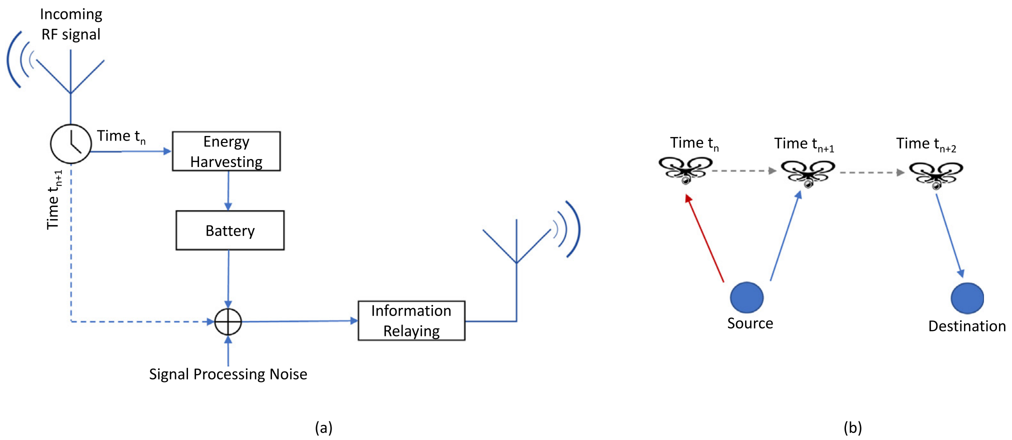

Fig. 5. Time-Sharing SWIPT — (a) receiver architecture (b) method overview.

- *Time-Sharing SWIPT*: In this type of SWIPT architecture [152,153], the processing of the received RF signal and energy harvesting from it, are done in different time iteration. In each time iteration, the SWIPT receiver has to decide whether to harvest energy from the received signal or to act as a relay by forwarding the signal. This decision profile shapes the further activities of the UAV. It is noteworthy to mention that in this type of system, the received RF signal power is fully utilized during the allocated time slot. Fig. 5 depicts (a) the receiver structure for time-sharing SWIPT and (b) the overview of the method. The receiver design consists of the time switching mechanism which depends on the decision profile of the receiver, and consequently, the energy harvesting and information relaying are performed.

In Table 8, we present and compare the existing works which applied SWIPT. It is evident that while most of the existing works adopted either power-splitting or time-sharing architecture of SWIPT, [154] which applied both these architectures together.

5.6.2. Constraints/trade-offs

- **Trajectory/power-profile vs throughput**: In power-splitting SWIPT, the UAV's end-to-end throughput depends on both the power-splitting ratio profile and the trajectory. [137,138] takes the approach of alternately solving the sub-problems — power profile optimization with fixed trajectory and trajectory optimization with fixed power profile.
- *PS vs TS and DF vs AF*: As reported in [143], the loss rate in power-splitting SWIPT (PS-SWIPT) is less than that of time-sharing SWIPT (TS-SWIPT) and thus, PS-SWIPT outperforms TS-SWIPT. Also, decode-and-forward (DF) protocols are better suitable for PS-SWIPT applications than amplify-and-forward (AF), due to flexible time allocation and less possibility of noise amplification in DF compared to AF.

5.6.3. Discussions and open issues

In the following, we briefly point out few issues affecting the SWIPT methods.

- *Number of UAVs and altitude*: The success of the SWIPT methods in multi-UAV scenarios depends on the collaboration between the UAVs and the dynamic altitude adjustment.
- *Coverage, data rate and interference*: For SWIPT methods, the joint problem of coverage, data rate and interference is relevant in IoT deployment scenarios.
- *Secure SWIPT*: To improve the security features in the SWIPT methods, jamming signal is transmitted by the receiving node while the source node is transmitting the information to the UAV. However, the existing works consider limited scenarios with less number of nodes. Thus, there is a need to develop a method for scaled up scenarios.

6. Spatial aspects

6.1. Coverage

We discuss the coverage aspects of single-UAV and multi-UAV scenarios where the UAV(s) works as the charge provider for the deployed nodes. We highlight different types of coverage along with the charger(s') details and their benefits and limitations.

Table 8
Comparison of different SWIPT methods.

Method	Architecture	SWIPT receiver	No. of UAVs	Pros	Cons
[137]	Power-splitting	UAV	Single	Improves end-to-end throughput	Fixed altitude of UAV
[152,153]	Time-sharing	UAV	Single	Improves end-to-end throughput, quick convergence	Fixed altitude and straight line path of UAV, constant position within a time slot
[138]	Power-splitting	UAV	Single	Improves power profiles for long-term and convergence	Fixed altitude of UAV
[139]	Power-splitting	Nodes	Multiple	Increases energy harvested at nodes while maintaining minimum data rate, achieved with UAV's power budget	UAVs remain stationary in air
[146]	Power-splitting	UAV	Single	Determines the optimal power-splitting ratio, best and secure location for UAV's hovering	Low and fixed altitude of UAV
[140]	Power-splitting	Nodes	Single	Maximizes energy harvested at nodes while maintaining minimum data rate achieved with UAV's power budget and maximum speed limit	Considers single UAV, limited coverage area
[141]	Power-splitting	Nodes	Multiple	Maximizes data rate maintaining minimum energy requirement of nodes with UAV's power budget	UAVs remain at fixed altitude
[142]	Power-splitting	Nodes	Single	Dynamic path planning based on node position and energy requirement, optimal power transfer based on data collection maximization	May have limited/non real-time coverage problem
[154]	Power-splitting/ Time-sharing	Nodes	Multiple	Non-linear energy harvesting model, considers both SWIPT architectures, analyzes throughout vs information-and-Energy coverage	No constrain on UAV's battery capacity
[143]	Power-splitting	Nodes	Single	Joint optimization of PS and time allocation, lower complexity and no requirement of channel state information	Less coverage area due to single UAV with low altitude
[148]	Power-splitting	Nodes	Single	Secure UAV-assisted NOMA communication, throughput maximization for nodes	Smaller coverage area, considers perfect interference cancellation technique
[151]	Power-splitting	Nodes	Multiple	Dynamic path planning considers users' service requirement	Less coverage area due to single UAV

6.1.1. Single-UAV-based scheduling algorithms

- *Period Area Coverage (PAC)*: In PAC, the observation area needs to be monitored periodically. In such scenario, a UAV is used as a mobile sensor to cover the vacant zones and an energy source for the deployed nodes [155] to recharge them. Therefore, the UAV has to schedule its tasks for sensing the uncovered regions and providing energy to the nodes having energy lower than the minimum energy. The UAV decides on charging the sensors as per their requirements — provide maximum energy to the nodes such that energy-efficiency is maximized.
- *Coverage breach-aware Charging*: Pauu et al. [156] proposed a method to deploy the UAV for aiding the recharging of the nodes which exhaust their energy and thereby, helping in the process of minimizing the coverage breach. The UAV is scheduled for recharging the nodes while considering the remaining energy and coverage degree of the deployed nodes.

6.1.2. Multiple-UAV-based scheduling algorithms

- *Constrained Coverage*: Trotta et al. [157] proposed two methods - one centralized and one distributed - for achieving constrained coverage of an area by multiple UAVs. The UAVs recharge themselves from the charging stations located at the ground. The objective of this work was to determine an optimal charging schedule such that the number of descent/ascent operations are minimized for the UAV while maintaining the coverage. The centralized approach assumes strict coordination among the UAVs and requires complete knowledge of the scenario. On the other hand, in distributed approach, each UAV autonomously decides the recharging time, and then, it coordinates with the 1-hop UAVs for starting the recharging process only if the neighbor UAVs are available. Therefore, the decentralized charging process of the UAVs relaxes the strict requirements of the centralized approach. Also, the charging process is aware of the coverage requirements. In the extended version of this work [158], the authors focused more on the distributed approach for the joint problem of achieving coverage, connectivity as well recharging of the UAVs. The

Table 9
Comparison of the UAV-based coverage and charging methods.

Method	Charging approach	Chargers' details	Coverage	No. of UAVs	Pros	Cons
[157]	Centralized & Distributed	Multiple, ground-distributed	Constrained	Multiple	Network lifetime enhancement, coverage guaranteed, self-organized	UAVs placed at same altitudes, linear charging/discharging considered
[158]	Centralized & Distributed	Single, ground-center	Constrained	Multiple	Network lifetime enhancement, 1-hop neighbor knowledge, low overhead	Only single charging station at ground, UAVs placed at same altitude
[159]	Centralized	Single, ground-corner	Seamless	Multiple	Long-term seamless coverage, energy-efficiency	UAVs at fixed altitude, requires full area knowledge
[155]	Centralized	Single, UAV-based	Period Area Coverage	Single	Network lifetime enhancement, period coverage guaranteed	Requires full area knowledge, non real-time scheduling
[160]	Distributed	Multiple, UAV-based	Seamless coverage	Multiple	Energy-efficient, scalable	UAVs placed at same altitude
[156]	Centralized	Single, UAV-based	Complete coverage	Single	Enhancement of network lifetime while providing complete coverage	Single charger, non-real time scheduling

approach considers the UAV specific issues (such as altitude, beacon frequency, energy required for ascend/descend) as well the cost for communication among the UAVs.

- *Seamless Coverage*: Li et al. [159] presented an approach for achieving seamless coverage by multiple UAVs by periodic recharge and reshuffling. The proposed approach focuses on cooperation among the UAVs to reshuffle their positions such that the area coverage is maintained as well as UAVs with low energy can move to the recharge station. In another work, [160] proposed a method for cooperation among the UAVs in terms of node assignment, trajectory planning and transmission power allocation. In this work, the deployed nodes were recharged by the UAVs which coordinate different tasks among themselves.

6.1.3. Discussions and open issues

In Table 9, we present a comparison of the different methods adopted for providing coverage as well as charging. We specifically highlight the type of coverage achieved, charger type, the pros and cons of each method. In the following, we discuss two relevant issues impacting coverage in UAV-WPT scenario.

- *Cooperation among UAVs*: The issue of cooperation among the UAVs is important when multiple UAVs are leveraged for jointly achieving the coverage and recharging task. However, it is important to note that while cooperation among UAVs help in optimizing the system objectives, it will demand increased information exchange among the UAVs, and may further increase the delay and energy consumption in decision making.
- *Priority-based Coverage with various constrains*: In mission-oriented application scenarios, the UAV(s) need to achieve priority-based coverage. However, there will also be various limitation such as UAV's battery power, communication range, hovering capability. Additionally, in case of multiple UAVs, another relevant issue is the cooperation between the UAVs to achieve the required coverage while minimizing the energy consumption of all the UAVs.

6.2. Navigation

In this section, we discuss the different navigation methods presented in the existing literature and highlight few important parameters with respect to WPT. Here, we discuss the aspects of *navigation*, which is concerned with the planning of UAV's movement from starting to ending point or over an area. However, the aspect related to the path/route followed in the navigation is discussed in Section 6.4. For example, the navigation methods discussed in the following may consider a fixed or a priori known trajectory.

6.2.1. Different navigation methods

- *Self-adaptive navigation (SAN)*: The objective of SAN [161] is to allocate ground-based charging stations to UAVs such that the travel delay is minimized. It is assumed that the trajectories of the UAVs are known to the central controller and are updated periodically. Also, the locations of the ground-based charging stations are known.
- *Multi-UAV navigation*: [162] proposed a method for navigation of UAVs to recharge the nodes deployed in a WSN such that the charging coverage utility is maximized. The navigation of the UAVs are planned considering the cost for travel, hovering, energy transfer and the energy requirement of the nodes.

- *Cloud-based UAV navigation*: [163] presented a cloud-based coordination system for UAVs to recharge from the ground-based charging stations while minimizing the charging delay and congestion. The system requires the knowledge of the UAVs' source, destination and speed to estimate the flight time, waiting time and charging time for each UAV. Based on these information, a suitable route for each UAV is computed. The system can also predict the future congestion time at the ground-based charging stations.

Apart from the above mentioned navigation methods, few notable methods proposed in the context of WPT using UAVs are discussed in [16,164]. Suzuki et al. [16] proposed a navigation method which leverages bilateration technique to estimate the location of the nodes such that the UAV is able to charge each node in less time. In [164], a target search problem scenario is considered where multiple commercially available UAVs and mobile recharging vehicles (MRVs) participate in the search operation. The use of commercial UAVs instead of military-grade UAVs reduces the flight time, and thus, the mobile vehicles recharge the UAVs to continue their operation. The proposed method, with an input of road networks, devises a route plan for UAV-MRV collaboration to recharge the UAVs.

6.2.2. Discussions and open issues

In the following, we discuss two specific issues that can impact the navigation decisions in a UAV-WPT scenario.

- *No. of chargers vs UAVs*: The navigation systems depend on the distribution of the charging stations over the area as well as the number of such chargers with respect to the number of UAVs. Depending on the distribution and the number of available chargers, the navigation decision for each UAV will be different.
- *Mobility of chargers*: Mobility of the charging stations increases the complexity of the problem. Therefore, the modeling of the mobility of the chargers should be considered while computing the cost of different navigation options.

6.3. Surveillance

In this section, we specifically focus on approaches considering UAV-WPT in a surveillance mission. We classify the methods based on their area of surveillance and discuss the associated parameters. It is important to note the differences between *coverage*, which is discussed previously in Section 6.1 and *surveillance*. Both these aspects require the UAV(s) to be able to *cover* the target area in terms of sensing information. However, with the introduction of WPT, in coverage, the focus is more on recharging the deployed nodes by the UAV. Whereas, in surveillance, the UAVs need to be recharged for covering the target location(s).

