drones

Communication

UAV-Aided Wireless Energy Transfer for Sustaining Internet of Everything in 6G

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Abstract: Unmanned aerial vehicles (UAVs) are a promising technology used to provide on-demand wireless energy transfer (WET) and sustain various low-power ground devices (GDs) for the Internet of Everything (IoE) in sixth generation (6G) wireless networks. However, an individual UAV has limited battery energy, which may confine the required wide-range mobility in a complex IoE scenario. Furthermore, the heterogeneous GDs in IoE applications have distinct non-linear energy harvesting (EH) properties and diversified energy and/or communication demands, which poses new requirements on the WET and trajectory design of UAVs. In this article, to reflect the non-linear EH properties of GDs, we propose the UAV's effective-WET zone (E-zone) above each GD, where a GD is assured to harvest non-zero energy from the UAV only when the UAV transmits into the E-zone. We then introduce the free space optics (FSO) powered UAV with enhanced mobility, and propose its adaptive WET for the GDs with non-linear EH. Considering the time urgency of the different energy demands of the GDs, we propose a new metric called the energy latency time, which is the time duration that a GD can wait before becoming fully charged. By proposing the energy-demand aware UAV trajectory, we further present a novel hierarchical WET scheme to meet the GDs' diversified energy latency time. Moreover, to efficiently sustain IoE communications, the multi-UAV enabled WET is employed by unleashing their cooperative diversity gain and the joint design with the wireless information transfer (WIT). The numerical results show that our proposed multi-UAV cooperative WET scheme under the energy-aware trajectory design achieves the shortest task completion time as compared to the state-of-the-art benchmarks. Finally, the new directions for future research are also provided.

Keywords: unmanned aerial vehicles (UAV); wireless energy transfer (WET); free space optics (FSO) powered UAV; diversified energy/communication demands; demand aware UAV trajectory; adaptive and cooperative WET

Citation: Che, Y.; Zhao, Z.; Luo, S.; Wu, K.; Duan, L.; Leung. V.C.M. UAV-Aided Wireless Energy Transfer for Sustaining Internet of Everything in 6G. *Drones* **2023**, 7, 628. https://doi.org/10.3390/drones7100628

Academic Editors: Wenzheng Xu, Tang Liu and Weifa Liang

Received: 18 September 2023
Revised: 1 October 2023
Accepted: 6 October 2023
Published: 9 October 2023

1. Introduction

With the proliferation of heterogeneous wireless devices (e.g., smart wearables, extended reality devices, and robotics), a number of innovative Internet of Everything (IoE) applications are emerging, yielding self-sustaining and intelligent wireless networks. As a key enabling technology in the sixth generation (6G) era, the wireless energy transfer (WET) over radio frequency (RF) spectrum promises self-sustainable network connections for the low-power ground devices (GDs) in the requisite IoE scenario [1]. However, due to the severe RF power decrease over the transmission distance, the low end-to-end energy transmission efficiency bottlenecks the performance of the WET [2]. To compensate for the resultant deficiency in the wireless power coverage, an ultra-dense deployment of the terrestrial power beacons (PBs) is required [3]. This, without any doubt, would tremendously increase the WET system's deployment and operational costs. Such a bulk terrestrial WET system with fixed PB locations is also hard to promptly sustain various GDs with different energy harvesting (EH) properties and dynamic IoE connections in 6G.

Recently, the rapid growth of unmanned aerial vehicles (UAVs) has brought in fertile wireless applications across the three-dimensional (3D) space [4–6]. UAVs can be efficiently commanded and controlled remotely by connecting to the ground base stations (BSs) [7]. As validated by the field test in Ref. [8], the UAV-aided WET can effectively prolong the lifetime of the low-power GDs, due to their line-of-sight (LoS) dominant air-to-ground (A2G) channels. By exploiting the UAV's flexible mobility to shorten its transmission distance to the GDs, the UAV-aided WET is shown to achieve much higher energy transmission efficiency than the terrestrial counterpart [9]. Therefore, the UAV-aided WET has attracted a great deal of research attention [10]. As illustrated in Figure 1, it is envisioned that the UAV-enabled mobile wireless power grids can be developed in the air to flexibly sustain various IoE applications. For example, UAVs can agilely respond to the unexpected or urgent energy demands (e.g., from a smart factory), or efficiently sustain the wireless information transfer (WIT) of heterogeneous GDs (such as low-power wildlife detectors in forests), where ground PBs are not readily available or expensive to deploy.

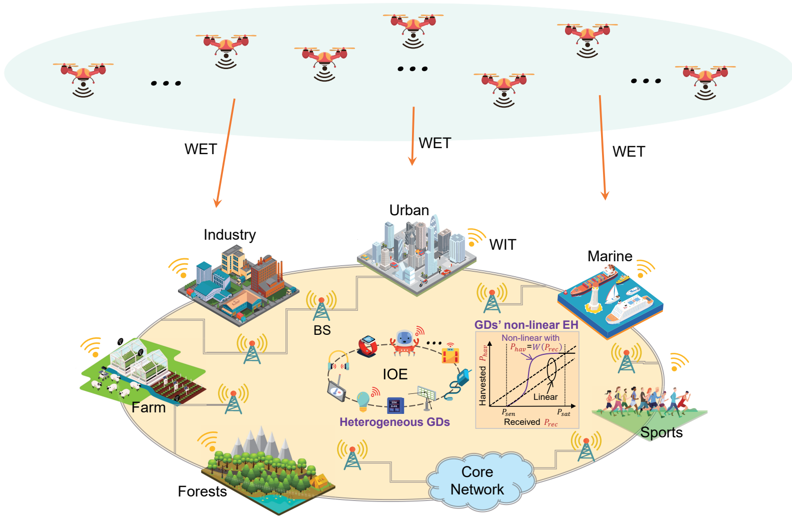

Figure 1. UAV-enabled mobile wireless power grids in the air: The UAVs transmit wireless energy to heterogeneous GDs with non-linear EH in various application scenarios, to satisfy their diversified energy and/or communication demands in the IoE-driven 6G network.

