Wireless Powering Internet of Things with UAVs: Challenges and Opportunities

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***Abstract*—Unmanned aerial vehicles (UAVs) have the potential to overcome the deployment constraint of Internet of Things (IoT) in remote or rural area. Wireless powered communications (WPC) can address the battery limitation of IoT devices through transferring wireless power to IoT devices. The integration of UAVs and WPC, namely UAV-enabled Wireless Powering IoT (Ue-WPIoT) can greatly extend the application scenarios of IoT from cities to remote or rural areas. In this article, we present a state-of-the-art overview of Ue-WPIoT by first illustrating the working flow of Ue-WPIoT and discussing the challenges. We then introduce the enabling technologies in realizing Ue-WPIoT. Simulation results validate the effectiveness of the enabling technologies in Ue-WPIoT. We finally outline the future directions and open issues.**

I. Introduction

We have witnessed the proliferation of IoT, which has been widely adopted in diverse urban applications, such as smart home, smart healthcare, smart industry, smart grid. IoT has been typically deployed in the scenarios with the availability of communications infrastructure, such as base stations, access points and IoT gateways [?]. However, the deployment and maintenance of infrastructure nodes inevitably bring huge operational expenditure. Moreover, it is difficult to deploy wireless infrastructure nodes at remote or rural area (e.g., forest surveillance and livestock monitoring). In addition, IoT devices are also life-limited due to their built-in battery limitations. These two fundamental constraints of IoT prevent its wide deployment in remote scenarios.

The recent advances in UAVs bring opportunities to overcome the limitations of IoT. Related work has regard UAVs as elastic communication nodes to increase the communication coverage and enhance the network capacity [?]. Especially, UAVs have the dominant advantage in air mobility when compared with ground vehicles. Then UAVs can be flexibly dispatched to remote, rural or disaster with complex-geographical regions where the ground vehicles can hardly or cannot directly reach [?]. Hence, UAVs can potentially develop remote IoT applications such as environment monitoring, weather forecast and emergency communication in such complex-geographic regions.

Radio frequency (RF)-based WPT is a promising method to prolong the life-term of the battery-limited nodes. In previous literature, RF-WPT has been presented to support wireless communications, i.e., WPC [?]. Particularly, WPC has two main application scenarios: WPC networks and simultaneous wireless information and power transfer (SWIPT). In WPC networks, IoT nodes first harvest wireless energy, which is then used for data transmission. SWIPT aiming to achieve WPT and information transmission simultaneously in the same channel has a critical hardware requirement on IoT nodes. Therefore, WPC is more preferred for energy-limited IoT devices, thereby overcoming the second constraint of IoT.

The integration of UAVs with WPC has opportunities to greatly extend the application scenarios of IoT from cities to remote or rural areas [?]. Combining with WPC, a UAV has capability to supply energy to IoT nodes with limited battery capacity for their data transmission. We name such UAV-enabled wireless powering Internet of Things as Ue-WPIoT. However, the realization of Ue-WPIoT suffers a number of challenges including limited powering range, energy efficiency improving, multi-node scheduling. This article aims at investigating a promising solution for realizing Ue-WPIoT. As a summery, we have the following contributions.

- We first present Ue-WPIoT to flexibly support ground-air communications in remote IoT applications. In Ue-WPIoT, IoT nodes are first activated flexibly by the UAV and then harvest energy from the UAV to transmit their data. Thus, all IoT nodes can save their energy from idle listening. In addition, the UAV has dedicated configurations including sufficient battery capacity, multiple antenna elements, and even auto-navigation capability. Consequently, our UAV is capable to support the long flight time, efficient WPT, and normal flight in complex-geographical environments of remote areas.
- We then discuss three rising challenges in realizing Ue-WPIoT. First, the RF-based WPT usually experiences high attenuation over a distance, thereby limiting the effective communication range. Second, the overall energy consumption during WPT and data transmission needs to be optimized. Third, a UAV may serve for multiple nodes through transmitting wireless energy to multiple nodes, which can transmit data packets to the UAV via multi-access schemes. Hence, the trajectory design of UAVs needs to be optimized after the joint consideration of these factors.
- We next introduce enabling technologies to address the discus challenges in realizing Ue-WPIoT. Specifically, we adopt the adaptive energy beam-forming technologies in the UAV, thereby prolonging the powering distance.