- *Persistent area surveillance*: This type of surveillance is performed over an area of interest with multiple UAVs. The challenge is to devise control policies for the movement of the UAVs, collision avoidance, timely recharge of the UAVs and mission time limit. Leahly et al. [165,166] presented automata-based methods to generate motion plans for the UAVs with temporal logic specifications with time-deadlines for covering specific regions of the area. In [167], the objective was to plan the UAV trajectories and charging schedule such that the time between the visits to a specific area is reduced. [168] focused on minimizing the number of required charging stations and overall mission time for an area coverage mission.
- *Border line surveillance*: In this type of surveillance mission, the objective is to cover a line-shaped area. Kim et al. [169] argued on using UAVs for border surveillance missions and to deploy them along with electrification lines for enabling WPT for the UAVs while in mission. The use of UAV with WPT feature in such scenario ensures higher operating time, higher quality of the surveillance and faster responsiveness.
- *Specific object surveillance*: In this type, the target is to observe specific points of interests inside the area. [170] proposed one such application where the mission was to take images of populated areas and road segments after a disaster. Here exists a trade-off between altitude and photo quality — with higher altitude photo quality is less but observed area is more, and with low altitude, photo quality is better but the less area is imaged. Thus, the challenge is maintain the required photo quality while routing the UAVs.

6.3.1. Discussions and open issues

In UAV-WPT methods designed for surveillance missions, the importance is on the availability of the charging stations which facilitates recharging of the UAVs. Therefore, the issues such as optimizing the number and placement of these charging stations, enabling UAVs are charge providers for other UAVs, cooperation between the UAVs are important here. We discuss these point in the following.

- *Facilitating charging of the UAV(s)*: To facilitate the charging of the UAVs, optimizing the number as well as the placement of the chargers are important for the enhancement of surveillance. In this regard, using a mobile charger can help in reduction of the number of stationary chargers and provide flexibility as well. However, in case the charger placement is not feasible (for example, in challenging terrains), UAVs can be used to aid the charging of other UAVs. We discuss such scenario in Section 6.4.2.

- *UAV-UAV and UAV-charging stations cooperation*: In surveillance missions, the use of multiple UAVs can provide mission benefit in terms of faster completion time, higher coverage resolution, and uninterrupted surveillance. In this regard, the collaboration between the UAVs for devising scheduling methods and coverage (parallel coverage vs sequential coverage) is one important issue. Along with placement of the charging station (static/mobile), the cooperation between the charging station and UAV is also need to considered.

6.4. Trajectory

In the following, we discuss the existing literature on UAV trajectory planning and management while supporting UAV-WPT. We classify the works based on different types of trajectory and network deployments. Next, we list several important factors in trajectory planning and management, discuss their importance and mention the works that considered those parameters. It is important to note that here we focus more on the path/route followed by the UAV(s) while discussing the effect of different factors on the path/route.

6.4.1. Types of trajectory

In this section, we discuss the different trajectories planned by the UAVs for providing charge to deployed nodes or for receiving charge from the ground-based fixed/mobile charging stations. We classify these trajectories in three categories — *fixed*, *dynamic-2D* which refers to 2D dynamic trajectories and *dynamic-3D* or 3D dynamic trajectories.

- *Fixed Trajectory*: As the name suggests, in this case, the UAV maintains fixed/predefined trajectory along with a finite number of nodes for providing WPT services with different constraints such as battery power, travel-time, hover-time. For example, in [171], multiple UAVs fly over a stationary IoT network following a predefined trajectory with limited battery power. A straight UAV trajectory with a fixed altitude was considered in [172].
- *Dynamic-2D Trajectory*: This type of trajectory is followed in most of the existing works. Here, the UAV follows trajectory with fixed altitude. However, the other related parameters such as transmit power, flight-time, hover-time are dynamically decided. A few example of such 2D trajectory is the *Successive Hover-and-Fly (SHF)* trajectory which is studied in multiple existing works [60,69,108,173,174]; *Spectral-Clustering*-based trajectory [61].
- *Dynamic-3D Trajectory*: In this type of trajectory, the UAV travels at an altitude within a range, creating a 3D trajectory, for which the parameters such as transmit power, hover-time are dynamically decided. In [175], a 3D trajectory for the UAV was proposed while considering an altitude range and fixed speed to provide WPT services for an area deployed with stationary nodes. Similarly, in [62], the joint problem of optimizing 3D position, beam pattern and charging time was considered.

6.4.2. Network deployments

The different network deployments considered in the existing literature can be classified from two different perspectives — based on the charge provider and based on the type of mobility. In the following, we discuss the different categories of works for each classification.

- *Based on the charge provider*: For this category, we can classify the existing works in two categories — *UAV as charge transmitter* and *UAV as charge receiver*. When the UAV acts as a charge transmitter, only the UAV provides WPT services to the deployed nodes [60–63,67,68,174,175]. Whereas, when the UAV acts as a charge receiver, the UAV receives WPT services from the ground-based stationary/mobile charging stations [64,65,176]. [66] considered a specific scenario, inspired by military mid-air refueling, where UAVs transmit power to other UAVs that are working as hotspot for ground deployed nodes.
- *Based on the type of mobility*: Considering the 'mobility' of the deployed nodes/stations (which were used as energy receivers or the energy providers), the existing works can be classified in three categories — *stationary*, *mobile* and *hybrid*. In [60,67,68], the deployed nodes and charging stations are stationary. Whereas, in [64,66], the UAV as well as the ground-based charging stations are mobile, and in [69–71], the UAV as well as nodes are mobile. [65] presented a scenario where the ground-based charging stations can be stationary or mobile (placed on ground-vehicles).

6.4.3. Different factors

There are numerous other factors that can be considered when optimizing UAVs trajectories. In this section we discuss the most important ones.

- *Charging power*: The UAV-based trajectory design methods, whether the UAV is the power source to the ground nodes [60–63,67,68,174,175] or the power receiver from the ground stations [64,65,176], targets to maximize the minimum amount of power transferred/received.
- *Charging period*: This parameter depends on the hover-time and has effect on the amount of charge transferred to the nodes. In [68], a fixed charging period was considered for maximizing the power transferred to the deployed nodes.

- *Node scheduling*: It is an important factor to design dynamic 2D/3D trajectories as well as to maintain the effectiveness of the deployed sensing application. Given the different levels of knowledge about the status of the nodes, determining the set of nodes or sequence of nodes is typically a NP-hard problem addressed using heuristics [177]. In [178], the sleep/wake schedule of nodes were exploited along with the UAV's trajectory and speed constrain, to ensure maximum received energy by the nodes. [179] studied the adaptive trajectory design problem with an objective to minimize the service delay for random user requests.
- *Battery power*: The objective of any trajectory planning method is to minimize the consumption of battery power [61,65,171,180,181] while fulfilling their target objectives such as maximized coverage, maximizing transferred/received power [182,183], minimizing the total flight/hover-time. [184] studied a trajectory optimization problem with an objective to minimize the task completion time for the UAV, given a limited battery capacity. [181] discussed the importance of UAV's energy utilization efficiency from two perspectives – fixed UAV position and fixed power transfer efficiency.
- *Speed*: UAV's total flying time and trajectory depends on the UAV's maximum speed limit.
- *Node localization*: To ensure efficient WPT, the UAV needs to be aligned over the sensor node by precisely localizing the node. [177] developed a system where the UAV, with the help of a magnetic resonance sensor, was able to localize within 30 cm of the sensor node.
- *Flight-time*: Flight-time directly impacts the total amount of power transferred/received by all the nodes. In the literature, the methods try to maximize the transferred/received power while minimizing the flight-time to cover the deployed nodes/stations.
- *Hover-time*: This parameter directly impacts the power transferred between the UAV and the nodes/stations. Therefore, joint consideration of the hovering points and the duration of hovering is required to optimize the amount of power transferred [173].
- *Task completion time*: Due to energy constraint, the task completion time for the UAV, which is also energy provider for the deployed nodes, is an critical parameter. [185] discussed a UAV trajectory optimization problem with the objective of minimizing the task completion time for the UAV. To model the effect of obstacles on the communication link between the UAV and nodes, a probabilistic LoS (PLoS) channel was considered. Towards improving the charging and transmission efficiency, [186] proposed a joint scheduling and trajectory optimization approach to minimize the total time of charging, data collection and flying.
- *Power and trajectory*: The efficiency of the UAV-WPT system depends on the joint problem of trajectory and transmission power for providing WPT to deployed nodes [69,70,172,175,176,187–191]. Jiang et al. [192] studied the two different objectives – maximizing the minimum information rate with a given transmission power budget, and minimizing the total power consumption with a required information rate. In [193], the users' mobility information was leveraged to find the initial UAV locations, and then, dynamically adjusting the UAV positions based on the movement of the users.
- *Coordination among UAVs*: The coordination among the multiple UAVs are important to achieve the WPT task optimally [71,194–196]. In [194], a Work-Gain algorithm is proposed where a master UAV coordinates with multiple UAVs deployed in different areas to jointly achieve the task of recharging the nodes such that the lifetime of the network is prolonged. [195] proposed coordination strategy between multiple UAVs in order to ensure seamless services for the deployed nodes. Oubbati et al. [71] proposed to divide the UAVs into two teams, for data collection and energy transfer, respectively, and then, jointly optimize their trajectory to maximize the throughput of the deployed nodes and minimize the age of information, while minimizing the energy utilization of the UAV.

6.4.4. Discussions and open issues

In the existing literature, the issues of trajectory design is well studied considering various objectives and optimization of the trajectory. We discuss few issues that impact the trajectory design decisions.

- *Balance between priority and constrains*: The existing works on design of trajectory for UAV-WPT scenario considers different objectives. In this regard, the joint optimization of multiple objectives (such as coverage maximization, charge transfer maximization) while limited by various constrains on trajectory (such as battery power, flight/hover time, task completion time) will be an interesting future study. Also, the trade-off between the priority and constrains, which depends on the application scenario, can be investigated.
- *Trajectory and coverage*: The aspects of trajectory and coverage are inter-related. In this regard, one important issue is the joint planning of the trajectory and coverage for enabling WPT to the deployed nodes in challenging terrains. The joint planning also need to consider the heterogeneity in terms of capabilities among the UAVs. The coverage and trajectory planning should be done accordingly.
- *Trajectory and data collection*: The UAV trajectory decision is often based on the objective of data collection. In such scenarios, the decision is influenced jointly by data generating nodes, the freshness of data (measured by Age of Information), energy of the UAV and deployed nodes.

7. Operational aspects

7.1. Energy management

Here, we discuss the works specifically focusing on the energy management aspects of a WPT-based system supported by UAVs. In contrast to the discussion of specific P2P-WPT enabling technologies presented in Section 5.2, in this section, we highlight the overall energy management in the scope of whole network including deployed nodes, UAVs (maybe the explicit charging source), other WPT sources (if available), base stations, etc. In this regard, some of the early works point out the benefits of using UAVs for energy harvesting of deployed nodes [197], the network lifetime enhancement for maximum benefit [198], autonomous recharging and mission planning [199], maximizing receiving energy [200] etc. We classify the existing works in different categories based on their considerations and sub-objectives in achieving energy management.

- *Optimal 3D position recharging*: In this problem, multiple UAVs are used for recharging the deployed sensor nodes. The objective is to place the UAVs in different available 3D positions over the deployed nodes such that the total power received by the nodes are maximized [201,202].
- *Battery level information*: Najeeb et al. [203] considered an energy management problem where one UAV is deployed for recharging the stationary nodes with no prior knowledge about the remaining battery power levels of the nodes. The UAV intelligently determines the efficiency of the power transfer and dynamically adapts to the scenario by changing the distance from the node. On the other hand, Jaffar et al. [89] considered a scenario where the UAVs are recharged by using a Laser source. In this work, the energy management problem considered the accurate battery levels to decide on recharging the UAVs. Therefore, the parameters related to the UAV's activity such as speed, battery size, turbulence, and distance to charging source are mapped to estimate the battery level and then decide the recharging of the UAVs.
- *Energy cost and scheduling*: With an objective of minimizing the energy cost, i.e., the electricity cost of the network of charging stations, Liu et al. [204] presented a strategy for deciding association between the UAVs and charging stations. The method specifically focus on allocating charging station for a requesting UAV, when to charge the UAV and how much energy to be purchased from the power supply grid based on multiple parameters such as UAV location, battery status, charging duration, deadline, and energy price. In [205], Q-learning is applied to optimize the UAV charging schedule with different distribution of UAVs. A proactive four-stage matching algorithm was proposed in [206] such that the amount of energy harvested in the deployed nodes is maximized.
- *Energy trading*: The idea of energy trading between the charging station and UAVs was conceptualized in [207]. The energy trading scenario was modeled as a game theoretic problem where both the charging station and UAVs interact to decide the charge price and look to improve their own profits. The UAVs use token to buy energy from the station and return the tokens within a fixed time with an interest rate and fined otherwise. Therefore, the charging stations expects to increase their profit by collecting more fines, whereas, the UAVs expect more tokens.
- *Power and efficiency*: Budhiraja et al. [208] studied the problem of energy management for D2D users which typically follows the harvest-then-relay strategy. To maximize the energy-efficiency of WPT, the joint allocation of two resources – energy harvesting time and transmission power – are performed. The energy management problem studied in [209] accounts the energy loss during WPT and the additional power consumption of the UAV during hovering and flight. The objective of the energy management process is same as the previous works — to maximize the power transferred to the deployed nodes. However, the consideration of the energy loss and additional power consumption, changes the estimation for UAV locations and power allocation for WPT.

Apart from the above mentioned works, few notable works which highlight various issues associated with energy management — optimized task completion in a mobile edge computing scenario [128], coordination among UAVs [194], impact of the density of UAV swarms [210].