However, to cater to the prevailing IoE applications in the 6G networks, it is still arduous to implement the UAV-aided WET practically and efficiently. First, as discussed in Ref. [11], GDs normally have non-linear EH circuits with high power sensitivity in practice, which requires the UAV to fly very close to each GD to assure effective WET. However, due to the limited on-board size of UAVs, the UAV's available battery energy is severely constrained. Since the UAV's consumed propulsion power to support its mobility is significantly higher than its maximally allowable transmit power (e.g., 1 KW [12] versus 200 mW [11]), the UAV's expected mobility to assure effective WET to the GDs with non-linear EH might not be achievable due to its limited battery energy. As a result, how to enhance the UAV's mobility for effective WET, where the GD's complicated non-linear EH characteristics can be properly blended into the design of the UAV's WET and trajectory, is a key problem to solve. Second, in the IoE scenario, the GDs usually have diversified energy demands, due to their different application and/or communication requirements. This then poses another challenging problem, i.e., how to adaptively supervise the UAVs to perform effective WET to the heterogeneous GDs according to their diversified energy demands. Third, in the future 6G era with the coexistence of wireless energy and information transmissions, it is also of paramount importance to note that the UAV-aided WET may be hindered from efficiently merging into the future 6G communications, if not addressed properly by the above two practical problems.

Considering the above new issues for the effective WET of UAVs in the future IoE-driven wireless networks, this article aims to first identify their key technical challenges and then propose promising solutions to tackle them. It is noted that the important UAV battery energy constraint is usually interpreted as a simple mission time constraint in the literature (see, e.g., Ref. [10]). Since the UAV's propulsion power consumption varies largely over its flying velocity, the UAV's feasible mission time may change tremendously under a given battery energy constraint [12]. Hence, the existing solutions on the UAV's WET under a mission time constraint may become ineffective to meet the more challenging battery energy constraint in practice. It is also noted that only limited works [11,13,14], have considered the GD's non-linear EH for the UAV's WET. Moreover, to the best of our knowledge, the diversified energy demands of GDs have not been considered in the WET related literature of UAVs. As such, it is necessary to revisit the conventional techniques for the UAV-aided WET and design new solutions for sustaining future wireless networks in an effective way.

Our main contributions are summarized as follows. In this article, to reflect the non-linear EH properties of GDs, we propose the novel effective-WET zone (E-zone) for the UAV to charge each GD. Considering the time urgency of the different energy demands of GDs, we also propose a new metric called the energy latency time. The key design problems and the challenges of the UAV-aided WET by applying the UAV's E-zones to meet the GDs' diversified energy latency time and required energy amounts, as well as the issue to integrate of the UAV-aided WET into the 6G communication, are all discussed. To address these issues, three novel solution ideas are proposed: (1) the free space optics (FSO) powered UAV with adaptive WET to meet the GDs' different non-linear EH properties; (2) the UAV's hierarchical WET scheme to cater to the GDs' diversified energy demands; and (3) the multi-UAV aided WET and wireless information transfer (WIT) with their cooperative trajectory designs to sustain the GDs' communications. Numerical results are also provided to corroborate the superiority of our proposed solution ideas by comparing them with the state-of-the-art approaches. Finally, the new directions for future research are provided.

2. Key Challenges

This section identifies the key challenges of using the UAV-aided WET to realize self-sustainable IoE connections.

2.1. Adaptation to the Non-Linear EH of GDs

The EH model at each GD is crucial for determining its EH performance. Most of the existing studies adopted a linear EH model [15–17], as shown in Figure 1. However, it is generally non-linear at a GD to transform its received RF signal power P_{rec} at the rectenna into the harvested power P_{harv} in direct current (DC). By focusing on harvesting energy in unit time, we use the terms of power harvesting and EH interchangeably in this article. The recent study of Ref. [18] showed that such non-linear EH at a GD can be properly captured by a non-linear EH model, which includes non-zero power sensitivity P_{sen}, a power saturation threshold P_{sat}, and a non-linear power transform function $W(\cdot)$, as illustrated in Figure 1. It is also observed that P_{sen} usually has a large value (e.g., -10 dBm) [19]. This requires the UAV to fly sufficiently close to the GD to assure the GD's non-zero EH.

To capture the GD's non-linear EH properties, we propose a circular region above each GD, such that the GD's received power from the UAV's WET is equal to its power sensitivity when the UAV locates exactly at the edge of the circular region. We refer to such a circular region as the UAV's effective-WET zone (E-zone). A GD is assured to harvest non-zero energy from the UAV's effective WET only when the UAV flies into the E-zone above the GD. Projections of the UAV's E-zones on ground for each of the GDs are depicted in Figures 2–4 to help their illustrations, where the distance from the UAV's ground location to a GD must be no larger than the E-zone radius to enable its effective WET. Moreover, as controlled by the non-linear power transform function $W(\cdot)$ shown in Figure 1, when the UAV locates within its E-zone above a GD, slightly shortening their distance or increasing the UAV's transmit power may help increase the GD's harvested RF power significantly, and vice versa.

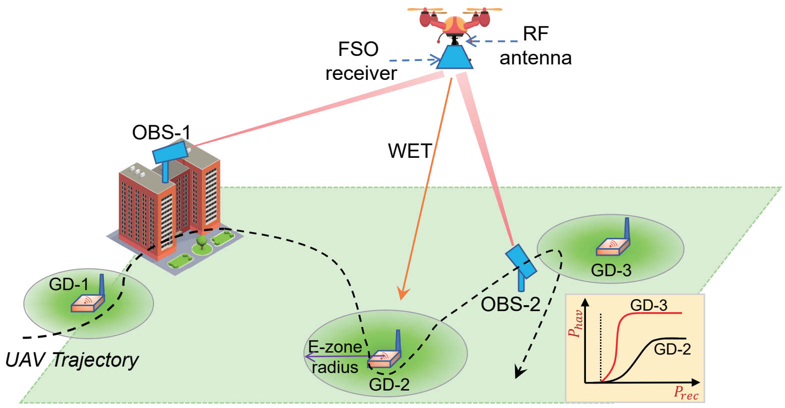

Figure 2. FSO-powered UAV performs effective and adaptive WET to the GDs.