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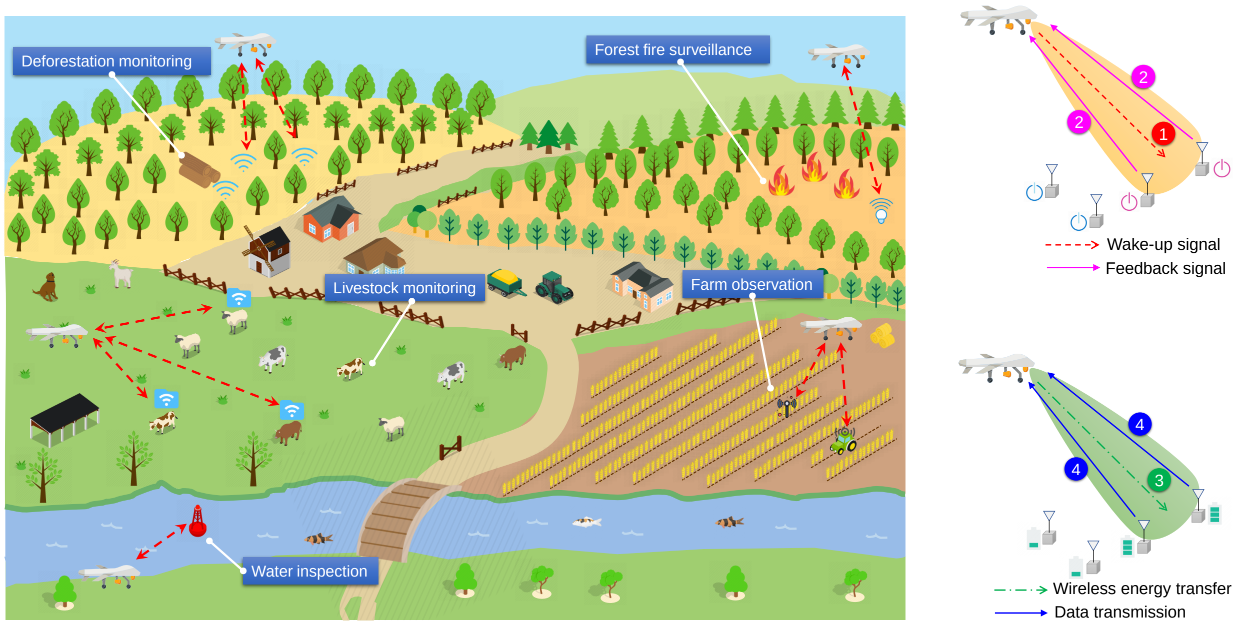


Fig. 1. An overview of Ue-WPIoT

Then, we present a common optimization model to find the optimal resource allocation for improving overall energy efficiency in Ue-WPIoT communications. Finally, we design the optimal flying trajectory of the UAV to find the shortest path under ensuring WPC performance of all IoT nodes. The numerical results also validate the effectiveness of the promising technologies. We also outline some open issues for future directions.

II. UAV-enabled Wireless Powering IoT

In this section, we present the working flow of a specific Ue-WPIoT communication and discuss the design challenges in the realization of Ue-WPIoT.

A. Working flow

As shown in Fig. 1, we adopt the fixed-wing UAV with the dedicated payload configurations to achieve Ue-WPIoT with a long flight time in remote scenarios. Except for the essential payload in battery capacity and flight system, we also configure the UAV with all required hardware payloads for flying, powering, and communications. These payloads consist of the battery with sufficient capacity for the whole flight process, and multiple antenna elements for efficient powering and communications. Additionally, our UAV also deploys robust auto-navigation to assist its obstacle avoidance, since it suffers a low-altitude flying environment with the account for better-powering performance. Even though so many configurations, our UAV can keep a medium-size shape compared with the traditional large-size UAVs for military usage [?]. Hence, the UAV has flexible mobility so as to perform a variety of low-altitude applications including forest deforestation monitoring, livestock monitoring, water inspection, farm observation, and forest fire surveillance [?].