7.1.1. Discussions and open issues

The goal of the energy management can be discussed from two perspectives — deployed nodes and UAV(s). The deployed nodes want to get maximum energy from the UAV(s). On the other hand, the goal of the UAV(s) may vary — to maximize the number of nodes that are recharged, or maximize the amount of energy transferred to the receiver nodes, or to maximize energy transferred to the nodes based on their requirement to get recharged. In the following, we highlight few issues related to energy management in UAV-WPT.

- *Joint management of energy, trajectory and priority*: The UAV(s) deployed for recharging nodes may need to prioritize which node to recharge first. Subsequently, the UAV's trajectory need to be decided, also considering the remaining energy of the UAV.
- *Energy management for multi-UAV missions*: In multi-UAV based missions, UAVs cooperate among themselves and the tasks are allocated accordingly. Here, the allocation of the tasks should consider the remaining battery power as well as recharging options available for the UAVs, in addition to other factors such as coverage priority, range, hovering capability.

- *Energy management for surveillance missions*: In surveillance missions or in scenarios where the area needs to continuously monitored, one UAV cannot be sufficient due to limited battery power. In such cases, wither the UAV needs to be replaced, or to be recharged by another UAV or alternate methods (few such methods are discussed in Section 6.3).

7.2. Data collection

In the following, we highlight the works which prioritize in data collection from deployed sensor using one/more UAV(s). We specifically highlight different issues such as application in challenging terrains, nonuniform energy requirement, multi-UAV coordination, hardware issues and information aging.

- *Data collection efficiency*: [211] proposed to apply UAVs for data collection from sensor clusters deployed in harsh terrains while also replenishing the battery of the sensors. A preference list for the UAVs were defined based on the distance between the UAVs and sensor clusters, data aggregation at the cluster and residual energy of the sensors. With an objective of maximizing the data collection utility, two different methods, one side matching and greedy matching were proposed. [212] argued that joint optimization of sub-slot allocation for deployed nodes and UAV's route plan can improve the data collection efficiency in terms of system energy efficiency and node's data transmission rate. Towards improving the data collection, [213] proposed to dynamically form clusters and select cluster heads based on deployment topology, energy transferred by the UAV, and the remaining energy of the nodes for one transmission round. Further, the nodes adjust the amount of data collection according to the remaining energy of the cluster head and neighboring nodes. However, the efficiency of this method depends on the trajectory of the UAV.
- *Weighted Harvest-then-Transmit*: Cho et al. [214] studied the double far problem — where nodes far from the UAV can harvest less energy and also, they need higher energy for achieving same throughput as the near nodes. To tackle this problem, a weighted harvest-then-transmit method, which consider dynamic channel power gain according to the location of the node, in contrast to considering constant channel power gains (both downlink and uplink) in similar works of WPCNs. Consequently, the UAV, which acts as a hybrid access point (H-AP), first completes the weighted energy transfer, and next, the information from the nodes are received. The flight path of the UAV is also optimized for maintaining energy-efficiency.
- *Multi-UAV networks*: Vashisht et al. [215] emphasized of the problem of channel congestion and flight time enhancement in multi-UAV networks. Inefficient handling of channel congestion may lead to increased dissipation of the battery energy, and thereby, resulting in shorter effective flight time. To tackle this problem, an opportunistic offloading and charging method is proposed to enhance the congestion issues using a software defined networks (SDN)-enabled control model, and the UAVs are opportunistically recharged from various energy sources such as solar panels or geo-distributed wireless charging stations. In another work, Lhazmir et al. [216] studied the problem of data transmission and energy-efficiency. The deployed nodes, based on their data buffer status and battery status, make requests for data transmission, energy transfer or nothing (as making a request will also consume energy). The UAV, on the other hand, decides on responding to each such request based on its energy status, data buffer status and requests from other nodes. The authors developed a packet delivery and energy transfer policy with a goal of maximizing the data transfer efficiency for the UAV and nodes. Towards achieving energy-efficient and cooperative data collection from sensors in a multi-UAV scenario, Liu et al. [217] deep learning based modules for concurrent UAV navigation decision making. A Convolution Neural Turing Machine (ConvNTM)-based module is applied for modeling the long-sequenced spatio-temporal data and a deep reinforcement learning (DRL)-based model is applied for various decision making purposes — continuous decisions such as route planning and discrete decisions such as to go for charging or data collection.
- *UAV hardware impairment*: Hou et al. [218] presented the problem of hardware impairments in UAVs and their effects in UAV missions of data collection and providing WPT to ground nodes. The authors consider the distortion in both transmitter and receiver radio frequency. Considering the hardware impairments, UAV's flying time, received data from ground nodes and energy harvesting limits, the objective is to minimize the energy consumption of the UAV during the mission.
- *Age of information (AoI)*: AoI helps in understanding the freshness of information, and thus, it is important to have a lower AoI in a data collection mission. Hu et al. [219] studied the problem of minimizing the average AoI of the collected data from the deployed nodes. A dynamic programming based solution is formulated using UAV's trajectory, time required for energy harvesting and data collection at sensor node. In [220], the solution for AoI minimization problem was proposed using joint optimization of the UAV's trajectory and scheduling of energy harvesting/data collection with the nodes. Additionally, the method also estimates the lower and upper bounds of the system average AoI.
- *Data collection time*: To enable the UAV to quickly gather information from the deployed nodes, [221] suggested the use of directional antennas which helps in increasing the transmission efficiency. However, to use directional antenna, we need to consider the adjustment trade-off between UAV's altitude and antenna beamwidth. [221] proposed a joint optimization of altitude and beamwidth towards minimizing the total data collection time.

7.2.1. Discussions and open issues

The data collection objectives in a UAV-WPT scenario are impacted by various parameters. In the following, we highlight few such issues.

- *Weighted harvest-then-transmit*: The weighted harvest-then-transmit method is able to mitigate the imbalance of energy consumption among the deployed nodes. However, in contrast to considering location of the nodes, we also need to consider the topology of the deployed network, as cluster head nodes and nodes having multiple neighbors are prone to exhaust their energy quickly compared to other nodes. Therefore, the weighted energy transfer should be designed considering this information.
- *Transmission rate, AoI and data collection time*: Data collection decisions in a UAV-WPT scenario will also vary depending on the transmission rate, AoI and data collection time. Accordingly, the UAV needs to decide the data collection sequence.

7.3. Operating utility

In this part, we discuss the approaches which emphasize on various operating utilities of any UAV-assisted WPT-based system — price, cost, and system efficiency. We also highlight the trade-offs between these factors in the following. The operating utility for any UAV-WPT system can be computed with respect to various parameters. It can be achieved with the help of intelligent coordination and scheduling methods between the UAVs, improved energy management as well as trajectory decisions. In this section, we emphasize on the related works which holistically focus on enhancing the system utility based on various parameters.

- *Price-based power allocation*: Liu et al. [222] presented the issue of downlink power allocation in a scenario where multiple UAVs serve as WPT power sources for the ground users. A price-based optimal power allocation scheme is proposed where the UAVs choose the optimal power price and the ground users choose the optimal power strategy to maximize their own utilities. The interaction between the UAVs and ground users using the power-vs-price technique leads to optimal allocation of power for the UAVs. Consequently, the interference among the UAVs reduces and the system capacity increases.
- *Cost benefit and design trade-offs*: The monetary benefits of using UAV-WPT in the context of low power wireless networks was studied by Tiurlikova et al. [223]. The study models the reduction of capital expenses, such as deployed network's energy cost, service and maintenance costs, by leveraging UAVs empowered with WPT systems. Further, an analysis of number of deployed nodes served by the UAV is also presented. Towards minimizing the overall cost related to WPT provider equipment and maximizing the efficiency of power transfer, Song et al. [224] devised an approach to select the best suitable WPT source points and the receiver nodes to be served by the WPT source.
- *Packet delivery and WPT*: The limited available energy of the deployed nodes as well as the UAV (which is the WPT source for replenishing the nodes' batteries) bring a decision making problem concerning the trade-off between packet delivery rate and energy consumption. Lhazmir et al. [225] presented a Markov Decision Process (MDP)-based method to enable the nodes and UAV to choose their actions to benefit their objectives. The nodes, when they have data to send to the UAV, choose whether to request energy from UAV based on their own energy status. On the other hand, the UAV, decides on accepting the energy transfer requests based on the requested energy amount (should be less than its available energy) and possible available data length (should have enough free data queue).

7.3.1. Factors and trade-offs

- *Power vs price*: Power vs price approach in [222] focused on maximizing the capacity of the UAV as well as reducing the interference with other UAVs, while the data transmission rate from the nodes is maximized.
- *System cost vs efficiency*: [223,224] focused on minimizing the system cost in terms of energy, service and maintenance, while maximizing system efficiency by deciding on number nodes to be served, optimal WPT source, etc.
- *Energy vs data*: [225] emphasized on the decision problem of energy vs data for both the nodes and UAV such that both target to utilize their available energy by maximizing transmitted and received data, respectively.

7.3.2. Discussions and open issues

As mentioned earlier, in this section, we focus on the methods which holistically focus on the problem of enhancing the operating utility. In the following, we discuss few open issues on operating utility. In single-UAV or multi-UAV based UAV-WPT missions, the operating utility can be defined jointly in terms of completion of the mission objectives energy consumption and time. In such scenarios, the UAV(s) needs to optimize its sequence of action for maximizing the operating utility.

7.4. Placement

In a UAV-WPT scenario, the placement of the UAV directly impacts the WPT aspects of the mission/application. We discuss the existing works by dividing in three different categories — *number of UAVs and altitude*, *placement, power and time*, *coverage and efficiency*.

- *Number of UAVs and altitude*: The UAV's operating altitude directly impacts the harvesting power by the deployed nodes. With lower flying altitude, the deployed nodes can harvest higher power. However, more number of nodes can be served with a higher flying altitude. Also, the energy demands of the deployed nodes can vary at different parts of the network. Based on this observation, [226] developed a method to find minimum number of UAV locations to charge all the nodes with the available energy of UAVs. Caillouet et al. [201,202] extended the problem of finding optimal UAV locations for recharging deployed nodes — UAVs are deployed in optimal 3D locations to ensure WPT services to the deployed nodes. The method considers the adjustments in the UAV's altitude such that to improve the energy harvesting and coverage. Du et al. [227] presented an iterative sum rate maximization problem where the energy harvesting time is optimized first, and then the UAV's position optimization is performed.
- *Placement, power and time*: Along with UAV's placement among the nodes, its power and time control are important parameters to achieve energy-efficient information transmission during the UAV's mission. Using these information, Chen et al. [228] devise a joint optimization considering UAV's position, power splitting ratio, time switching ratio and users' data rate for achieving energy-efficiency for the UAV while maintaining QoS requirements for the users. In contrast to works focusing on either downlink or uplink transmission, Li et al. [229,230] considered a two-way communication between the base station and the deployed nodes where the UAV acts as a relay. Next, the transmission powers of the base station, UAV and the nodes are jointly optimized for maximizing the data rate of the two-way communication channel, while maintaining the QoS of the communication link between the base station and the UAV. Towards a fine-grained energy transfer model, [209] accounted the energy consumption of the UAVs during flying and hovering as well as the energy conversion efficiency for WPT between the UAVs and the deployed nodes. The optimal location of the UAVs are determined such that the energy received by the nodes are maximized.
- *Coverage and efficiency*: Towards finding optimal UAV hovering positions for maximizing the data rate of the deployed nodes, Chen et al. [231] proposed to divide the entire area into designated service areas for each UAVs. Next, a greedy algorithm for optimal hovering position for each area is determined. In any UAV-assisted WPCN network, the charging efficiency between the UAV and the nodes is not uniform throughout the network. Li et al. [232] considered this problem, and devised a method to maximize the number of nodes served with WPT as well as maximize the minimum charging efficiency while minimizing the energy required for movement of the UAVs. In contrast to the assumption that the UAV knows the position of the deployed nodes, [233] studied a WPCN scenario where the UAV has only partial knowledge about the deployment scenario (due to limited accuracy of the typical localization methods such as GPS). Subsequently, the UAV explore radio maps technology [234,235] to know the propagation information, and leverage it for maximizing the minimum energy transferred to the deployed nodes from the UAV.

7.4.1. Discussions and open issues

- *3D positioning, coverage and efficiency*: As discussed in this section, 3D positioning of UAV(s) towards jointly achieving coverage and efficiency is an important issue in real-life scenarios, where the nodes may be deployed at different heights.
- *Balancing uneven network energy distribution*: The remaining energy throughput the network may be unevenly distributed due to the different workload of the nodes. In such cases, a balanced energy distribution will require providing higher energy to nodes with higher energy consumption rate. Accordingly, the UAVs need to position themselves such that the energy distribution is balanced while minimizing the energy transfer duration.

7.5. Scheduling

In this section, we highlight the works specifically dealing with the UAV scheduling issues in the context of WPT. The existing works mainly focus on charging priorities, cost minimization, schedule allocation, dynamic adjustment as well as information quality-aware scheduling.

- *UAV charging schedule*: In any UAV mission, the deployment of charging platforms are important to provide timely battery replenishment to the UAVs. In this regard, the number of such stations and charging time is important. Therefore, such stations need to have a proper charging schedule of the UAVs for maximum utilization of the station. Motivated by this problem, Shin et al. [236] developed an auction-based mechanism, where the charging slots are auctioned among the UAVs and accordingly a bidding process is followed to determine the slot assignments. The charging schedule auction method uses 'second price auction' to maintain truthful bids from the UAVs and developed self-configurable auction process. Another work for designing schedule [237] of UAV charging considered the UAV's recharging priority and accordingly sets a deadline for each such charging request. The optimal charging schedule

was formed using a double auction-based method such that the profits of both the charging station and the UAV both increases. Few other notable works devising UAV charging schedule are discussed in the following works — energy cost minimization [204] and learning-based scheduling [205].
- *Information quality-aware scheduling*: The quality of information in data collected from deployed sensors is measured by age of information (AoI). Therefore, in any data collection mission, it is important to design a AoI-aware data collection schedule while also considering the UAV's battery capacity limit. Ahani et al. [238] designed an optimal data collection schedule which minimizes the AoI cost for a given time period.