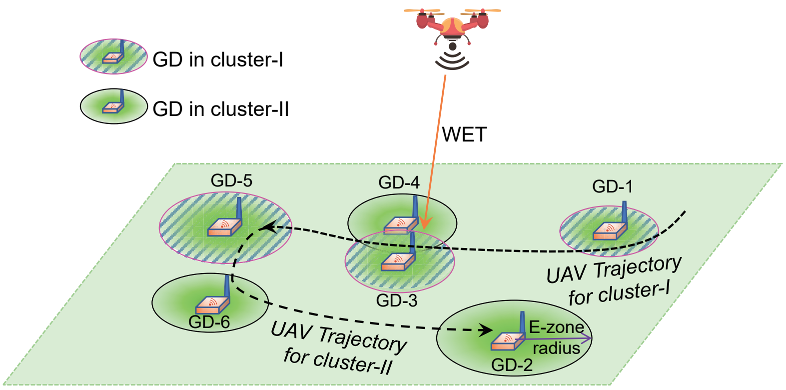

Figure 3. UAV's hierarchical WET.

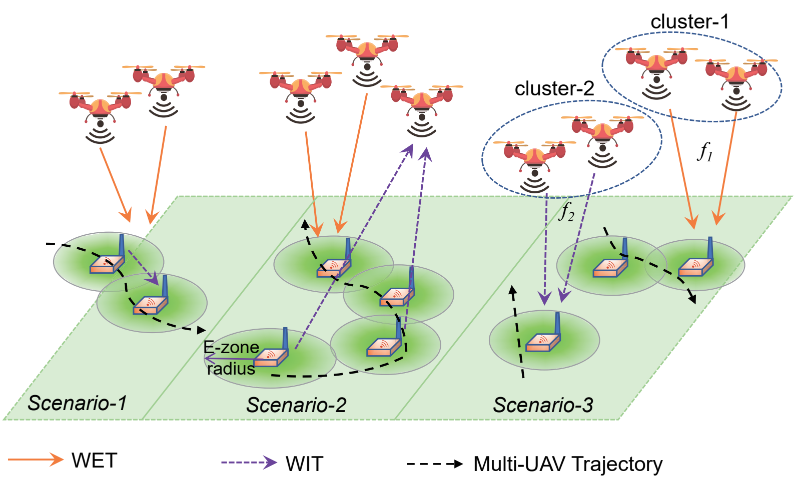

Figure 4. Multi-UAV cooperations in three useful scenarios.

Although there exist few studies that have considered non-linear EH for the ground-based WET [20], the GDs' non-EH properties have not been fully utilized for the design of the UAV's WET. Therefore, a new and practical UAV WET design enabling elastic mobility and adaptive WET is required to cater to GDs' non-linear EH properties.

2.2. Diversified Energy Demands in IoE

The UAV's on-board energy is usually limited [21]. Although the existing work considered to minimize the UAV's energy consumption [22] or minimize the UAV's task time [23], the UAV's limited on-board energy may not be able to meet its task requirement. For the UAV's WET, to meet the different energy amount requirements of a large number of GDs, the UAV needs to move fast between the GDs to obtain more time to linger (by hovering or moving slowly) within its E-zones. This helps ensure that the UAV's effective WET can last for a long time duration. However, due to the UAV's limited battery energy, the UAV's moving space and velocity are still confined, and thus may not be able to achieve the expected free mobility in the 3D space for achieving highly-efficient WET.

We also note that due to the different mission purposes, some of the GDs' energy demands may be quite urgent (e.g., for rescues in the event of a disaster), while some other GDs (e.g., the wireless sensors working in duty cycles) can wait or even sleep for a certain time duration before being charged. The time duration that a GD can wait before fully charged is referred to as the GD's *energy latency tolerance*. However, the energy latency tolerance at a GD is barely mentioned or considered in the existing literature about the UAV-aided WET.

In a complex IoE scenario with a large number of heterogeneous GDs, it is essential to carefully predict the performance of the UAV-aided WET for sustaining the GDs' operations, where both the energy demand metrics on the GDs' required energy amounts and energy latency tolerances should be jointly considered under the UAV's on-board energy limitation.

2.3. Integration of UAV-Aided WET into 6G Wireless Communications

It is vital to properly integrate the UAV's WET into the future 6G networks for sustainable IoE wireless communications. The existing studies have made efforts to co-design the UAV-aided WET and WIT [24,25]. One of the promising schemes is the UAV-aided wireless powered communication network (WPCN). Under the so-called RF EH constraint, which requires that the harvested RF energy at each GD is no smaller than its consumed energy for WIT, the UAV's WET in the downlink and all the GDs' WIT in the uplink are jointly designed [26–28].

However, the important issues on the GDs' non-linear EH and the UAV's battery energy constraint have not been seriously addressed yet. Another plausible method is to consider the UAV as a hybrid transmission platform for both WET and WIT to the GDs in the downlink [11]. Exploiting its limited battery energy, how to adaptively determine the UAV's WET and WIT status to meet the GDs' diversified energy and communication demands is a new challenge. Further, in the real-life IoE scenario, the GDs' energy and communication demands may vary significantly, which in turn asks for a more advanced network structure with more dynamic transmission schemes to incorporate the UAVs' WET.

3. Novel Solutions

To address the new challenges in Section 2, we present novel solutions in this section.