Fig. 1 also shows the working flow of a specific Ue-WPIoT communication as follows: 1) *Wake-up procedure.* Since IoT nodes have usually been in sleeping or hibernating mode to save energy, the UAV wakes up IoT nodes by transmitting the Wake-up Radio (WuR) signals [?] (*i.e.*, Step ① as shown in Fig. 1b). Then IoT nodes can be activated when they detect enough power from the wake-up radio signals. The activated IoT nodes transmit the feedback signals to the UAV which can then identify the activated IoT nodes (*i.e.*, Step ② as shown in Fig. 1b). In the Ue-WPIoT system, each UAV is equipped with a multi-antenna-element array, which can effectively differentiate arrivals of multiple feedback signals and locate the precise orientation of each IoT node [?]. 2) *Wireless powering and data transmission.* The UAV next transfers wireless energy toward the activated IoT nodes. With an antenna array, the UAV is capable of generating a sharp beam-forming toward IoT nodes, thereby improving the wireless powering efficiency of IoT nodes [?] (*i.e.*, Step ③ as shown in Fig. 1c). IoT nodes can leverage the harvested energy to transmit the data to the UAV (*i.e.*, Step ④ as shown in Fig. 1c).

During the above procedure, Steps ① and ② can locate and then activate the IoT nodes, thereby paving the way for the following wireless power transfer and data transmission. It is worth mentioning that the performance of data transmission greatly relies on the harvested energy in the previous wireless powering step. Thereafter, IoT nodes can harvest enough energy from the UAV (i.e., Step ③) to support the data transmission in Step ④. Ue-WPIoT can essentially support multiple concurrent communications since multiple nodes can be activated as the same time when they are close to each other. In this case, a multi-access mechanism (e.g., time-division-multiple-access, spatial division-multiple-access) shall be adopted to support multiple concurrent communications with different IoT nodes. We will further introduce a detailed working design for multi-access communications in Section III-B.

B. Design Challenges

Ue-WPIoT can promote the wide adoption of UAVs to connect IoT nodes in remote or rural area while the realization of Ue-WPIoT is faced with the following design challenges.

- *Feasible Communication Range.* Generally, WPT has a much shorter range than data transmission as indicated in [?]. Thus, the feasible communication range of Ue-WPIoT is essentially limited by the achievable WET range. The communication range constraint may limit the wide application of Ue-WPIoT in different scenarios.
- *Energy-efficiency optimization.* The UAV is required to support both flight propulsion and Ue-WPIoT communications with limited battery capacity. Hence, improving the energy efficiency in the whole Ue-WPIoT communication is imperative for the UAV. For this reason, we meet a challenge of energy-efficiency optimization for seeking an optimal allocation on both flight time and communication resources.
- *Flying Trajectory Design.* In Ue-WPIoT, a UAV is expected to serve WPC for multiple IoT nodes in a wide area. Meanwhile, the serving period for multiple nodes of the UAV is constrained by a maximum flight time, because of the limited battery. Thus, it is challenging to design a suitable flying trajectory of UAVs with the joint consideration of multiple factors, such as multi-node access, multi-task scheduling and the flight time.

III. Enabling Technologies

This section discusses several enabling technologies to address the above challenges of Ue-WPIoT. Table I summarizes the state-of-the-art solutions in different aspects.

A. Adaptive Energy Beamforming

Ue-WPIoT is suffering from the limited communication range, which is mainly constrained by the WET range. The fundamental limitation of the WET range lies in much higher threshold for energy harvesting (EH) than that for information decoding [?]. The advent of energy beam-forming (BF) technology brings opportunities to overcome this limitation. In particular, the energy transmitter employing multiple antenna elements can generate the BF radio in a certain direction. Thereby, a focused energy is formed to prolong the powering distance.

In Ue-WPIoT, to serving energy BF for different IoT nodes, we adopt the adaptive energy BF technology in the UAV. Specifically, a UAV needs to employ multiple antenna elements thereby generating BF radio signal toward different IoT nodes. The adaptive BF is usually constructed via the prior-knowledge of channel state information (CSI), which can be obtained after analysing the feedback signals from the activated IoT nodes (i.e., Step ②). In addition, the adaptive BF vector can be optimized by maximizing the harvested power of the IoT nodes as in [?].

Furthermore, sensitivity configurations of EH circuits at IoT devices can also extend the powering distance [?]. Specifically, the sensitivity improving can be achieved via different dedicated hardware adjustments (including antenna, frequency, modulation, digital-analogy circuit module). Herein, we mainly introduce the adjustment of the radio frequency. In previous studies, most of prototypes of WuRs/energy harvesters are based on the frequency about 2.4GHz, 400MHz, and 900MHz, where 2.4GHz-based circuits are more compatible for 802.11-based wireless communication networks, while 400MHz or 900MHz based circuits may result in longer communication range.