7.5.1. Discussions and open issues

In the following, we discuss few issues relevant to the scheduling in UAV-WPT scenarios.

- *Scheduling in multi-UAV scenarios*: In multi-UAV scenarios, it is necessary to schedule the UAV trajectories such that energy transfer to the deployed nodes is maximized, while minimizing the travel and hover time of the UAVs.
- *Task offloading between UAVs*: In collaborative mission, there might be different types of UAVs involved in the mission. In such cases, the UAVs with lower computing resources can offload few computing tasks to the UAVs with higher computing resources. Such scheduling will also help in minimizing the energy consumption of the UAVs, and thus, higher amount of energy will be available for WPT.

7.6. Security

Due to the broadcast nature of the medium, WPT for UAV and deployed sensor networks are impaired by the security vulnerabilities of the transmission channel. In this regard, the objective is to ensure secure communication between the base stations, UAVs and deployed sensor nodes while maintaining energy-efficiency. We also highlight the security parameters such as secrecy rate, considered in the existing literature. Interested readers can check [239] for a more detailed survey of security issues in terms of sensors, communication and multiple UAVs.

- *Secrecy rate and energy-efficiency*: Wang et al. [240] pointed out the need of enabling secure wireless transmission without greedy and energy-hungry methods in a scenario with multi-hop communication among the deployed nodes wirelessly powered by a UAV. Towards this goal, the authors compute the secrecy outage probability (SOP) and secure energy efficiency (SEE) for relay selection, and then, devise an energy-efficient secure transmission protocol. In another work based on a multi-UAV scenario, Hua et al. [241] focused on the limited energy availability of the UAVs while targeting to maximize SEE, the possible secrecy rate per energy consumption. Towards this objective, a joint optimization of UAV's transmission power, trajectory and user scheduling were proposed. In [240], it was shown that with reduced UAV altitude, the secrecy rate increases. In [242], to maximize the secrecy rate, optimization of wireless charging duration along with UAV's trajectory, transmit power was considered with constraints such as battery capacity, energy harvesting limit and UAV's maximum flying speed. Further, few other works also studied the issues of secure communication in the context of UAV-assisted SWIPT [243–246]. These works considered various constraints such as average and maximum power of the UAV, energy harvesting limit of the nodes, mobility and position limits of the UAV. Also, these works considered fixed and known locations for the deployed nodes [240,241,243,244], as well as fixed UAV positions [245].
- *Alternate security measures*: In contrast to the existing works emphasizing on secrecy rate, [247] focused on ensuring security by generating artificial jamming by the UAV while performing information exchange in a SWIPT system. Similar idea was incorporated in [148,149,248], where the UAV transfer energy to a few helper nodes which in turn transmit an artificial noise to interfere with eavesdropper. The intended receiver nodes can decode the actual information with the information about the artificial noise. Wu et al. [249] considered the problem of UAV jitter, both horizontal (yaw) and vertical (pitch) jitter due to airflow and body vibration, affecting the secure communication between UAVs and deployed nodes due to imperfect estimation. To mitigate the problem, the UAV transmits confidential information along with artificial noise. In [250], a directional modulation technique was adopted to maximize the secrecy rate for enabling secure communication between the UAV and deployed nodes.
- *Imperfect knowledge on eavesdropper*: Sun et al. [251] argued that the deployed nodes or UAVs may not be aware of the presence of passive eavesdroppers and their locations. Based on this motivation, the secrecy rate is evaluated while considering the impact of eavesdropper node density and multiple carrier frequencies. Next, a joint optimization of UAV's transmit power, power splitting ratio and UAV's location was proposed to improve the secrecy rate.

7.6.1. Discussions and open issues

In the following, we discuss few relevant security issues for the UAV-WPT scenarios. Due to the ad hoc settings, there can be multiple combined attacks for the UAVs. Mitigating these attacks, specifically with these low computing resource-enabled UAVs are challenging.

8. Open research challenges

In the following, we discuss few research challenges that are not addressed in the current literature. Previously, we discussed the open issues for each of the topics and sub-topics in Sections 5–7. To be specific, we highlight the research challenges for each of the main technological and operation aspects.

8.1. Power and communication related aspects

- *Efficient localization of ground station and coil alignment*: The efficiency of the energy transfer depends on the efficiency of the UAV in localizing the ground station and then correctly aligning the source and receiver coils. The existing methods use image processing techniques and sensors to improve the quality of alignment as well as for localizing the station. Also, this process needs to be energy-efficient for the UAV, as computation intensive methods will consume more onboard energy of the UAV. Therefore, improved and energy-efficient solutions are required for such solutions. Additionally, the ground station needs to be designed such as to accommodate UAVs having different dimensions.
- *Resource management in multi-UAV-assisted WPCNs*: A multi-UAV-assisted WPCN is a suitable system model for many potential applications. In such systems, the aspects of collaboration among the UAVs for power allocation, time allocation, and computation management as well as joint optimization with UAV placement, trajectory planning with limited UAV battery power, speed are important issues.

8.2. Spatial aspects

- *Joint problem of trajectory planning and energy harvesting in difficult terrains*: The mobility models and the different UAV navigation alternatives constitute traditionally a big challenge during the design of a joint WPT and data collection approach. Additionally, the diverse communications channels and the existing terrestrial obstructions are able to decrease the data collection efficiency, especially in heterogeneous ad hoc architectures with uncertain WPT options. In this regard, for trajectory planning, we need to consider maximizing the coverage and data collection also.
- *Priority missions - joint problem of coverage, trajectory and energy harvesting*: In disaster scenarios, the UAVs involved in the mission need to handle real-time events with different priorities. Also, based on the application requirements, there can be different priorities assigned for recharging the deployed nodes, amount of energy transferred, overall energy budget, etc. Accordingly, the participating UAVs should be able to dynamically readjust their coverage and trajectories, while also recharging themselves when required. Here, we also need to consider the various UAV-related constraint such as limited battery power, flight/hover time, task completion deadline.

8.3. Operational aspects

- *Joint problem of data collection, latency and energy harvesting*: Among the challenges that hinder the data exchange between interconnected UAVs are the introduced latency, the additional data overhead, the energy requirements of UAVs and terrestrial devices. Additional challenges are posed by the problem instances where a more holistic knowledge on the network topology is needed. Therefore, there is a crucial necessity to implement efficient joint data collection and energy harvesting, taking into account all the diverse application aspects to minimize or eliminate the data losses and the latencies.
- *Dynamic charging scheduling for priority-based missions*: In disaster scenarios with real-time priorities, we also need to consider the remaining on-board battery capacity of the UAVs and need to devise dynamic charging schedules such that the mission objectives and deadlines are maintained. Additionally, the aspects of device heterogeneity of the UAVs and the possibilities of computation offloading can be considered while devising the scheduling techniques.
- *Improved security features for UAV-WPT*: UAV-related deployments are prone to diverse security threats because of their ad hoc nature and their open communication links. The threat impact magnify when the UAVs are operating over terrestrial communication settings, where they can be multiple combined types of attacks, like eavesdropping with ground-air physical threats. Diverse security methodologies have appeared in order to cope with both digital and physical threats and to mitigate malicious incidents. Such security methodologies can, however, provoke new problematic aspects, like increased data delivery latencies or additional energy consumption, which are due to the additional computing and communication resources needed on UAVs. Therefore, a crucial future direction would be the careful design of fine-grained security methodologies and robust encryption approaches for highly ad hoc settings.

9. Conclusion

In this paper, we present a holistic survey of the recent literature on the wireless power transfer (WPT) with UAVs. To the best of our knowledge, we, for the first time, specifically point out the intrinsic design, technological and operational challenges in a comprehensive manner. In this survey, we take a horizontal approach to cover the selected publications from across all vertical areas of research on UAVs. Towards this goal, we classify the vast research corpus in four fundamental categories, namely architectures, power and communications, spatial, operational. For each category, we divide the research works in various sub-categories and discuss their specific objectives and associated WPT-related challenges. In our survey, we present a taxonomy of various methodologies, architectures, deployment scenarios and technological roles of the UAVs with spatial and operational aspects of achieving WPT. We analyze the research works by comparing with other related works with respect to different parameters, and highlight the advantages and limitations of each work. We conclude the survey by pointing out open challenges for future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgment

This work was carried out during the tenure of an ERCIM 'Alain Bensoussan' Fellowship Programme of the first author. T. Raptis', M. Conti's and A. Passarella's work was partly funded by the PNRR - M4C2 - Investimento 1.3, Partenariato Esteso PE00000001 - "RESTART", funded by the European Commission under the NextGeneration EU programme.

References

[1] H. Zhao, H. Wang, W. Wu, J. Wei, Deployment algorithms for UAV airborne networks toward on-demand coverage, IEEE J. Sel. Areas Commun. 36 (9) (2018) 2015–2031.
[2] A. Couturier, M.A. Akhloufi, A review on absolute visual localization for UAV, Robot. Auton. Syst. 135 (2021) 103666, URL https://www.sciencedirect.com/science/article/pii/S0921889020305066.
[3] N.H. Motlagh, M. Bagaa, T. Taleb, UAV-based IoT platform: A crowd surveillance use case, IEEE Commun. Mag. 55 (2) (2017) 128–134.
[4] M. Samir, S. Sharafeddine, C.M. Assi, T.M. Nguyen, A. Ghrayeb, UAV trajectory planning for data collection from time-constrained IoT devices, IEEE Trans. Wireless Commun. 19 (1) (2020) 34–46.
[5] Z. Yang, W. Xu, M. Shikh-Bahaei, Energy efficient UAV communication with energy harvesting, IEEE Trans. Veh. Technol. 69 (2) (2020) 1913–1927.
[6] T. Ojha, T.P. Raptis, M. Conti, A. Passarella, Wireless crowd charging with battery aging mitigation, in: 2022 IEEE International Conference on Smart Computing, SMARTCOMP, 2022, pp. 142–149.
[7] A. Dhungana, E. Bulut, Peer-to-peer energy sharing in mobile networks: Applications, challenges, and open problems, Ad Hoc Netw. 97 (2020) 102029, URL https://www.sciencedirect.com/science/article/pii/S1570870519306018.
[8] Z. Zhang, H. Pang, A. Georgiadis, C. Cecati, Wireless power transfer—An overview, IEEE Trans. Ind. Electron. 66 (2) (2019) 1044–1058.
[9] Cost Action IC1301 Team, Europe and the future for WPT : European contributions to wireless power transfer technology, IEEE Microw. Mag. 18 (4) (2017) 56–87.
[10] S. Nikoletseas, T.P. Raptis, C. Raptopoulos, Wireless charging for weighted energy balance in populations of mobile peers, Ad Hoc Netw. 60 (2017) 1–10, URL https://www.sciencedirect.com/science/article/pii/S1570870517300495.
[11] J. Lim, H. Jung, Drone delivery scheduling simulations focusing on charging speed, weight and battery capacity: Case of remote islands in South Korea, in: 2017 Winter Simulation Conference, WSC, IEEE, 2017, pp. 4550–4551.
[12] W. Zeng, J. Zhang, K.P. Peppas, B. Ar, Z. Zhong, UAV-aided wireless information and power transmission for high-speed train communications, in: 2018 21st International Conference on Intelligent Transportation Systems, ITSC, IEEE, 2018, pp. 3409–3414.
[13] O. Cetinkaya, D. Balsamo, G.V. Merrett, Internet of MIMO things: UAV-assisted wireless-powered networks for future smart cities, IEEE Internet of Things Mag. 3 (1) (2020) 8–13.
[14] H. Chen, F. Yin, W. Huang, M. Liu, D. Li, Ocean surface drifting buoy system based on UAV-enabled wireless powered relay network, Sensors 20 (9) (2020) 2598.
[15] W.-C. Chien, M.M. Hassan, A. Alsanad, G. Fortino, UAV–assisted joint wireless power transfer and data collection mechanism for sustainable precision agriculture in 5G, IEEE Micro 42 (1) (2021) 25–32.
[16] K. Suzuki, R. Shigeta, Y. Kawahara, T. Asami, Bilateration-based position estimation of sensor nodes for UAV-assisted wireless power transfer systems, in: Adjunct Proceedings of the 13th International Conference on Mobile and Ubiquitous Systems: Computing Networking and Services, 2016, pp. 66–71.
[17] J.A.L. Calvo, G. Alirezaei, R. Mathar, Wireless powering of drone-based MANETs for disaster zones, in: 2017 IEEE International Conference on Wireless for Space and Extreme Environments, WiSEE, IEEE, 2017, pp. 98–103.
[18] B. Li, S. Patankar, B. Moridian, N. Mahmoudian, Planning large-scale search and rescue using team of uavs and charging stations, in: 2018 IEEE International Symposium on Safety, Security, and Rescue Robotics, SSRR, IEEE, 2018, pp. 1–8.
[19] D. Sikeridis, E.E. Tsiropoulou, M. Devetsikiotis, S. Papavassiliou, Wireless powered public safety IoT: A UAV-assisted adaptive-learning approach towards energy efficiency, J. Netw. Comput. Appl. 123 (2018) 69–79.
[20] R.G. Ribeiro, J.R. Júnior, L.P. Cota, T.A. Euzébio, F.G. Guimaraes, Unmanned aerial vehicle location routing problem with charging stations for belt conveyor inspection system in the mining industry, IEEE Trans. Intell. Transp. Syst. 21 (10) (2019) 4186–4195.
[21] G. Vom Bögel, L. Cousin, N. Iversen, E.S.M. Ebeid, A. Hennig, Drones for inspection of overhead power lines with recharge function, in: 2020 23rd Euromicro Conference on Digital System Design, DSD, IEEE, 2020, pp. 497–502.
[22] L. Cheng, L. Zhong, S. Tian, J. Xing, Task assignment algorithm for road patrol by multiple UAVs with multiple bases and rechargeable endurance, IEEE Access 7 (2019) 144381–144397.