3.1. Enhancing UAV's WET via Harvesting FSO Energy

As discussed in Section 3.1, due to the GDs' non-linear EH properties, the UAV's effective WETs to each of the GDs are assured only if it has sufficient battery energy to support its travel to all the E-zones above the GDs. This may be difficult to realize under the UAV's limited battery energy, especially when serving sparsely-deployed GDs. By exploiting the technique of the energy-concentrated free space optics (FSO) transmission, this subsection proposes the FSO-powered UAV with enhanced mobility to assure effective WETs to all the GDs. Note that the FSO-powered UAV is largely different from the tethered UAV with very limited mobility. Although the UAV performance may be degraded due to the FSO pointing errors in practice, with the emerging fast tracking technology for the FSO systems, such performance loss can be effectively compensated [29]. The FSO-powered UAV with an 48-hour continuous operation aloft has been successfully demonstrated by PowerLight Technologies (https://powerlighttech.com/traction/ (accessed on 10 September 2023)).

In Figure 2, we consider that the UAV is equipped with an FSO receiver and a RF antenna, and thus is able to harvest FSO energy from the optic base stations (OBSs) continually to prolong its battery life. At the same time, the UAV can consume the stored FSO energy to support its enhanced mobility over a larger moving space. To avoid transmission blockage to the UAV, the OBSs are usually deployed on top of high-rise buildings (e.g., OBS-1 in Figure 2) or directly on ground in open fields (e.g., OBS-2). Note that the OBSs usually adopt high transmit power for charging the UAV over a long distance [30]. Thus, although the UAV's moving space can be expanded, its trajectory still needs to be carefully designed in order to improve the FSO energy efficiency of the UAV.

As the example shown in Figure 2, due to the long traveling distances between the GDs, the UAV flies to OBS-1 and OBS-2 after serving GD-1 and GD-2, respectively, to harvest more FSO energy to assure its proper service to the next-to-visit GD. Considering the GDs' different non-linear EH, we further propose an adaptive trajectory design for the UAV. Take the cases of charging GD-2 and GD-3, for example. Since the power transform efficiency, given by P_{hav}/P_{rec}, is low at GD-2, after flying into its E-zone for GD-2, the UAV continues flying to the neighborhood very close to GD-2, to ensure that GD-2 is properly charged under a largely-shortened transmission distance. In contrast, exploiting the GD-3's more efficient non-linear power transform, the UAV only slightly shortens its distance to GD-3 after flying into its E-zone, thus consuming less propulsion energy. By doing so, the UAV's harvested FSO energy can be more efficiently used to serve multiple GDs with different non-linear power transform efficiencies.

Moreover, since the UAV's harvested FSO energy varies over the UAV-to-OBS distances, the UAV must control its trajectory to satisfy a new FSO-EH constraint, which requires the UAV's consumed energy to be no larger than its harvested FSO energy from the OBSs. Since both the expressions of the UAV's propulsion energy consumption [12] and the FSO energy transmission [30] are very complicated, it is challenging to jointly design the UAV's trajectory and effective WET under the FSO-EH constraint. We extend the successive fly-hover trajectory for the UAV's WET in Ref. [10] to our considered WET scenario with an FSO-powered UAV, where the UAV successively flies to certain hovering locations in the neighborhood of each GD and each OBS for effective WET and efficient FSO EH, respectively. With the purpose to maximize the UAV's FSO energy efficiency for charging all the GDs with non-linear EH, the UAV's hovering locations and its flying velocities between them are optimized jointly under the FSO-EH constraint.

3.2. Energy-Demand Aware Trajectory for Hierarchical WET

As discussed in Section 3.2, all the GDs' required energy amounts and energy latency tolerances should be properly met. This subsection proposes UAV's hierarchical WET scheme by clustering GDs according to their diversified energy demands.

An example is shown in Figure 3, where GD-1, GD-3, and GD-5 (although at different locations) with tight energy latency tolerance are grouped into cluster-I, and the remaining GDs with loose energy latency tolerance are grouped into cluster-II. Different from the traditional geographic clustering, the clustered GDs may not be located closely in the proposed energy-demand aware GD clustering. Based on the GD clustering, the UAV first routes and serves cluster-I with tight energy tolerance, where the UAV conducts effective WET to each of the involved GDs to meet their required energy amounts within their energy latency tolerances. After that, the UAV flies to serve GDs in cluster-II using its remaining battery energy. To ensure that the GDs in cluster-II are also properly served, we must jointly design the UAV's energy-demand aware trajectories and hierarchical WET schemes across both clusters. Such a cross-cluster joint design problem is generally very complicated. Note that by grouping GDs based on their different energy demands, each GD only belongs to one GD cluster. This motivates us to divide the cross-cluster joint design problem into two subproblems, each of which targets at the UAV's transmit power allocation and trajectory design for serving one GD cluster. The two subproblems are then alternately solved, by properly allocating the UAV's battery energy for serving each GD cluster.

To further save the UAV's battery energy, we also propose to exploit the UAV's overlapped E-zones (if any). In Figure 3, when the UAV charges GD-3 in cluster-I at the overlapped area of GDs-3 and -4's E-zones, GD-4 in cluster-II also harvests non-zero energy from the UAV. If GD-4 is sufficiently charged, the UAV does not need to fly back to charge GD-4 when serving cluster-II, and thus improves its battery energy efficiency.

3.3. Multi-UAV Cooperation for Sustaining GD Communications

As discussed in Section 3.3, the integration of UAV-aided WET into the 6G network is a complicated task, especially due the UAV's limited battery energy and the large number of GDs to serve. This subsection employs a number of UAVs to cooperatively sustain the communications of GDs. The following three useful scenarios are considered:

- *Exploiting UAVs' WETs to power WITs between GDs:* As shown in Scenario-1 in Figure 4, multiple UAVs transmit energy cooperatively to sustain the ground-to-ground (G2G) communications between the GDs. The GDs' various quality-of-service (QoS) requirements for communications are constrained by their available energy for G2G WITs, which in turn are converted as the GDs' diversified energy demands under the UAVs' cooperative WETs. The hierarchical WET proposed in the last subsection can then be extended to the multi-UAV case, for a joint design of the UAVs' cooperative energy beaming as in, e.g., Refs. [9,13] and their energy-demand aware trajectories.
- *Exploiting UAVs' WETs to power GDs' WITs to the UAVs:* As shown in Scenario-2 in Figure 4, the UAVs' cooperative energy beaming are performed to sustain the GDs' uplink WITs. Due to the GDs' diversified energy and communication demands, the UAVs' WET to a GD in the downlink may occur simultaneously with another fully-charged GD's WIT in the uplink. To avoid such co-channel interference, we apply the time-division-multiple-access (TDMA) based protocol to coordinate the UAVs' cooperative energy beaming in the downlink and different GDs' WITs in the uplink along the UAVs' energy-demand aware trajectories, under the GDs' RF EH constraints to sustain their WITs.
- *Joint WETs and WITs from the UAVs to the GDs:* As shown in Scenario-3 in Figure 4, the UAVs are grouped into multiple clusters, each of which dedicatedly serves a group of GDs. The UAV clusters can adopt different trajectories to serve different GD groups. As each UAV can freely switch between WET and WIT, we assign different operation frequency bands for different UAV clusters to avoid their inter-cluster interference; and for the case within a cluster, by adopting a dynamic WET and WIT protocol as in Ref. [11], the UAVs jointly and adaptively determine their WET and WIT status over different slots under the GDs' RF EH constraints to sustain their information reception, where each GD's QoS requirement is also met by properly controlling the intra-cluster interference during the UAVs' cooperative WIT.

4. Performance Evaluations and Discussions

We conduct simulation experiments to evaluate the proposed solutions. As in Refs. [9,11], each UAV transmits with 200 mW at an altitude of 5 meters (m) for efficient WET. The UAV's velocity is 5 meters/second (m/s). We consider compact-size UAVs with limited battery energy for worst-case study, where each UAV's battery energy is only sufficient to support its propulsion and transmission over a distance of 700 m [12]. Each GD is equipped with a PowerCast module P2110B for non-linear EH [18]. The widely-used LoS A2G channel model in Ref. [10] is applied.

Only the very limited work in Ref. [9] has discussed multi-UAV enabled WETs, where all the GDs are assumed to have identical energy demands. In this section, we consider a typical IoE scenario with diversified GD energy demands and QoS requirements. Specifically, in total of three UAVs are dispatched from the origin at $(0,0)$ to serve four GDs. The locations of GD-1, GD-2, and GD-3 are fixed as $(0,50)$, $(-7,-50)$, and $(7,-50)$ on the two-dimensional ground plane, respectively. GD-4 locates on the x-axis with a variable location at least 20 m away from the origin. We consider that the closely-located GD-2 and GD-3 have the same energy and communication demands, and therefore group them as a cluster as in Section 4. GD-1 and GD-4 are two individual GD clusters, each with a single GD.

The energy and communication demands of the GDs in each cluster are specified as below:

- GD-1 requires to harvest 50 mW·s of energy from the UAVs' WETs, and then uses the harvested energy to receive the UAVs' downlink information file of 10 Mbits. Its communication latency tolerance is 8 s.
- Both GD-2 and GD-3 require to harvest 40 mW·s of energy from the UAVs' WETs, to power GD-2's transmission of an information file of 5 Mbits to GD-3. Their communication latency tolerance is 12 s.
- GD-4 does not communicate, but requires to harvest 340 mW·s of energy from the UAVs' WETs (e.g., for sensing purposes). Its energy latency tolerance is 40 s.

To avoid co-channel interference, we assign orthogonal frequency bands (each of which has 10 MHz) to the UAVs' WETs, the WITs from the UAVs to GD-1, and the WIT from GD-2 to GD-3. The communication latency for GD-1, GD-3, or GD-2 is estimated as the time duration between the UAVs' departure from the origin and the time that its required communication file is completely received or transmitted, respectively. Similarly, the energy latency for GD-4 is estimated as the time duration between the UAVs' departure from the origin and the time that its required energy amounts are completely satisfied.

To demonstrate the performance of the multi-UAV enabled WET, we focus on the following three simple trajectories, as shown in Figure 5:

- No cooperation with Trajectory I: the three UAVs operate individually, where each of the three UAVs flies directly to GD-1, the cluster of GD-2 and GD-3, and GD-4, respectively, and hovers above the GD (or the center of the cluster) to serve it.
- Full cooperation with Trajectory II: all three UAVs operate cooperatively as a team, where according to the GDs' energy and communication latency tolerances, the UAVs sequentially visit GD-1, the cluster of GD-2 and GD-3, and GD-4 to serve them.
- Partial cooperation under UAV clustering with Trajectory III: the UAVs are grouped into two clusters, with a single UAV-1 in one cluster, and UAV-2 and UAV-3 working cooperatively in the other cluster. The former and the latter UAV clusters separately fly to GD-1 and the cluster of GD-2 and GD-3 to serve them, and then join at GD-4's E-zone edge (i.e., GD-4's x-location minus its E-zone radius on x-axis) for cooperative WET by flying to GD-4.

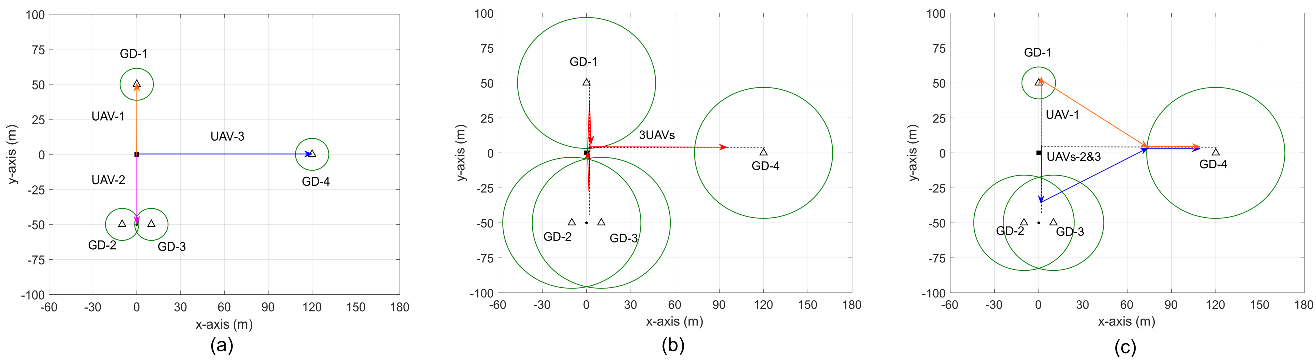

Figure 5. Multi −UAV enabled WET with GDs' diversified energy and communication demands. (**a**) Trajectory I: No cooperation. (**b**) Trajectory II: Full cooperation. (**c**) Trajectory III: Partial cooperation under UAV clustering.