B. Resource Allocation and Optimization

The Ue-WPIoT communication is susceptible to the channel fluctuation and path loss effect since the IoT node can only transmit their data after harvesting enough wireless energy from the UAV. Meanwhile, different IoT nodes may gain the varied portion of wireless energy due to various air-to-ground (A2G) channels. Thus, it is necessary to design optimal resource allocation strategies for both UAVs and IoT nodes for improving energy efficiency of the entire Ue-WPIoT system.

We introduce a common optimization model with the objective of minimizing the joint energy-and-latency cost during a Ue-WPIoT communication period. The energy cost is the total supplied energy emitted from the UAV, and the latency cost is the overall communication latency (that also is the UAV's flight time during this period). The optimization is subject to some constraints including the *sufficient harvested energy* to ensure the successful data transmission, *limited communication latency* to ensure an efficient communication task, and also the feasible value ranges for specific parameters (such as energy transferring power). The variables to be optimized may consist of, the energy BF signal that can be controlled by the UAV to ensure the optimal orientation and power, the wireless powering duration that also can be adjusted by the UAV, and the data transmission power at the IoT node. Our previous work shows a detailed optimization scheme for resource allocation of using UAVs to enable directional WPT and data acquisition [?].

The resource allocation result in our model may have some adjustments for practical applying. For instance, for the case that multiple neighboring nodes may be simultaneously activated by one UAV, the optimal allocation needs to be adjusted to achieve multi-node powering and multi-node access. First, for concurrent multi-node powering, the energy BF vector needs to be re-optimized by jointly considering the maximized received power in multiple nodes. Then, since multiple nodes may have different allocation values in both the powering duration and data transmitting power, the UAV requires a task scheduling for multi-access data transmission. Especially when using time-division-multiple-address (TDMA), the UAV needs to schedule the access time slot for every node. Furthermore, the data transmissions of multiple nodes can be achieved concurrently by using space-division multiple access (SDMA) or orthogonal frequency-division multiple access (OFDMA) that can support independent multiple accesses [?]. Moreover, the UAV's position can also be a variable to be optimized based on the same constraints aforementioned, with the objective of minimizing the flight length/time. We will give the specific trajectory optimization strategies in the next subsection.

TABLE I. Summary of Enabling Technologies to Address Ue-WPIoT Challenges

Challenges	**Enabling Technologies**
Feasible Communication Range	Adaptive energy beam-forming
Energy-efficiency optimization	Resource allocation and optimization
Flying trajectory design	Joint trajectory optimization of multi-access and critical nodes

C. UAV Trajectory Design

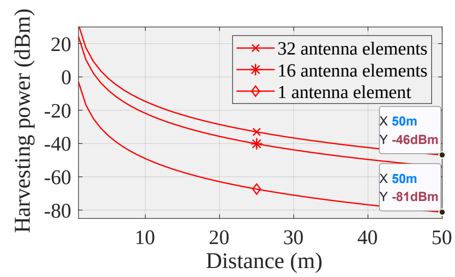
In UAV-assisted networks, the UAV trajectory is usually designed to extend coverage or schedule multi-node communications [?], [?]. In this paper, our trajectory design needs to consider not only multi-node coverage but also the WPC performance of each node. First, the designed flying trajectory is required to be as short as possible to save the global flight time. Importantly, the designed trajectory needs to be completed under the maximum flight time of the UAV. Second, not all IoT nodes need to be traveled by the UAV. Because some nodes can concurrently transmit data to the UAV due to their dense distribution as discussed in Section III-B, we call these nodes as a cluster. In each cluster, the UAV can just select one node to travel while the other nodes can concurrently communicate with the UAV.

Therefore, our trajectory can be optimized as the shortest path to travel a series of selected IoT nodes. The un-selected nodes are filtered due to they can be served communications concurrently when the UAV travels to the selected IoT nodes. Intuitively, with the account for the multi-node cluster, our trajectory has a shorter path than a simple shortest path that travels every node in a one-by-one manner. In previous work, there is a similar trajectory design with us in Ref. [?] that considers the use of UAVs to data collection from the ground. The authors in Ref. [?] investigate the joint route planning and task assignment for mobile crowd sensing of several regions. In contrast, our work focuses on serving multiple nodes with WPC tasks, in which different clusters that need to be traveled are formed by the feasible powering range of the UAV.