[23] L. Gupta, R. Jain, G. Vaszkun, Survey of important issues in UAV communication networks, IEEE Commun. Surv. Tutor. 18 (2) (2015) 1123–1152.
[24] H. Shakhatreh, A.H. Sawalmeh, A. Al-Fuqaha, Z. Dou, E. Almaita, I. Khalil, N.S. Othman, A. Khreishah, M. Guizani, Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges, IEEE Access 7 (2019) 48572–48634.
[25] A. Mohiuddin, T. Tarek, Y. Zweiri, D. Gan, A survey of single and multi-UAV aerial manipulation, Unmanned Syst. 8 (02) (2020) 119–147.
[26] A.I. Hentati, L.C. Fourati, Comprehensive survey of UAVs communication networks, Comput. Stand. Interfaces 72 (2020) 103451.
[27] C. Kanellakis, G. Nikolakopoulos, Survey on computer vision for UAVs: Current developments and trends, J. Intell. Robot. Syst. 87 (1) (2017) 141–168.
[28] P. Mittal, R. Singh, A. Sharma, Deep learning-based object detection in low-altitude UAV datasets: A survey, Image Vis. Comput. 104 (2020) 104046.
[29] A.A. Khuwaja, Y. Chen, N. Zhao, M.-S. Alouini, P. Dobbins, A survey of channel modeling for UAV communications, IEEE Commun. Surv. Tutor. 20 (4) (2018) 2804–2821.
[30] C. Yan, L. Fu, J. Zhang, J. Wang, A comprehensive survey on UAV communication channel modeling, IEEE Access 7 (2019) 107769–107792.
[31] A. Otto, N. Agatz, J. Campbell, B. Golden, E. Pesch, Optimization approaches for civil applications of unmanned aerial vehicles (UAVs) or aerial drones: A survey, Networks 72 (4) (2018) 411–458.
[32] Y. Zhao, Z. Zheng, Y. Liu, Survey on computational-intelligence-based UAV path planning, Knowl.-Based Syst. 158 (2018) 54–64.
[33] B. Rubí, R. Pérez, B. Morcego, A survey of path following control strategies for UAVs focused on quadrotors, J. Intell. Robot. Syst. 98 (2) (2020) 241–265.
[34] S. Aggarwal, N. Kumar, Path planning techniques for unmanned aerial vehicles: A review, solutions, and challenges, Comput. Commun. 149 (2020) 270–299.
[35] X. Zhou, Z. Yi, Y. Liu, K. Huang, H. Huang, Survey on path and view planning for UAVs, Virtual Real. Intell. Hardw. 2 (1) (2020) 56–69.
[36] D. Popescu, F. Stoican, G. Stamatescu, O. Chenaru, L. Ichim, A survey of collaborative UAV–WSN systems for efficient monitoring, Sensors 19 (21) (2019) 4690.
[37] L. Zhang, H. Zhao, S. Hou, Z. Zhao, H. Xu, X. Wu, Q. Wu, R. Zhang, A survey on 5G millimeter wave communications for UAV-assisted wireless networks, IEEE Access 7 (2019) 117460–117504.
[38] Z. Ullah, F. Al-Turjman, L. Mostarda, Cognition in UAV-aided 5G and beyond communications: A survey, IEEE Trans. Cogn. Commun. Network. 6 (3) (2020) 872–891.
[39] R. Shakeri, M.A. Al-Garadi, A. Badawy, A. Mohamed, T. Khattab, A.K. Al-Ali, K.A. Harras, M. Guizani, Design challenges of multi-UAV systems in cyber-physical applications: A comprehensive survey and future directions, IEEE Commun. Surv. Tutor. 21 (4) (2019) 3340–3385.
[40] G. Skorobogatov, C. Barrado, E. Salamí, Multiple UAV systems: A survey, Unmanned Syst. 8 (02) (2020) 149–169.
[41] A. Fotouhi, H. Qiang, M. Ding, M. Hassan, L.G. Giordano, A. Garcia-Rodriguez, J. Yuan, Survey on UAV cellular communications: Practical aspects, standardization advancements, regulation, and security challenges, IEEE Commun. Surv. Tutor. 21 (4) (2019) 3417–3442.
[42] D. Mishra, E. Natalizio, A survey on cellular-connected UAVs: Design challenges, enabling 5G/B5G innovations, and experimental advancements, Comput. Netw. 182 (2020) 107451.
[43] A. Sharma, P. Vanjani, N. Paliwal, C.M.W. Basnayaka, D.N.K. Jayakody, H.-C. Wang, P. Muthuchidambaranathan, Communication and networking technologies for UAVs: A survey, J. Netw. Comput. Appl. 168 (2020) 102739.
[44] H.T. Nguyen, T.V. Quyen, C.V. Nguyen, A.M. Le, H.T. Tran, M.T. Nguyen, Control algorithms for UAVs: A comprehensive survey, EAI Endorsed Trans. Ind. Netw. Intell. Syst. 7 (23) (2020).
[45] W. Gu, K.P. Valavanis, M.J. Rutherford, A. Rizzo, UAV model-based flight control with artificial neural networks: A survey, J. Intell. Robot. Syst. 100 (3) (2020) 1469–1491.
[46] M.M. Alam, M.Y. Arafat, S. Moh, J. Shen, Topology control algorithms in multi-unmanned aerial vehicle networks: An extensive survey, J. Netw. Comput. Appl. (2022) 103495.
[47] D.K. Villa, A.S. Brandao, M. Sarcinelli-Filho, A survey on load transportation using multirotor UAVs, J. Intell. Robot. Syst. 98 (2) (2020) 267–296.
[48] M. Ghamari, P. Rangel, M. Mehrubeoglu, G.S. Tewolde, R.S. Sherratt, Unmanned aerial vehicle communications for civil applications: A review, IEEE Access 10 (2022) 102492–102531.
[49] X. Lu, P. Wang, D. Niyato, D.I. Kim, Z. Han, Wireless networks with RF energy harvesting: A contemporary survey, IEEE Commun. Surv. Tutor. 17 (2) (2015) 757–789.
[50] X. Mou, H. Sun, Wireless power transfer: Survey and roadmap, in: 2015 IEEE 81st Vehicular Technology Conference, VTC Spring, IEEE, 2015, pp. 1–5.
[51] Z. Zhang, H. Pang, A. Georgiadis, C. Cecati, Wireless power transfer - an overview, IEEE Trans. Ind. Electron. 66 (2) (2018) 1044–1058.
[52] W. Zhang, C.C. Mi, Compensation topologies of high-power wireless power transfer systems, IEEE Trans. Veh. Technol. 65 (6) (2015) 4768–4778.
[53] X. Lu, P. Wang, D. Niyato, D.I. Kim, Z. Han, Wireless charging technologies: Fundamentals, standards, and network applications, IEEE Commun. Surv. Tutor. 18 (2) (2016) 1413–1452.
[54] N.A. Bhatti, M.H. Alizai, A.A. Syed, L. Mottola, Energy harvesting and wireless transfer in sensor network applications, ACM Trans. Sensor Netw. 12 (3) (2016) 1–40.
[55] A. Kaswan, P.K. Jana, S.K. Das, A survey on mobile charging techniques in wireless rechargeable sensor networks, IEEE Commun. Surv. Tutor. 24 (3) (2022) 1750–1779.
[56] M. Lu, M. Bagheri, A.P. James, T. Phung, Wireless charging techniques for UAVs: A review, reconceptualization, and extension, IEEE Access 6 (2018) 29865–29884.
[57] P.K. Chittoor, B. Chokkalingam, L. Mihet-Popa, A review on UAV wireless charging: Fundamentals, applications, charging techniques and standards, IEEE Access 9 (2021) 69235–69266.
[58] A.M. Le, L.H. Truong, T.V. Quyen, C.V. Nguyen, M.T.N.T. Nguyen, Wireless power transfer near-field technologies for unmanned aerial vehicles (UAVs): A review, EAI Endorsed Trans. Ind. Netw. Intell. Syst. 7 (22) (2020) e5.
[59] L. Xie, X. Cao, J. Xu, R. Zhang, UAV-enabled wireless power transfer: A tutorial overview, IEEE Trans. Green Commun. Netw. 5 (4) (2021) 2042–2064.
[60] J. Xu, Y. Zeng2, R. Zhang, UAV-enabled multiuser wireless power transfer: Trajectory design and energy optimization, in: Proceedings of IEEE Asia-Pacific Conference on Communications, APCC, Perth, WA, Australia, 2017, pp. 1–6.
[61] Z. Liu, W. Xu, L. Guo, Z. Zhang, J. Lin, Flying path optimization of UAV for wireless power transfer systems: A spectral-clustering-enabled approach, in: 2019 IEEE 19th International Conference on Communication Technology, ICCT, IEEE, 2019, pp. 1220–1225.
[62] W. Feng, N. Zhao, S. Ao, J. Tang, X. Zhang, Y. Fu, D.K.C. So, K.-K. Wong, Joint 3D trajectory design and time allocation for UAV-enabled wireless power transfer networks, IEEE Trans. Veh. Technol. 69 (9) (2020) 9265–9278.
[63] L. Cheng, L. Zhong, X. Zhang, J. Xing, A staged adaptive firefly algorithm for UAV charging planning in wireless sensor networks, Comput. Commun. 161 (2020) 132–141.
[64] K. Yu, A.K. Budhiraja, S. Buebel, P. Tokekar, Algorithms and experiments on routing of unmanned aerial vehicles with mobile recharging stations, J. Field Robot. (Wiley) 36 (2019) 602–616.