Trajectories I and II are obtained based on the state-of-the-art methods in Ref. [9], where we further consider the GDs' different energy and communication latencies to determine the UAVs' visiting sequence to the GDs in Trajectory II.

The E-zone radii for each GD when charged by a single UAV, two cooperative UAVs, and three cooperative UAVs are 10.76 m, 15.57 m, and 18.68 m, respectively. The E-zones for GD-2 and GD-3, with only 14 m in-between, are always overlapped under all the three trajectories above. To exploit the overlapped E-zones, under each trajectory, the UAVs fly toward the mid-point at $(0, -50)$ between GD-2 and GD-3 for effective WET.

We focus on the average mission completion time of the UAVs, which is the ratio of the UAVs' overall mission completion time of transmitting the required energy and/or information to all GD clusters over the GD cluster number. Figure 6 shows that the UAVs' average mission completion time increases as GD-4 moves further away from the origin for all three trajectories due to the increased UAV flying time to serve GD-4.

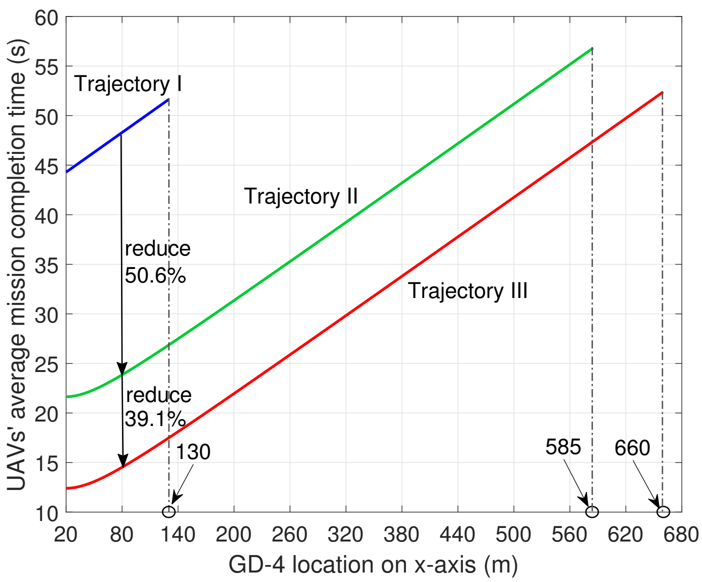

Figure 6. Effects of multi-UAV cooperations for WET.

Under Trajectory I, due to the small E-zone radius for each GD, the UAV consumes a long time of 357.11 s to satisfy the energy demands of GD-2 and GD-3, and thus cannot meet their communication latency. The resultant average mission completion time under Trajectory I is the highest among the three trajectories. It is also observed that since the single UAV hovers above GD-4 to rapidly meet its energy demands and thus consumes more propulsion energy than flying with a constant speed of 5 m/s, under the UAV's limited battery energy, the largest reachable serving distance for GD-4 is only 130 m. The UAV's battery energy is not sufficient to support its traveling to GD-4, which is located more than 130 m away.

For Trajectories II and III in Figure 6, with the cooperative UAVs to expand the E-zones for the GDs, all of the communication or energy latency of the GDs are satisfied. The average mission completion time under Trajectory II is reduced significantly (e.g., by 50.6% when GD-4 locates at $(80, 0)$) as compared to Trajectory I, which is in accordance with the observations in Ref. [9]. It is also observed that Trajectory III under our proposed UAV clustering-based partial cooperation in Figure 5c further reduces the average mission completion time (e.g., by 39.1% with GD-4 at $(80, 0)$ as compared to Trajectory II). This is because instead of sequentially serving GD-1 and the pair of GD-2 and GD-3 as in Trajectory II, these GDs are concurrently served by two UAV clusters under Trajectory III, which saves the UAVs' visiting time and battery energy. Hence, the largest reachable serving distance for GD-4 is 660 m under Trajectory III, but 585 m under Trajectory II. Therefore, since the UAV clustering based partial cooperation under Trajectory III achieves a proper balance between improving the UAVs' cooperative diversity gain for effective WET and reducing the UAVs' flying time between the GDs for saving battery energy, it is more reliable for the IoE scenario with diversified energy and communication demands.

At last, by increasing the UAV number N, Figure 7 shows the UAVs' mission completion time for each GD cluster under the most efficient Trajectory III, where $[N/2]_+$ and $N - [N/2]_+$ UAVs serve GD-1 and the cluster of GD-2 and GD-3, respectively, with $[x]_+$ representing the floor operation to x. The distance from the origin to GD-4 is set as 40 m. It is found that the mission completion time for each GD is always within its required energy or communication latency tolerance. It decreases as the number of UAVs increases, where GD-1 and GD-4 always has the shortest and the longest mission completion time for any given UAV number, respectively.

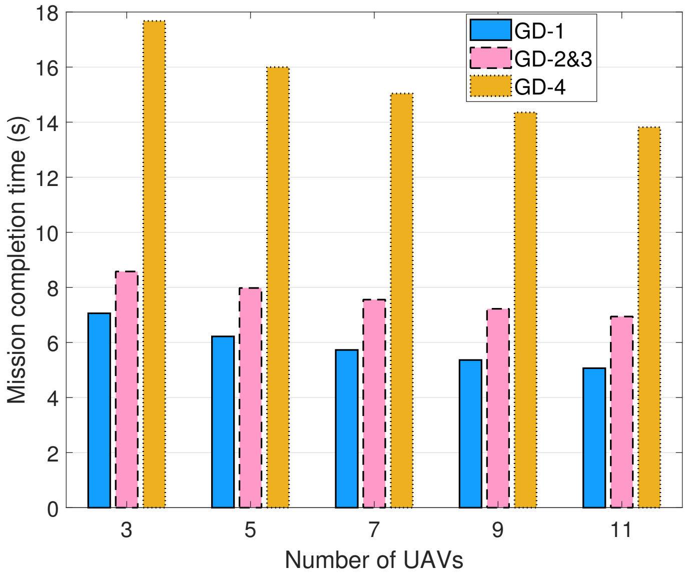

Figure 7. Effects of the UAV numbers.