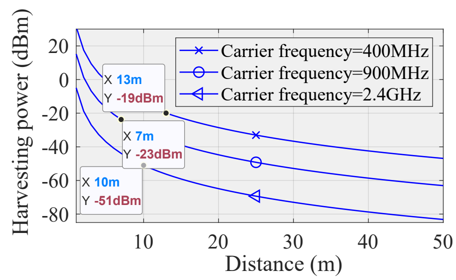
Theoretically, the maximum powering distance denoted by d_{EH} is nearly fixed when giving the input power threshold of the EH circuit. Then, for the UAV with height denoted by H, its horizontal coverage range is a ground circle underneath the UAV with the radius $R = \sqrt{d_{EH}^2 - H^2}$. Hence, we can confirm that all nodes in this circle form a cluster; these nodes can communicate with the UAV concurrently. In this context, the lower height of the UAV leads to a larger serving circle, which means more IoT nodes can be served as a cluster. Consequently, in our trajectory design, the lower height of the UAV can lead to a shorter path length due to the more IoT nodes no need to travel.

IV. Numerical Results and Analysis

This section provides numerical results to demonstrate the effectiveness of enabling technologies mainly from two aspects.



(a) Under carrier frequency 400MHz



(b) Under 32 antenna elements

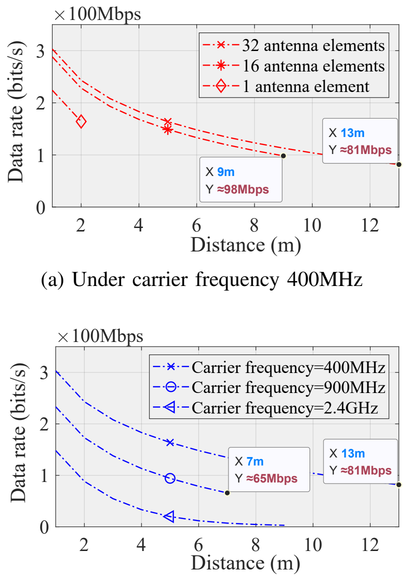
Fig. 2. Harvested power at the IoT node versus the distance, carrier frequency and number of antenna elements, with the energy transmitting power being 10W and the energy conversion efficiency being 0.3.

A. Achievable EH distance and Data rate

We first present simulation results on the achievable EH distance and the data transmission rate in Ue-WPIoT. We consider that an IoT node can harvest the wireless energy emitted by one UAV and consequently use the harvested energy to transmit the sensory data to the UAV. It is worth mentioning that the achievable EH distance (i.e., the maximum WET range) can be derived by analyzing the radio propagation condition between the UAV and one IoT node. The data rate can be obtained by solving the optimization problem of minimizing overall energy consumption of the UAV for WET. In this case, the achievable data rate is simulated by substituting the optimal data transmitting power into Shannon theory, where the optimal data transmitting power is directly determined by the harvested power.

In our simulations, the A2G channel model is determined by the probability-based Line of Sight (LoS)/Non Line of Sight (NLoS) path loss under suburban geographical parameters. It is worth mentioning that the LoS component usually dominates the A2G channel. In Ue-WPIoT, NLoS component can make the channel model more tractable, since the limited powering range leads to the low-altitude applications suffering widespread obstacles (such as plants, rocks). The energy transmitting power at the UAV is fixed at 10W. The energy conversion efficiency at the IoT node is set as 0.3. The communication bandwidth for data transmission is 15MHz. We choose different settings of the adaptive energy beam-forming technology (as discussed in Section III-A) to evaluate the performance in terms of the achievable powering distance and data rate.

1) We consider that a UAV is equipped with a smart antenna with different numbers of antenna elements. In particular,



(a) Under carrier frequency 400MHz

(b) Under 32 antenna elements

Fig. 3. Achievable data rate versus the distance, carrier frequency and antenna elements, with the bandwidth being 15MHz.

we denote the number of antenna elements of the smart antenna by N, which is equal to 1, 16, and 32, where 1 antenna element denotes a single isotropic antenna (or omnidirectional antenna); $N = 16$ and $N = 32$ represent 16 antenna elements and 32 antenna elements, respectively. Generally, the more antenna elements imply the higher antenna gain (the more directivity toward a direction).