[65] K. Yu, A.K. Budhiraja, P. Tokekar, Algorithms for routing of unmanned aerial vehicles with mobile recharging stations, in: Proceedings of IEEE International Conference on Robotics and Automation, ICRA, Brisbane, Australia, 2018, pp. 5720–5725.
[66] S.A. Hoseini, J. Hassan, A. Bokani, S.S. Kanhere, Trajectory optimization of flying energy sources using Q-learning to recharge hotspot UAVs, in: IEEE INFOCOM 2020 - IEEE Conference on Computer Communications Workshops, INFOCOM WKSHPS, IEEE, 2020, pp. 683–688.
[67] J. Xu, Y. Zeng, R. Zhang, UAV-enabled wireless power transfer: Trajectory design and energy region characterization, in: Proceedings of IEEE GLOBECOM Workshops, Singapore, 2017, pp. 1–6.
[68] J. Xu, Y. Zeng, R. Zhang, UAV-enabled wireless power transfer: Trajectory design and energy optimization, IEEE Trans. Wireless Commun. 17 (8) (2018) 5092–5106.
[69] Y. Zhang, W. Cheng, Trajectory and power optimization for multi-UAV enabled emergency wireless communications networks, in: 2019 IEEE International Conference on Communications Workshops, ICC Workshops, IEEE, 2019, pp. 1–6.
[70] F. Huang, J. Chen, H. Wang, Z. Xue, G. Ding, X. Yang, UAV-enabled wireless power transfer for mobile users: Trajectory optimization and power allocation, in: International Conference on Advanced Hybrid Information Processing, Springer, 2018, pp. 287–296.
[71] O.S. Oubbati, M. Atiquzzaman, H. Lim, A. Rachedi, A. Lakas, Synchronizing uav teams for timely data collection and energy transfer by deep reinforcement learning, IEEE Trans. Veh. Technol. (2022).
[72] M. Simic, C. Bil, V. Vojisavljevic, Investigation in wireless power transmission for UAV charging, Procedia Comput. Sci. 60 (2015) 1846–1855.
[73] C.H. Choi, H.J. Jang, S.G. Lim, H.C. Lim, S.H. Cho, I. Gaponov, Automatic wireless drone charging station, in: Proceedings of International Conference on Control, Automation and Information Sciences, ICCAIS, Ansan, Korea, 2016, pp. 132–136.
[74] S. Chen, Y. Shuy, B. Yu, C. Liang, Z. Shi, J. Chen, Mobile wireless charging and sensing by drones, in: Proceedings of ACM MobiSys, Singapore, 2016, p. 99.
[75] M. Khonji, M. Alshehhi, C.-M. Tseng, C.-K. Chau, Autonomous inductive charging system for battery-operated electric drones, in: Proceedings of E-Energy, Hong Kong, 2017, pp. 322–327.
[76] K. Sang-Won, C. In-Kui, H. Sung-Yong, Comparison of charging region differences according to receiver structure in drone wireless charging system, in: International Conference on Information and Communication Technology Convergence, ICTC, IEEE, 2017, pp. 1058–1060.
[77] T. Ohira, S. Tsukamoto, N. Sakai, S. Abe, M. Sugino, N. Sakura, K. Sasaki, Live demonstration: An HF capacitive wireless power transfer to a quad-rotor drone, in: IEEE International Symposium on Circuits and Systems, ISCAS, IEEE, 2019, p. 1.
[78] C. Woo, S. Kang, H. Ko, H. Song, J.O. Kwon, Auto charging platform and algorithms for long-distance flight of drones, in: IEEE International Conference on Consumer Electronics, ICCE, 2017, pp. 1–2.
[79] A. Aboumrad, J. Haun, A. McGinnis, N. Wu, An automatic platform for landing and charging of UAVs to extend UAV operations, in: Proceedings of IEEE DCOSS, Marina del Rey, CA, USA, 2020, pp. 343–347.
[80] [Online] URL https://www.bitcraze.io/documentation/hardware/qi_deck_1_2/qi_deck_1_2-datasheet.pdf. (Accessed 30 November 2022).
[81] B. Griffin, C. Detweiler, Resonant wireless power transfer to ground sensors from a UAV, in: Proceedings of IEEE International Conference on Robotics and Automation, 2012, pp. 2660–2665.
[82] Y. Yan, W. Shi, X. Zhang, Design of UAV wireless power transmission system based on coupling coil structure optimization, EURASIP J. Wireless Commun. Networking 1 (2020) 1–13.
[83] C. Cai, J. Liu, S. Wu, Y. Zhang, L. Jiang, Z. Zhang, J. Yu, Development of a cross-type magnetic coupler for unmanned aerial vehicle IPT charging systems, IEEE Access (2020) 67974–67989.
[84] C. Song, H. Kim, Y. Kim, D. Kim, S. Jeong, Y. Cho, S. Lee, S. Ahn, J. Kim, EMI reduction methods in wireless power transfer system for drone electrical charger using tightly coupled three-phase resonant magnetic field, IEEE Trans. Ind. Electron. 65 (9) (2018) 6839–6849.
[85] J. Zhou, B. Zhang, W. Xiao, D. Qiu, Y. Chen, Nonlinear parity-time-symmetric model for constant efficiency wireless power transfer: Application to a drone-in-flight wireless charging platform, IEEE Trans. Ind. Electron. 66 (5) (2019) 4097–4107.
[86] A. Carloni, F. Baronti, R. Di Rienzo, R. Roncella, R. Saletti, DC-link capacitor sizing method for a wireless power transfer circuit to be used in drone opportunity charging, in: International Conference on Applications in Electronics Pervading Industry, Environment and Society, 2019, pp. 397–403.
[87] X. Gao, C. Liu, Y. Huang, Z. Song, Design of an UAV-oriented wireless power transfer system with energy-efficient receiver, in: IECON 2020 the 46th Annual Conference of the IEEE Industrial Electronics Society, IEEE, 2020, pp. 2025–2030.
[88] J. Ouyang, Y. Che, J. Xu, K. Wu, Throughput maximization for laser-powered UAV wireless communication systems, in: Proceedings of IEEE ICC Workshops, Kansas City, MO, USA, 2018, pp. 1–6.
[89] W. Jaafar, H. Yanikomeroglu, Dynamics of laser-charged UAVs: A battery perspective, IEEE Internet Things J. 8 (13) (2021) 10573–10582.
[90] L. Angrisani, G. d'Alessandro, M. D'Arco, V. Paciello, A. Pietrosanto, Autonomous recharge of drones through an induction based power transfer system, in: IEEE International Workshop on Measurements & Networking, 2015, pp. 1–6.
[91] D. Ke, C. Liu, C. Jiang, F. Zhao, Design of an effective wireless air charging system for electric unmanned aerial vehicles, in: IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, 2017, pp. 6949–6954.
[92] Y. He, J. Wu, S. Shi, Z. Song, Q. Qiao, C. Wang, Wireless electricity transmission design of unmanned aerial vehicle charging systems, in: International Conference in Communications, Signal Processing, and Systems, Springer, 2019, pp. 762–768.
[93] B. Park, S. Huh, H. Kim, Y. Shin, S. Woo, S. Ahn, Design and analysis of magnetic energy harvester with improved power density for drone charging station near high voltage power line, in: 2022 International Conference on Electronics, Information, and Communication, ICEIC, IEEE, 2022, pp. 1–2.
[94] A.A. Nasir, X. Zhou, S. Durrani, R.A. Kennedy, Relaying protocols for wireless energy harvesting and information processing, IEEE Trans. Wireless Commun. 12 (7) (2013) 3622–3636.
[95] H.-T. Ye, X. Kang, Y.-C. Liang, J. Joung, Full-duplex wireless-powered IoT networks with unmanned aerial vehicle, in: Proceedings of International Conference on Information and Communication Technology Convergence, ICTC, 2018, pp. 124–129.
[96] S. Chen, J. Zhang, W. Zeng, K.P. Peppas, B. Ai, Performance analysis of wireless powered UAV relaying systems over κ-μ fading channels, in: Proceedings of IEEE GLOBECOM Workshops, Abu Dhabi, UAE, 2018, pp. 1–6.
[97] J. Park, H. Lee, S. Eom, I. Lee, Wireless powered communication networks aided by an unmanned aerial vehicle, in: Proceedings of IEEE 88th Vehicular Technology Conference, VTC-Fall, 2018, pp. 1–5.
[98] M. Hua, C. Li, Y. Huang, L. Yang, Throughput maximization for UAV-enabled wireless power transfer in relaying system, in: Proceedings of International Conference on Wireless Communications and Signal Processing, WCSP, Nanjing, China, 2017, pp. 1–6.
[99] Y. Huo, X. Dong, T. Lu, W. Xu, M. Yuen, Distributed and multilayer UAV networks for next-generation wireless communication and power transfer: A feasibility study, IEEE Internet Things J. 6 (4) (2019) 7103–7115.
[100] H.-T. Ye, X. Kang, J. Joung, Y.-C. Liang, Optimal time allocation for full-duplex wireless-powered IoT networks with unmanned aerial vehicle, in: Proceedings of IEEE International Conference on Communications, ICC, 2019, pp. 1–6.
[101] T. Shen, H. Ochiai, A UAV-aided data collection for wireless powered sensor network over rician fading channels, in: Proceedings of IEEE Annual Consumer Communications & Networking Conference, CCNC, 2019, pp. 1–5.

[102] T.D.P. Perera, S. Panic, D.N.K. Jayakody, P. Muthuchidambaranathan, UAV-assisted data collection in wireless powered sensor networks over multiple fading channels, in: IEEE INFOCOM 2020-IEEE Conference on Computer Communications Workshops, INFOCOM WKSHPS, IEEE, 2020, pp. 647–652.
[103] J. Zheng, J. Zhang, S. Chen, H. Zhao, B. Ai, Wireless powered UAV relay communications over fluctuating two-ray fading channels, Phys. Commun. 35 (2019) 100724.
[104] P. Zhang, H. Du, Y. Cao, J. Zhang, Wireless powered UAV relay communications over the Fisher-snedecoer $\mathcal{F}$ fading channels, in: Proceedings of IEEE 90th Vehicular Technology Conference, VTC2019-Fall, 2019, pp. 1–5.
[105] Y. Li, D. Yang, Y. Xu, L. Xiao, H. Chen, Throughput maximization for UAV-enabled relaying in wireless powered communication networks, Sensors 19 (13) (2019) URL https://www.mdpi.com/1424-8220/19/13/2989.
[106] H. Jia, Y. Wang, M. Liu, Y. Chen, Sum-rate maximization for UAV aided wireless power transfer in space-air-ground networks, IEEE Access 8 (2020) 216231–216244.
[107] L. Xie, J. Xu, R. Zhang, Throughput maximization for UAV-enabled wireless powered communication networks - invited paper, in: 2018 IEEE 87th Vehicular Technology Conference, VTC Spring, 2018, pp. 1–7.
[108] L. Xie, J. Xu, R. Zhang, Throughput maximization for UAV-enabled wireless powered communication networks, IEEE Internet Things J. 6 (2) (2019) 1690–1703.
[109] H.-T. Ye, X. Kang, J. Joung, Y.-C. Liang, Joint uplink and downlink 3D optimization of an UAV swarm for wireless-powered NB-IoT, in: 2019 IEEE Global Communications Conference, GLOBECOM, 2019, pp. 1–6.
[110] F. Wu, D. Yang, L. Xiao, L. Cuthbert, Minimum-throughput maximization for multi-UAV-enabled wireless-powered communication networks, Sensors 7 (19) (2019) 1491.
[111] X. Hong, P. Liu, F. Zhou, S. Guo, Z. Chu, Resource allocation for secure UAV-assisted SWIPT systems, IEEE Access 7 (2019) 24248–24257.
[112] L. Xie, J. Xu, Y. Zeng, Common throughput maximization for UAV-enabled interference channel with wireless powered communications, IEEE Trans. Commun. 68 (5) (2020) 3197–3212.
[113] J. Miao, P. Wang, Q. Zhang, Y. Wang, Throughput maximization for multi-UAV enabled millimeter wave WPCN: Joint time and power allocation, China Commun. 17 (10) (2020) 142–156.
[114] C. Zhang, S. Liang, C. He, K. Wang, Multi-UAV trajectory design and power control based on deep reinforcement learning, J. Commun. Inform. Netw. 7 (2) (2022) 192–201.
[115] H.-T. Ye, X. Kang, J. Joung, Y.-C. Liang, Optimization for full-duplex rotary-wing UAV-enabled wireless-powered IoT networks, IEEE Trans. Wireless Commun. 19 (7) (2020) 5057–5072.
[116] A. Bhowmick, S.D. Roy, S. Kundu, Throughput maximization of a UAV assisted CR network with NOMA-based communication and energy-harvesting, IEEE Trans. Veh. Technol. 71 (1) (2021) 362–374.
[117] Z. Wei, X. Yu, D.W.K. Ng, R. Schober, Resource allocation for simultaneous wireless information and power transfer systems: A tutorial overview, Proc. IEEE (2021).
[118] W. Lu, S. Fang, Y. Gong, L. Qian, X. Liu, J. Hua, Resource allocation for OFDM relaying wireless power transfer based energy-constrained UAV communication network, in: 2018 IEEE International Conference on Communications Workshops, ICC Workshops, 2018, pp. 1–6.
[119] B. Liu, H. Xu, X. Zhou, Resource allocation in unmanned aerial vehicle (UAV)-assisted wireless-powered internet of things, Sensors 19 (8) (2019).
[120] J. Park, H. Lee, S. Eom, I. Lee, UAV-aided wireless powered communication networks: Trajectory optimization and resource allocation for minimum throughput maximization, IEEE Access 7 (2019) 134978–134991.
[121] S. Yin, L. Li, F.R. Yu, Resource allocation and basestation placement in downlink cellular networks assisted by multiple wireless powered UAVs, IEEE Trans. Veh. Technol. 69 (2) (2020) 2171–2184.
[122] K. Li, W. Ni, E. Tovar, A. Jamalipour, Deep Q-learning based resource management in UAV-assisted wireless powered IoT networks, in: ICC 2020 - 2020 IEEE International Conference on Communications, ICC, 2020, pp. 1–6.
[123] L. Xie, J. Xu, Cooperative trajectory design and resource allocation for a two-uav two-user wireless powered communication system, in: 2018 IEEE International Conference on Communication Systems, ICCS, 2018, pp. 7–12.
[124] W. Lu, P. Si, G. Huang, H. Peng, S. Hu, Y. Gao, Interference reducing and resource allocation in UAV-powered wireless communication system, in: 2020 International Wireless Communications and Mobile Computing, IWCMC, 2020, pp. 220–224.
[125] J. Ji, K. Zhu, D. Niyato, R. Wang, Joint cache placement, flight trajectory, and transmission power optimization for multi-UAV assisted wireless networks, IEEE Trans. Wireless Commun. 19 (8) (2020) 5389–5403.
[126] S. Chai, V.K.N. Lau, Online trajectory and radio resource optimization of cache-enabled UAV wireless networks with content and energy recharging, IEEE Trans. Signal Process. 68 (2020) 1286–1299.
[127] Z. Hadzi-Velkov, S. Pejoski, R. Schober, N. Zlatanov, Wireless powered ALOHA networks with UAV-mounted-base stations, IEEE Wirel. Commun. Lett. 9 (1) (2020) 56–60.
[128] X. Hu, K.-K. Wong, Z. Zheng, Wireless-powered mobile edge computing with cooperated UAV, in: 2019 IEEE 20th International Workshop on Signal Processing Advances in Wireless Communications, SPAWC, IEEE, 2019, pp. 1–5.
[129] X. Hu, K.-K. Wong, Y. Zhang, Wireless-powered edge computing with cooperative UAV: Task, time scheduling and trajectory design, IEEE Trans. Wireless Commun. 19 (12) (2020) 8083–8098.
[130] Y. Du, K. Yang, K. Wang, G. Zhang, Y. Zhao, D. Chen, Joint resources and workflow scheduling in UAV-enabled wirelessly-powered MEC for IoT systems, IEEE Trans. Veh. Technol. 68 (10) (2019) 10187–10200.
[131] S. Yin, Y. Zhao, L. Li, F.R. Yu, Resource allocation and basestation placement in cellular networks with wireless powered UAVs, in: ICC 2019 - 2019 IEEE International Conference on Communications, ICC, 2019, pp. 1–6.
[132] S. Yin, Y. Zhao, L. Li, Resource allocation and basestation placement in cellular networks with wireless powered UAVs, IEEE Trans. Veh. Technol. 68 (1) (2019) 1050–1055.
[133] F. Zhou, Y. Wu, R.Q. Hu, Y. Qian, Computation rate maximization in UAV-enabled wireless-powered mobile-edge computing systems, IEEE J. Sel. Areas Commun. 36 (9) (2018) 1927–1941.
[134] Y. Liu, K. Xiong, Q. Ni, P. Fan, K.B. Letaief, UAV-assisted wireless powered cooperative mobile edge computing: Joint offloading, CPU control, and trajectory optimization, IEEE Internet Things J. 7 (4) (2020) 2777–2790.
[135] W. Feng, J. Tang, N. Zhao, X. Zhang, X. Wang, K.-K. Wong, J.A. Chambers, Hybrid beamforming design and resource allocation for UAV-aided wireless-powered mobile edge computing networks with NOMA, IEEE J. Sel. Areas Commun. 39 (11) (2021) 3271–3286.
[136] L. Liu, R. Zhang, K.-C. Chua, Wireless information and power transfer: A dynamic power splitting approach, IEEE Trans. Commun. 61 (9) (2013) 3990–4001.
[137] S. Yin, Y. Zhao, L. Li, UAV-assisted cooperative communications with power-splitting SWIPT, in: Proceedings of IEEE International Conference on Communication Systems, ICCS, Chengdu, China, 2018, pp. 162–167.
[138] S. Yin, Y. Zhao, L. Li, F.R. Yu, UAV-assisted cooperative communications with power-splitting information and power transfer, IEEE Trans. Green Commun. Netw. 3 (4) (2019) 1044–1057.