5. Conclusions and Future Work

In this article, we depict the new design challenges and directions of the UAV-aided WET, to embrace the forthcoming IoE-driven 6G era. We first identify the practical issues on the GDs' distinct non-linear EH and diversified energy demands, and the UAV's severely constrained battery energy, as well as the resultant technical challenges for the design of the UAV's WET in practice. We then propose novel approaches to address these issues for achieving self-sustained IoE communications. At last, we consider a typical IoE scenario and corroborate the superiority of our proposed multi-UAV cooperative WET scheme under the energy-aware trajectories with numerical results.

Some related problems are listed as below to motivate future work:

- *Efficient retrieval of the demands of GDs:* A complete and timely retrieval of all the GDs' different non-linear EH properties and energy demands is essential for the UAVs to properly implement our proposed adaptive trajectory and hierarchical WET in Section 4. It may be difficult to reliably establish direct GD-to-UAV connections in the complex IoE scenario. In this case, a more promising method is to employ the cellular-connected UAVs, where the UAVs are integrated as cellular users and are reliably served by the BSs [7]. As shown in Figure 1, the GDs' EH properties and demand information at any required locations can be efficiently obtained by the UAVs via these GDs' associated BSs connected by the core network.
- *Expanding E-zones for GDs:* Besides exploiting the multi-UAV cooperation as shown in Section 3.3, we can also employ the intelligent reflected surface (IRS) to expand the E-zones for the GDs for more efficient UAV-aided WET, where the A2G channel path loss can be largely reduced via the assistance from IRS [31]. For a UAV with multiple

antennas, the active and inactive energy beamforming at the UAV and the IRS can be jointly designed along the UAV's energy-demand trajectory, to efficiently improve the UAVs' WET performance for serving multiple GDs.

- *Intelligent UAV swarming for cost-effective WET:* While multi-UAV cooperation can boost the efficiency of the UAV-aided WET, repeating UAV interactions is required to assure their synchronous moving and transmissions. This can increase the UAVs' operational overhead and/or cost substantially. By allowing the UAVs to automatically move and transmit under a pre-defined proactive set of operation rules, the method of intelligent UAV swarming can be alternatively adopted [32]. However, it is still challenging to determine the UAVs' automatic operation rules in the complex IoE scenario. More research efforts are expected to develop efficient UAV swarming systems for cost-effective WET.

Author Contributions: Conceptualization, Y.C. and L.D.; methodology and validation, Y.C., S.L., Z.Z. and K.W.; investigation, Y.C., Z.Z. and K.W.; writing and editing, Y.C., L.D., Z.Z. and S.L.; supervision, Y.C., S.L., L.D., K.W. and V.C.M.L.; project administration, Y.C., S.L. and K.W.; funding acquisition, Y.C., S.L. and V.C.M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the National Natural Science Foundation of China under Grant 62072314, the Guangdong Natural Science Foundation under Grant 2023A1515011327, the Guangdong "Pearl River Talent Recruitment Program" under Grant 2019ZT08X603, the Guangdong "Pearl River Talent Plan" under Grant 2019JC01X235, the Shenzhen Talents Special Project—Guangdong Provincial Innovation and Entrepreneurship Team Supporting Project under Grant 2021344612, and the Shenzhen Science and Technology Innovation Commission under Grant R2020A045.

Data Availability Statement: Not applicable.

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

References

1. Saad, W.; Bennis, M.; Chen, M. A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. *IEEE Netw.* **2020**, *34*, 134C–142C. [CrossRef]
2. Liu, J.; Peng, J.; Xu, W.; Liang, W.; Liu, T.; Peng, X.; Xu, Z.; Li, Z.; Jia, X. Maximizing sensor lifetime via multi-node partial-charging on sensors. *IEEE Trans. Mobile Comp.* **2022**, *forthcoming*. [CrossRef]
3. Che, Y.L.; Duan, L.; Zhang, R. Spatial throughput maximization of wireless powered communication networks. *IEEE J. Sel. Areas Commun.* **2015**, *33*, 1534–1548. [CrossRef]
4. Wang, L.; Che, Y. L.; Wu, K.; Duan, L. Multiple access mmWave design for UAV-aided 5G communications. *IEEE Wirel. Commun.* **2019**, *26*, 64–71. [CrossRef]
5. Xu, W.; Sun, Y.; Zou, R.; Liang, W.; Xia, Q.; Shan, F.; Wang, T.; Jia, X.; Li, Z. Throughput maximization of UAV networks. *IEEE/ACM Trans. Netw.* **2021**, *30*, 881–895. [CrossRef]
6. Shen, Q.; Peng, J.; Xu, W.; Sun, Y.; Liang, W.; Chen, L.; Zhao, Q.; Jia, X. Fair communications in UAV networks for rescue applications. *IEEE Internet Things J.* **2023**, *forthcoming*. [CrossRef]
7. Zeng, Y.; Lyu, J.; Zhang, R. Cellular-connected UAV: Potential, challenges and promising technologies. *IEEE Wirel. Commun.* **2019**, *26*, 120–127. [CrossRef]
8. Chen, S.; Shu, Y.; Yu, B.; Liang, C.; Shi, Z.; Chen, J. Demo: Mobile wireless charging and sensing by drones. In Proceedings of the 14th Annual International Conference on Mobile Systems, Applications and Services Companion—MobiSys Companion, New York, NY, USA, 25–30 June 2016; p. 99.
9. Xie, L.; Cao, X.; Xu, J.; Zhang, R. UAV-enabled wireless power transfer: A tutorial overview. *IEEE Trans. Green Commun. Netw.* **2021**, *5*, 2042–2064. [CrossRef]
10. Xu, J.; Zeng, Y.; Zhang, R. UAV-enabled wireless power transfer: Trajectory design and energy optimization. *IEEE Trans. Wirel. Commun.* **2018**, *17*, 5092–5106. [CrossRef]
11. Che, Y.L.; Lai, Y.; Luo, S.; Wu, K.; Duan, L. UAV-aided information and energy transmissions for cognitive and sustainable 5G networks. *IEEE Trans. Wirel. Commun.* **2021**, *20*, 1668–1683. [CrossRef]
12. Zeng, Y.; Xu, J.; Zhang, R. Energy minimization for wireless communication with rotary-wing UAV. *IEEE Trans. Wirel. Commun.* **2019**, *18*, 2329–2345. [CrossRef]
13. Zhao, Z.Y.; Che, Y.L.; Luo, S.; Wu, K.; Leung, V.C.M. Multi-agent graph reinforcement learning based on-demand wireless energy transferin multi-UAV-aided IoT network. *arXiv* **2023**, arXiv:2307.14626.