2) We adopt three carrier frequencies, 400MHz, 900MHz, and 2.4GHz for WPT. Note that each IoT receiver (i.e., energy harvester) has its input power threshold corresponding to the different carrier frequencies. In particular, as indicated in latest studies [**?**], the 400MHz-based energy harvester requires the input power at least -20dBm, while the 900MHz-based energy harvester and the 2.4GHz-based energy harvester can support the input power threshold of -23dBm and -50dBm, respectively.

Note that, we adopt the above setting to combine different antenna elements and different carrier frequencies for better powering performance. The practical UAV needs to configure the corresponding antenna payload to experiment with our system. Such an experiment may be a new trial compared with the existing studies.

Fig. 2 presents the harvested power at IoT node versus the distance with varied carrier frequencies and different numbers of antenna elements. In particular, Fig. 2a plots the harvested power at IoT node versus the distance when the carrier frequency is fixed at 400MHz. We observe from Fig. 2a that the harvested power drops dramatically with the increased distance due to the path loss effect over the long distance. Moreover, Fig. 2a also shows that the increased number of antenna elements can counteract the path loss effect. For example, when the number of antenna elements is 32, the harvested power at 10m is still above -20dBm (i.e., the threshold of input circuit at the harvester) while omnidirectional antenna does not reach this threshold. This is because the more antenna elements implies the higher antenna gain (i.e., the more directivity of an antenna).

Moreover, the carrier frequency also affects the harvested power. Fig. 2b plots the harvested power at IoT node versus the distance when the number of antenna elements is fixed at 32. We observe from Fig. 2b that the lower frequency can lead to a longer achievable energy harvested range. For example, the achievable EH distance is 13m when the carrier frequency is 400MHz and the minimum input power -19m.

Fig. 3 presents the achievable data rate versus the distance with varied carrier frequencies and different numbers of antenna elements. Obviously, the achievable data rate has a similar trend to the harvested power. In particular, Fig. 3a plots the achievable data rate when the carrier frequency is fixed at 400MHz. We also find that the achievable data transmission rate decreases with the increased distance due the path loss effect while the more antenna elements can compensate for the path loss. Fig. 3b plots the achievable data rate versus the distance when the number of the antenna elements is fixed to 32. We have similar findings to the harvested power, that is, the lower carrier frequency can compensate for the data rate loss. It is observed that the magnitude of all simulated values of data rate ranges in tens of Mbps. This is because the data rate is the weighted combination of the system bandwidth (i.e., 15MHz here) and also the logarithm related to the signal-to-noise ratio. For practical applications with specific data rate, our system can adjust the bandwidth or choose the specific coding forms to cater to specific requirements of data rate.

B. Trajectory Design for multi-node communications

We next conduct simulations to analyze the UAV trajectory with consideration of multi-node communications. In particular, our experiments were conducted in a $100\text{m} \times 100\text{m}$ area where the IoT nodes are randomly distributed with density of 0.25, as shown in Fig. 4. Implied by the results in Section IV-A, we consider the following optimal settings: 1) the maximum EH distance being given by $d_{EH} = 13\text{m}$, 2) the smart antenna consisting of 32 antenna elements, 3) the carrier frequency being fixed at 400MHz.

We consider the following three trajectory strategies: 1) the shortest-path trajectory when the UAV covers all IoT nodes in one-by-one manner; 2 the designed shortest-path trajectory with multi-node communications when the UAV hovers at height being 10m to serve multiple IoT nodes within the same achievable EH distance d_{EH}; 3) the designed shortest-path trajectory with multi-node communications when the UAV hovers at height being 5m to serve multiple IoT nodes within the same achievable EH distance d_{EH}. Regarding strategies 2) and 3), the horizontal coverage range of the UAV can be derived by the triangular relation. Specifically, given $H = 5\text{m}, 10\text{m}$ in strategies 2) and 3), the corresponding horizontal coverage range $R = \sqrt{13^2 - 10^2} \approx 8.31\text{m}$ and $R = \sqrt{13^2 - 5^2} = 12\text{m}$, respectively.