[139] F. Huang, J. Chen, H. Wang, G. Ding, Y. Gong, Y. Yang, Multiple-UAV-assisted SWIPT in internet of things: User association and power allocation, IEEE Access 7 (2019) 124244–124255.
[140] F. Huang, J. Chen, H. Wang, G. Ding, Z. Xue, Y. Yang, F. Song, UAV-assisted SWIPT in internet of things with power splitting: Trajectory design and power allocation, IEEE Access 7 (2019) 68260–68270.
[141] M. Yang, F. Huang, Y. Zeng, Y. Wu, C. Zhang, User association and power allocation in UAV-based SWIPT system, in: International Conference on Intelligent Robotics and Applications, Vol. 11743, Springer, 2019, pp. 3–13.
[142] Z. Li, J. Feng, J. Li, X. Gou, An information and power simultaneous transfer strategy in UAV and wireless rechargeable sensor networks, in: International Conference on Machine Learning for Cyber Security, Springer, 2020, pp. 66–78.
[143] Y.H. Kim, I.A. Chowdhury, I. Song, Design and analysis of UAV-assisted relaying with simultaneous wireless information and power transfer, IEEE Access 8 (2020) 27874–27886.
[144] J. Wang, G. Wang, G. Chen, B. Li, R. Zhou, R. Zhang, Design and optimization for UAV-enabled two-way relaying system with SWIPT, EURASIP J. Wireless Commun. Networking 2020 (1) (2020) 1–12.
[145] X. Wang, M.C. Gursoy, I. Guvenc, Simultaneous wireless information and power transfer in UAV-assisted cellular IoT networks, in: 2020 IEEE 17th Annual Consumer Communications & Networking Conference, CCNC, IEEE, 2020, pp. 1–6.
[146] M.T. Mamaghani, Y. Hong, On the performance of low-altitude UAV-enabled secure AF relaying with cooperative jamming and SWIPT, IEEE Access 7 (2019) 153060–153073.
[147] M.T. Mamaghani, R. Abbas, Security and reliability performance analysis for two-way wireless energy harvesting based untrusted relaying with cooperative jamming, IET Commun. 13 (4) (2019) 449–459.
[148] W. Wang, J. Tang, N. Zhao, X. Liu, X.Y. Zhang, Y. Chen, Y. Qian, Joint precoding optimization for secure SWIPT in UAV-aided NOMA networks, IEEE Trans. Commun. 68 (8) (2020) 5028–5040.
[149] X. Sun, W. Yang, Y. Cai, Secure communication in NOMA-assisted millimeter-wave SWIPT UAV networks, IEEE Internet Things J. 7 (3) (2019) 1884–1897.
[150] A. Hassan, R. Ahmad, W. Ahmed, M. Magarini, M.M. Alam, UAV and SWIPT assisted disaster aware clustering and association, IEEE Access 8 (2020) 204791–204803.
[151] W. Feng, J. Tang, Y. Yu, J. Song, N. Zhao, G. Chen, K.-K. Wong, J. Chambers, UAV-enabled SWIPT in IoT networks for emergency communications, IEEE Wirel. Commun. 27 (5) (2020) 140–147.
[152] S. Yin, Y. Zhao, L. Li, UAV-assisted cooperative communications with time-sharing SWIPT, in: 2018 IEEE International Conference on Communications, ICC, IEEE, 2018, pp. 1–6.
[153] S. Yin, Y. Zhao, L. Li, F.R. Yu, UAV-assisted cooperative communications with time-sharing information and power transfer, IEEE Trans. Veh. Technol. 69 (2) (2019) 1554–1567.
[154] R. Jiang, K. Xiong, T. Liu, D. Wang, Z. Zhong, Coverage probability-constrained maximum throughput in UAV-aided SWIPT networks, in: 2020 IEEE International Conference on Communications Workshops, ICC Workshops, IEEE, 2020, pp. 1–6.
[155] C. Lin, C. Guo, W. Dux, J. Deng, L. Wang, G. Wu, Maximizing energy efficiency of period-area coverage with UAVs for wireless rechargeable sensor networks, in: Proceedings of IEEE SECON, Boston, MA, USA, 2019, pp. 1–9.
[156] K.T. Pauu, H. Xu, B. Wang, A novel UAV charging scheme for minimizing coverage breach in rechargeable sensor networks, in: Proceedings of International Conference on International Conference on Green, Pervasive, and Cloud Computing, Lecture Notes in Computer Science, Vol. 12398, 2020, pp. 347–361.
[157] A. Trotta, M.D. Felice, K.R. Chowdhury, L. Bononi, Fly and recharge: Achieving persistent coverage using small unmanned aerial vehicles (SUAVs), in: Proceedings of IEEE ICC, Paris, France, 2017, pp. 1–6.
[158] A. Trotta, M.D. Felice, F. Montori, K.R. Chowdhury, L. Bononi, Joint coverage, connectivity, and charging strategies for distributed UAV networks, IEEE Trans. Robot. 34 (4) (2018) 883–900.
[159] X. Li, H. Yao, J. Wang, C. Jiang, F.R. Yu, An energy-efficient UAV recharging and reshuffling strategy for seamless coverage, in: Proceedings of IEEE GLOBECOM, Waikoloa, HI, USA, 2019, pp. 1–6.
[160] X. Li, H. Yao, J. Wan, S. Wu, C. Jiang, Y. Qian, Rechargeable multi-UAV aided seamless coverage for QoS-guaranteed IoT networks, IEEE Internet Things J. 6 (6) (2019) 10902–10914.
[161] J. Kim, J. Lee, J.P. Jeong, H. Kim, J.-S. Park, T. Kim, SAN: Self-adaptive navigation for drone battery charging in wireless drone networks, in: Proceedings of International Conference on Advanced Information Networking and Applications Workshops, Crans-Montana, Switzerland, 2016, pp. 248–251.
[162] T. Wu, P. Yang, H. Dai, P. Li, X. Rao, Near optimal bounded route association for drone-enabled rechargeable WSNs, Comput. Netw. 145 (2018) 107–117.
[163] J. Kim, S. Kimg, J. Jeong, H. Kim, J.-S. Park, T. Kim, CBDN: Cloud-based drone navigation for efficient battery charging in drone networks, IEEE Trans. Intell. Transp. Syst. 20 (11) (2019) 4174–4191.
[164] K.E. Booth, C. Piacentini, S. Bernardini, J.C. Beck, Target search on road networks with range-constrained UAVs and ground-based mobile recharging vehicles, IEEE Robot. Autom. Lett. 5 (4) (2020) 6702–6709.
[165] K. Leahy, D. Zhou, C.-I. Vasile, K. Oikonomopoulos, M. Schwager, C. Belta, Persistent surveillance for unmanned aerial vehicles subject to charging and temporal logic constraints, Auton. Robots 40 (8) (2016) 1363–1378.
[166] K. Leahy, D. Zhou, C.-I. Vasile, K. Oikonomopoulos, M. Schwager, C. Belta, Provably correct persistent surveillance for unmanned aerial vehicles subject to charging constraints, in: Experimental Robotics, Springer, 2016, pp. 605–619.
[167] S. Seyedi, Y. Yazicioğlu, D. Aksaray, Persistent surveillance with energy-constrained uavs and mobile charging stations, IFAC-PapersOnLine 52 (20) (2019) 193–198.
[168] J.L.E.K. Fendji, I.K. Bayaola, C. Thron, M.D. Fendji, A. Förster, Cost-effective placement of recharging stations in drone path planning for surveillance missions on large farms, Symmetry 12 (10) (2020) 1661.
[169] S.J. Kim, G.J. Lim, Drone-aided border surveillance with an electrification line battery charging system, J. Intell. Robot. Syst. 92 (3) (2018) 657–670.
[170] I.K. Singgih, J. Lee, B.-I. Kim, Node and edge surveillance using drones considering required camera altitude and battery charging, in: IFIP International Conference on Advances in Production Management Systems, Springer, 2018, pp. 172–180.
[171] P. Wu, F. Xiao, H. Huang, C. Sha, S. Yu, Adaptive and extensible energy supply mechanism for UAVs-aided wireless-powered internet of things, IEEE Internet Things J. 7 (9) (2020) 9201–9213.
[172] Y. Ma, Y. Tang, J. Tao, D. Zhang, S. Tao, W. Li, Energy-efficient transmit power and straight trajectory optimization in uav-aided wireless sensor networks, in: 2020 IEEE 91st Vehicular Technology Conference, VTC2020-Spring, IEEE, 2020, pp. 1–7.
[173] T. Yang, Y. Hu, X. Yuan, R. Mathar, Genetic algorithm based UAV trajectory design in wireless power transfer systems, in: Proceedings of IEEE WCNC, Marrakesh, Morocco, 2019, pp. 1–6.
[174] Y. Hu, X. Yuan, J. Xu, Optimal 1D trajectory design for UAV-enabled multiuser wireless power transfer, IEEE Trans. Commun. 67 (8) (2019) 5674–5688.