14. Yuan, X.; Yang, T.; Hu, Y.; Xu, J.; Schmeink, A. Trajectory design for UAV-enabled multiuser wireless power transfer with nonlinear energy harvesting. *IEEE Trans. Wirel. Commun.* **2021**, *20*, 1105–1121.
15. Oubbati, O.S.; Atiquzzaman, M.; Lim, H.; Rachedi, A.; Lakas, A. Synchronizing UAV teams for timely data collection and energy transfer by deep reinforcement learning. *IEEE Trans. Veh. Technol.* **2022**, *71*, 6682–6697.
16. Oubbati, O.S.; Lakas, A.; Guizani, M. Multiagent deep reinforcement learning for wireless-powered UAV networks. *IEEE Internet Things J.* **2022**, *9*, 16044–16059.
17. Peng, H.; Wang, L.C. Energy Harvesting Reconfigurable Intelligent Surface for UAV Based on Robust Deep Reinforcement Learning. *IEEE Trans. Wirel. Commun.* **2023**, *forthcoming*.
18. Alevizos, P.N.; Bletsas, A. Sensitive and nonlinear far-field RF energy harvesting in wireless communications. *IEEE Trans. Commun.* **2018**, *17*, 3670–3685. [CrossRef]
19. PowerCast Module. Available online: http://www.mouser.com/ds/2/329/P2110B-Datasheet-Rev-3-1091766.pdf (accessed on 8 July 2020). [CrossRef]
20. Singh, S.K.; Agrawal, K.; Singh, K.; Li, C.P.; Alouini, M.S. NOMA Enhanced UAV-Assisted Communication System with Nonlinear Energy Harvesting. *IEEE Open J. Commun. Soc.* **2022** , *3*, 936–957. [CrossRef]
21. Liu, Y.; Dai, H. N.; Wang, Q.; Imran, M.; Guizani, N. Wireless Powering Internet of Things with UAVs: Challenges and Opportunities. *IEEE Net.* **2022**, *36*, 146–152.
22. Lin, J.; Huang, L.; Zhang, H.; Yang, X.; Zhao, P. A novel lyapunov based dynamic resource allocation for UAVs-assisted edge computing. *Comp. Netw.* **2022**, *205*, 108710.
23. Shi, T.; Qin, K.; Luo, G. Completion Time Optimization in UAV-Relaying-Assisted MEC Networks with Moving Users. *IEEE Trans. Consumer Electr.* **2023**, *forthcoming*. [CrossRef]
24. Jia, H.; Wang, Y.; Chen, Y.; Liu, M.; Li, Z. Sum Rate Maximization for Multi-UAV Enabled Space-Air-Ground Wireless Powered Communication Networks. In Proceedings of the IEEE Wireless Communications and Networking Conference Workshops, Nanjing, China, 29 March 2021.
25. Yang, H.; Ye, Y.; Chu, X.; Sun, S. Energy Efficiency Maximization for UAV-Enabled Hybrid Backscatter-Harvest-Then-Transmit Communications. *IEEE Trans. Wirel. Commun.* **2022**, *21*, 2876–2891.
26. Xie, L.; Xu, J.; Zhang, R. Throughput maximization for UAV-enabled wireless powered communication networks. *IEEE Internet Things J.* **2019**, *6*, 1690–1703.
27. Pan, H.; Liu, Y.; Sun, G.; Fan, J.; Liang, S.; Yuen, C. Joint Power and 3D Trajectory Optimization for UAV-Enabled Wireless Powered Communication Networks with Obstacles. *IEEE Trans. Commun.* **2023**, *71*, 2364–2380. [CrossRef]
28. Tang, Q.; Yang, Y.; Liu, L.; Yang, K. Minimal Throughput Maximization of UAV-enabled Wireless Powered Communication Network in Cuboid Building Perimeter Scenario. *IEEE Trans. Net. Serv. Manag.* **2023**, *forthcoming*. [CrossRef]
29. Kartalopoulos, S.V. *Free-Space Optical Networks for Ultra-Broad Band Services*; Wiley: Hoboken, NJ, USA, 2011. [CrossRef]
30. Che, Y. L.; Long, W.; Luo, S.; Wu, K.; Zhang, R. Energy-efficient UAV multicasting with simultaneous FSO backhaul and power transfer. *IEEE Wirel. Commun. Lett.* **2021**, *10*, 1537–1541. [CrossRef]
31. Wu, Q.; Zhang, R. Joint active and passive beamforming optimization for intelligent reflecting surface assisted SWIPT under QoS constraints. *IEEE J. Sel. Areas Commun.* **2020**, *38*, 1735–1748. [CrossRef]
32. Hu, F.; Ou, D.; Huang, X. *UAV Swarm Networks: Models, Protocols, and Systems*; CRC Press: Boca Raton, FL, USA, 2020.