Fig. 4 compares three trajectory strategies. It is observed that strategy 2) and strategy 3) correspond to the travelling path length of 427.7429m and 400.8843m when the flying

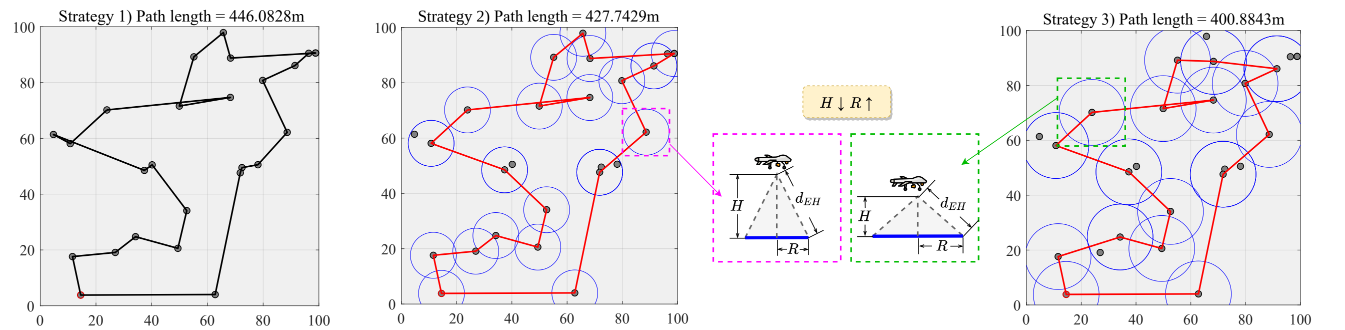


Fig. 4. The UAV trajectory in the 100m $\times$ 100m area with the nodes density being 0.25, where the blue circle denotes the achievable powering range.

height is $H = 5\text{m}, 10\text{m}$, respectively. In contrast, the travelling path length in strategy 1) is 446.0828m, which is much longer than those in strategies 2) and 3). This is because our trajectory design with consideration of multi-node communications can serve for multiple nodes for one Ue-WPIoT procedure while the conventional one-by-one shortest path strategy can only cover one node at a time. In addition, comparing strategies 2) and 3), we can observe that the travelling path length of strategy 3) is even shorter than that of strategy 2). The reason may lie in more nodes to be served in strategy 3) when the horizontal coverage range $R = 12\text{m}$, which is longer than $R \approx 8.31\text{m}$ of strategy 2), thereby further shortening the travelling path.

V. Conclusion and Future Directions

In this article, we present an overview of UAV-enabled wireless powering Internet of Things (Ue-WPIoT), which can potentially overcome two major constraints of IoT: 1) energy constraint of IoT nodes and 2) difficulty in deploying and maintaining infrastructure nodes in remote or rural area. We then elaborate the design challenges of Ue-WPIoT and discuss the enabling technologies to address these challenges. Simulation results validate the effectiveness of the presented solutions. We outline several future directions in Ue-WPIoT as follows.

A. Resource limitation of UAVs

In Ue-WPIoT, UAVs are serving as both energy suppliers and data collectors. Although the optimization of wireless energy transferring and data collection processes can somehow save energy of UAVs, UAVs still suffer from a substantial energy consumption. Energy charging or fuel filling may severely affect the trajectory and the coverage of UAVs, especially in the remote and rural area. Thus, energy-harvesting UAVs from ambience will be an important future direction. The possible energy-harvesting technologies for UAVs include energy harvesting from solar panels and the adoption of windmilling propellers.

B. Trajectory Privacy Protection

The trajectory information of UAVs is a prerequisite for the effective control, efficient route planning and navigation, especially in adverse weathers or disaster situations. However, UAVs can be vulnerable to malicious attacks such as hijacking after stealing or intercepting the trajectory information [**?**]. For example, UAVs can be tracked, intercepted and even hijacked once the trajectories of UAVs are exposed to malicious users [**?**]. Moreover, the behaviours of UAV users can be tracked and deduced through analysing the trajectories of UAVs. Therefore, the trajectory privacy protection of UAVs will be an important future direction.

C. Intelligent Algorithms for Trajectory Design of UAVs

As analyzed in the earlier part of this article, the trajectory of UAVs in Ue-WPIoT needs to consider multiple factors, such as multi-node communications and priority of data collection tasks. However, it is challenging to design optimal trajectories for UAVs with consideration of all these factors together. In addition, the dynamicity of IoT (e.g., the failure of some IoT nodes) makes the situation even worse, i.e., the pre-designed trajectory needs to be adjusted. The advent of AI, deep learning, reinforcement learning brings the opportunities to address this rising challenge. The lightweight or portable AI models are expected to be designed for UAVs in the future.

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