[175] Y. Guo, S. Yin, J. Hao, Resource allocation and 3-D trajectory design in wireless networks assisted by rechargeable UAV, IEEE Wirel. Commun. Lett. 8 (3) (2019) 781–784.
[176] W. Chen, S. Zhao, Q. Shi, R. Zhang, Resonant beam charging-powered UAV-assisted sensing data collection, IEEE Trans. Veh. Technol. 69 (1) (2019) 1086–1090.
[177] C. Detweiler, M. Eiskamp, B. Griffin, J. Johnson, J. Leng, A. Mittleider, E. Basha, Unmanned aerial vehicle-based wireless charging of sensor networks, in: Wireless Power Transfer Algorithms, Technologies and Applications in Ad Hoc Communication Networks, Springer, 2016, pp. 433–464.
[178] Y. Wang, M. Hua, Z. Liu, D. Zhang, H. Dai, Y. Hu, Joint scheduling and trajectory design for UAV-aided wireless power transfer system, in: International Conference on 5G for Future Wireless Networks, Springer, 2019, pp. 3–17.
[179] M. Bliss, N. Michelusi, Power-constrained trajectory optimization for wireless UAV relays with random requests, in: ICC 2020-2020 IEEE International Conference on Communications, ICC, IEEE, 2020, pp. 1–6.
[180] Z. Wang, W. Xu, D. Yang, J. Lin, Joint trajectory optimization and user scheduling for rotary-wing UAV-enabled wireless powered communication networks, IEEE Access 7 (2019) 181369–181380.
[181] P. Wu, F. Xiao, C. Sha, H. Huang, L. Sun, Trajectory optimization for UAVs efficient charging in wireless rechargeable sensor networks, IEEE Trans. Veh. Technol. 69 (4) (2020) 4207–4220.
[182] J. Baek, S.I. Han, Y. Han, Optimal UAV route in wireless charging sensor networks, IEEE Internet Things J. 7 (2) (2019) 1327–1335.
[183] J. Zhang, Y. Yu, Z. Wang, S. Ao, J. Tang, X. Zhang, K.-K. Wong, Trajectory planning of UAV in wireless powered IoT system based on deep reinforcement learning, in: 2020 IEEE/CIC International Conference on Communications in China, ICCC, IEEE, 2020, pp. 645–650.
[184] J. Yao, N. Ansari, Qos-aware rechargeable UAV trajectory optimization for sensing service, in: ICC 2019-2019 IEEE International Conference on Communications, ICC, IEEE, 2019, pp. 1–6.
[185] X. Yuan, G. Sun, Y. Hu, L. Wu, H. Wang, A. Schmeink, UAV trajectory design on completion time minimization of WPT task in UAV-enabled multi-user network, in: 2022 IEEE International Conference on Communications Workshops, ICC Workshops, IEEE, 2022, pp. 1047–1052.
[186] Z. An, Y. Liu, G. Sun, H. Pan, A. Wang, UAV-enabled wireless powered communication networks: A joint scheduling and trajectory optimization approach, in: 2022 IEEE Symposium on Computers and Communications, ISCC, IEEE, 2022, pp. 1–7.
[187] H. Tang, Q. Wu, J. Xu, W. Chen, B. Li, A novel alternative optimization method for joint power and trajectory design in UAV-enabled wireless network, IEEE Trans. Veh. Technol. 68 (11) (2019) 11358–11362.
[188] H. Tang, Q. Wu, B. Li, An efficient solution for joint power and trajectory optimization in UAV-enabled wireless network, IEEE Access 7 (2019) 59640–59652.
[189] S. Zhang, S. Shi, S. Gu, X. Gu, Power control and trajectory planning based interference management for UAV-assisted wireless sensor networks, IEEE Access 8 (2019) 3453–3464.
[190] M.-M. Zhao, Q. Shi, M.-J. Zhao, Efficiency maximization for UAV-enabled mobile relaying systems with laser charging, IEEE Trans. Wireless Commun. 19 (5) (2020) 3257–3272.
[191] M. Liu, Y. Wang, Y. Chen, H. Jia, Joint stochastic computational resource and UAV trajectory for wireless-powered space-air-ground IoRT networks, IEEE Access 8 (2020) 193728–193743.
[192] X. Jiang, Z. Wu, Z. Yin, Z. Yang, Joint power and trajectory design for UAV-relayed wireless systems, IEEE Wirel. Commun. Lett. 8 (3) (2018) 697–700.
[193] X. Liu, Y. Liu, Y. Chen, L. Hanzo, Trajectory design and power control for multi-UAV assisted wireless networks: A machine learning approach, IEEE Trans. Veh. Technol. 68 (8) (2019) 7957–7969.
[194] Y. Wei, Z. Bai, Y. Zhu, An energy efficient cooperation design for multi-UAVs enabled wireless powered communication networks, in: 2019 IEEE 90th Vehicular Technology Conference, VTC2019-Fall, IEEE, 2019, pp. 1–5.
[195] X. Li, H. Yao, J. Wang, Y. Liu, Joint node assignment and trajectory optimization for rechargeable multi-UAV aided IoT systems, in: 2019 11th International Conference on Wireless Communications and Signal Processing, WCSP, IEEE, 2019, pp. 1–6.
[196] P. Wu, F. Xiao, H. Huang, R. Wang, Load balance and trajectory design in multi-UAV aided large-scale wireless rechargeable networks, IEEE Trans. Veh. Technol. 69 (11) (2020) 13756–13767.
[197] F. Sangare, A. Arab, M. Pan, L. Qian, S.K. Khator, Z. Han, RF energy harvesting for WSNs via dynamic control of unmanned vehicle charging, in: 2015 IEEE Wireless Communications and Networking Conference, WCNC, IEEE, 2015, pp. 1291–1296.
[198] E. Basha, M. Eiskamp, J. Johnson, C. Detweiler, UAV recharging opportunities and policies for sensor networks, Int. J. Distrib. Sens. Netw. 11 (8) (2015) 824260.
[199] C.-M. Tseng, C.-K. Chau, K.M. Elbassioni, M. Khonji, Flight tour planning with recharging optimization for battery-operated autonomous drones, CoRR, 2017, abs/1703.10049.
[200] Y. Wu, L. Qiu, J. Xu, UAV-enabled wireless power transfer with directional antenna: A two-user case, in: 2018 15th International Symposium on Wireless Communication Systems, ISWCS, IEEE, 2018, pp. 1–6.
[201] C. Caillouet, T. Razafindralambo, D. Zorbas, Recharging wireless sensor networks using drones and wireless power transfer, in: 2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, 2018, pp. 1136–1137.
[202] C. Caillouet, T. Razafindralambo, D. Zorbas, Optimal placement of drones for fast sensor energy replenishment using wireless power transfer, in: 2019 Wireless Days, WD, 2019, pp. 1–6.
[203] C. Caillouet, T. Razafindralambo, D. Zorbas, UAV based wireless charging of sensor networks without prior knowledge, in: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, Madrid, Spain, 2018, pp. 3151–3158.
[204] J. Liu, W. Li, N.B. Shroff, P. Sinha, Energy management for timely charging a system of drones, in: 2019 IEEE 58th Conference on Decision and Control, CDC, IEEE, 2019, pp. 5180–5186.
[205] J. Xu, K. Zhu, R. Wang, RF aerially charging scheduling for UAV fleet: A Q-learning approach, in: 2019 15th International Conference on Mobile Ad-Hoc and Sensor Networks, MSN, IEEE, 2019, pp. 194–199.
[206] C. Su, F. Ye, L.-C. Wang, L. Wang, Y. Tian, Z. Han, UAV-assisted wireless charging for energy-constrained IoT devices using dynamic matching, IEEE Internet Things J. 7 (6) (2020) 4789–4800.
[207] V. Hassija, V. Chamola, D.N.G. Krishna, M. Guizani, A distributed framework for energy trading between UAVs and charging stations for critical applications, IEEE Trans. Veh. Technol. 69 (5) (2020) 5391–5402.
[208] I. Budhiraja, N. Kumar, M. Alazab, S. Tyagi, S. Tanwar, G. Srivastava, Energy management scheme for wireless powered D2D users with NOMA underlaying full duplex UAV, in: Proceedings of the ACM MobiCom Workshop on Drone Assisted Wireless Communications for 5G and beyond, DroneCom, 2020, pp. 7–12.
[209] H. Yan, Y. Chen, S.-H. Yang, UAV-enabled wireless power transfer with base station charging and UAV power consumption, IEEE Trans. Veh. Technol. 69 (11) (2020) 12883–12896.
[210] Y. Yao, Z. Zhu, S. Huang, X. Yue, C. Pan, X. Li, Energy efficiency characterization in heterogeneous IoT system with UAV swarms based on wireless power transfer, IEEE Access 8 (2020) 967–979.
[211] Y. Pang, Y. Zhang, Y. Gu, M. Pan, Z. Han, P. Li, Efficient data collection for wireless rechargeable sensor clusters in harsh terrains using UAVs, in: 2014 IEEE Global Communications Conference, 2014, pp. 234–239.

[212] X. Ma, Z. Na, B. Lin, L. Liu, Energy efficiency optimization of UAV-assisted wireless powered systems for dependable data collections in internet of things, IEEE Trans. Reliab. (2022) 1–11.
[213] I. Yoon, D.K. Noh, Adaptive data collection using UAV with wireless power transfer for wireless rechargeable sensor networks, IEEE Access 10 (2022) 9729–9743.
[214] S. Cho, K. Lee, B. Kang, K. Koo, I. Joe, Weighted harvest-then-transmit: UAV-enabled wireless powered communication networks, IEEE Access 6 (2018) 72212–72224.
[215] S. Vashisht, S. Jain, Software-defined network-enabled opportunistic offloading and charging scheme in multi-unmanned aerial vehicle ecosystem, Int. J. Commun. Syst. (Wiley) 32 (8) (2019) e3939.
[216] S. Lhazmir, O.A. Oualhaj, A. Kobbane, L. Mokdad, A decision-making analysis in UAV-enabled wireless power transfer for IoT networks, Simul. Model. Pract. Theory 103 (102102) (2020).
[217] C.H. Liu, C. Piao, J. Tang, Energy-efficient UAV crowdsensing with multiple charging stations by deep learning, in: IEEE INFOCOM 2020 - IEEE Conference on Computer Communications, 2020, pp. 199–208.
[218] J. Hou, Z. Yang, M. Shikh-Bahaei, Hardware impairment-aware data collection and wireless power transfer using a MIMO full-duplex UAV, in: 2020 IEEE International Conference on Communications Workshops, ICC Workshops, 2020, pp. 1–6.
[219] H. Hu, K. Xiong, G. Qu, Q. Ni, P. Fan, K.B. Letaief, AoI-Minimal trajectory planning and data collection in UAV-assisted wireless powered IoT networks, IEEE Internet Things J. 8 (2) (2021) 1211–1223.
[220] L. Liu, K. Xiong, J. Cao, Y. Lu, P. Fan, K.B. Letaief, Average AoI minimization in UAV-assisted data collection with RF wireless power transfer: A deep reinforcement learning scheme, IEEE Internet Things J. 9 (7) (2021) 5216–5228.
[221] H.-H. Choi, J.-R. Lee, Joint optimization of altitude and beamwidth for UAV-powered wireless sensor networks, IEEE Trans. Veh. Technol. (2022) 1–7.
[222] X. Liu, L. Li, F. Yang, X. Li, W. Chen, W. Xu, Price-based power allocation for multi-UAV enabled wireless networks, in: Proceedings of Wireless and Optical Communications Conference, WOCC, Beijing, China, 2019, pp. 1–5.
[223] A. Tiurlikova, N. Stepanov, K. Mikhaylov, Wireless power transfer from unmanned aerial vehicle to low-power wide area network nodes: Performance and business prospects for LoRaWAN, Int. J. Distrib. Sens. Netw. 15 (11) (2019) 1550147719888165.
[224] Y. Song, Y. Liu, W. Xu, X. Yang, R. Wang, Research on the multiobjective optimization of microwave wireless power receiving in an unmanned aerial vehicle network, Complexity 2020 (2020).
[225] S. Lhazmir, O.A. Oualhaj, A. Kobbane, E.M. Amhoud, J. Ben-Othman, UAV for wireless power transfer in IoT networks: A GMDP approach, in: ICC 2020 - 2020 IEEE International Conference on Communications, ICC, 2020, pp. 1–6.
[226] D. Zorbas, C. Douligeris, Computing optimal drone positions to wirelessly recharge IoT devices, in: IEEE INFOCOM 2018 - IEEE Conference on Computer Communications Workshops, INFOCOM WKSHPS, 2018, pp. 628–633.
[227] J. Du, Z. Wang, Z. Fan, X. Wan, Sum rate maximization for UAV-enabled wireless powered NOMA systems, in: 2020 IEEE/CIC International Conference on Communications in China, ICCC, IEEE, 2020, pp. 753–757.
[228] S. Chen, X. Li, C. Luo, H. Ji, H. Zhang, Energy-efficient power, position and time control in UAV-assisted wireless networks, in: 2019 IEEE Globecom Workshops, GC Wkshps, 2019, pp. 1–6.
[229] L. Li, T.-H. Chang, S. Cai, UAV positioning and power control for wireless two-way relaying, in: 2019 IEEE 20th International Workshop on Signal Processing Advances in Wireless Communications, SPAWC, IEEE, 2019, pp. 1–5.
[230] L. Li, T.-H. Chang, S. Cai, UAV positioning and power control for two-way wireless relaying, IEEE Trans. Wireless Commun. 19 (2) (2020) 1008–1024.
[231] H. Chen, D. Li, Y. Wang, F. Yin, UAV hovering strategy based on a wirelessly powered communication network, IEEE Access 7 (2018) 3194–3205.
[232] S. Li, A. Wang, G. Sun, L. Liu, Improving charging performance for wireless rechargeable sensor networks based on charging UAVs: a joint optimization approach, in: 2020 IEEE Symposium on Computers and Communications, ISCC, 2020, pp. 1–7.
[233] X. Mo, Y. Huang, J. Xu, Radio-map-based robust positioning optimization for UAV-enabled wireless power transfer, IEEE Wirel. Commun. Lett. 9 (2) (2020) 179–183.
[234] O. Esrafilian, R. Gangula, D. Gesbert, Learning to communicate in UAV-aided wireless networks: Map-based approaches, IEEE Internet Things J. 6 (2) (2018) 1791–1802.
[235] S. Bi, J. Lyu, Z. Ding, R. Zhang, Engineering radio maps for wireless resource management, IEEE Wirel. Commun. 26 (2) (2019) 133–141.
[236] M. Shin, J. Kim, M. Levorato, Auction-based charging scheduling with deep learning framework for multi-drone networks, IEEE Trans. Veh. Technol. 68 (5) (2019) 4235–4248.
[237] V. Hassija, V. Saxena, V. Chamola, Scheduling drone charging for multi-drone network based on consensus time-stamp and game theory, Comput. Commun. 149 (2020) 51–61.
[238] G. Ahani, D. Yuan, Y. Zhao, Age-optimal UAV scheduling for data collection with battery recharging, IEEE Commun. Lett. 25 (4) (2020) 1254–1258.
[239] Y. Zhi, Z. Fu, X. Sun, J. Yu, Security and privacy issues of UAV: a survey, Mob. Netw. Appl. 25 (1) (2020) 95–101.
[240] Y. Wang, W. Yang, X. Shang, Y. Cai, Energy-efficient secure transmission for UAV-enabled wireless powered communication, in: 2018 10th International Conference on Wireless Communications and Signal Processing, WCSP, IEEE, 2018, pp. 1–5.
[241] M. Hua, Y. Wang, Q. Wu, H. Dai, Y. Huang, L. Yang, Energy-efficient cooperative secure transmission in multi-UAV-enabled wireless networks, IEEE Trans. Veh. Technol. 68 (8) (2019) 7761–7775.
[242] G. Tang, P. Du, H. Lei, I.S. Ansari, Y. Fu, Trajectory design and communication resources allocation for wireless powered secure UAV communication systems, IEEE Syst. J. (2021).
[243] X. Sun, W. Yang, Y. Cai, R. Ma, L. Tao, Physical layer security in millimeter wave SWIPT UAV-based relay networks, IEEE Access 7 (2019) 35851–35862.
[244] X. Hong, P. Liu, F. Zhou, S. Guo, Z. Chu, Resource allocation for secure UAV-assisted SWIPT systems, IEEE Access 7 (2019) 24248–24257.
[245] S. Li, C. Li, H. Zhong, Secure transmission design for UAV-based SWIPT networks, in: International Conference on Intelligent Robotics and Applications, Springer, 2019, pp. 73–83.
[246] J.-M. Kang, C.-J. Chun, Joint trajectory design, Tx power allocation, and Rx power splitting for UAV-enabled multicasting SWIPT systems, IEEE Syst. J. 14 (3) (2020) 3740–3743.
[247] W. Wang, J. Tang, N. Zhao, X. Liu, X.Y. Zhang, Y. Chen, Y. Qian, Secure transmission for UAV-aided NOMA networks with SWIPT via precoding optimization, in: 2019 11th International Conference on Wireless Communications and Signal Processing, WCSP, IEEE, 2019, pp. 1–6.
[248] Q. Wang, H.-N. Dai, X. Li, M.K. Shukla, M. Imran, Artificial noise aided scheme to secure UAV-assisted internet of things with wireless power transfer, Comput. Commun. 164 (2020) 1–12.
[249] H. Wu, Y. Wen, J. Zhang, Z. Wei, N. Zhang, X. Tao, Energy-efficient and secure air-to-ground communication with jittering UAV, IEEE Trans. Veh. Technol. 69 (4) (2020) 3954–3967.
[250] X. Sun, W. Yang, Y. Cai, M. Wang, Secure mmwave UAV-enabled SWIPT networks based on random frequency diverse arrays, IEEE Internet Things J. 8 (1) (2020) 528–540.
[251] X. Sun, W. Yang, Y. Cai, Z. Xiang, X. Tang, Secure transmissions in millimeter wave SWIPT UAV-based relay networks, IEEE Wirel. Commun. Lett. 8 (3) (2019) 785–788.