Unmanned Aerial Vehicle-enabled Internet of Things (UeIoT)

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This dissertation proposal is submitted for the degree of

Master of Telecommunication Engineering

Supervisor: Prof. Hong-Ning Dai 2020

摘要

物聯網是未來資訊通信技術的發展趨勢之一。物聯網的實現在於提供高效智慧的物聯服務，因此它需要具備可擴展性、智慧性和多樣性。然而，由於現有網路技術的覆蓋受限問題以及物聯網節點的資源受限問題，物聯網的擴展性、智慧性和多樣性難以完全實現。無人機具有高機動性、低成本以及可靈活部署的特點，是最適合用來解決物聯網覆蓋受限/資源受限的技術。結合最新的無人機應用到通信和人工智慧方面的技術，無人機可幫助物聯網實現進一步的網路覆蓋並藉以提供更多樣化的物聯網服務。

在此背景下，本論文旨在研究無人機面對物聯網挑戰問題的解決方案。首先，我們對無人機在物聯網上應用的機遇和挑戰做了一個詳細的概述。我們討論了無人機可解決物聯網連接受限、計算受限和供能受限等方面的機遇；進而我們提出了無人機使能物聯網的解決方案，其中詳述了無人機針對實現物聯網擴展性、智慧性和多樣性的使能技術。再者，本論文提出無人機結合無線供能技術實現物聯網節點資料獲取的方案。具體地，我們通過優化資料獲取過程中的總體能量消耗，得到了最優的資源配置。最後，本論文總結了一些無人機使能物聯網的研究問題，並提出了未來在相關工作上的研究方向。

關鍵字：物聯網；無人機；無線能量傳輸；低功率廣域網路；人工智慧；凸優化問題

Abstract

Realizing internet of things (IoT) is the growing trend of the future information and communication technology (ICT). To our perspective, IoT is expected to be scalable, intelligence and also diverse, thus can enable intelligence of everyday items and serve high efficiency life for human. However, the restricted coverage of existing network technologies and the limited resource of current IoT nodes present the indispensable issues to the realization of IoT. With high mobility, low cost, and inflexible deployment, unmanned aerial vehicles (UAVs) have the most potential to address the restricted coverage and resources issues of IoT. Combined with the state-of-the-art UAV technologies in communication and AI, UAV can enable a scalable IoT network and support diverse IoT services.

In this context, we intend to propose a general solution for using UAV to solve the challenges of IoT. Firstly, we present a comprehensive survey of applying UAV in IoT. Particularly, we overview the enabling technologies of IoT according to three expectations (i.e., scalability, intelligence, and diversity) and also review the UAV-based literature. We discuss the opportunities brought by UAV to IoT, in addressing the challenges of IoT in connection, computing, energy supply, etc. We summary a general solution - UAV-enabled IoT (also called UeIoT) that introduces UAV-enabled scalable IoT, UAV-enabled intelligent IoT, and UAV-enabled diverse IoT. Secondly, aiming to address the restricted coverage and limited battery of IoT, we consider a technical work of using UAVs as both data collector and also energy supplier. We specifically present a data acquisition scheme within the assistance of UAV and directional wireless energy transfer (WET), in which the optimal resource allocation is obtained by an energy minimization problem. Finally, we summary some other research issues existed in UeIoT, in which opportunities of future works are shown.

Keywords: Unmanned Air Vehicle (UAV); Internet of Things (IoT); UAV-enabled IoT (UeIoT); Artificial intelligence (AI); Low power wide area network (LPWAN); Wireless Energy Tranfer (WET); Wireless Sensor Networks (WSN)

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Chapter 1

Introduction

1.1 Background

The state-of-the-art ICT technology is developing to construct a high-capacity and scalability of wired or wireless network for accommodating the era of information explosion; this development lays the foundation of communication networks for IoT [1–7].

To our perspective, IoT is expected to be scalable, intelligence and also diverse, thus can enable intelligence of everyday items and serve high efficiency life for human. So far, many communication technologies concentrate on extending connection of existing internet to “things” or sensors such as wireless sensor networks (WSN) and low power wide area network (LPWAN). In addition, artificial intelligence (AI) technology is developing with the coming era of big data, hatching a great amount of computing based applications such as intelligent recognition, intelligent management, intelligent decision. Integrating AI into IoT, we can achieve diverse applications including smart city, smart manufacturing, industrial internet of things, etc. Thus, a huge sharing database including pictures, video, voice, and text will be formed in IoT and further enables intelligence to our manufacturing, industry and daily life [8]. Accordingly, we can extract on-demand information including critical decide for business, real-time controlling commands and long-term predictions from the sharing database. In this way, IoT can be widely used for improving the efficiency of production and life in human society, such as smart manufacturing, agricultural monitoring, intelligent traffic scheduling, and real-time monitoring and tracking.

However, the current ICT technologies are still not enough to achieve IoT. There are many problems hindering the wide applying of IoT. Firstly, the existing network for IoT cannot cover everywhere due to the inflexible network infrastructures, leading to restricted coverage of IoT. Then, the requirement of countless IoT nodes must be design with limited resources such as battery storage, computation capability, resulting in lack of edge intelligence and redundant massive access. Besides, the inflexible network deployment and also brief access protocols will also cause weak security and low sustainability. All those problems come from the conflict between limited resources and requirements of massive access; we always pursue the low cost under this conflict, resulting in restricted coverage, the security problem, the sustainability problem, etc. Therefore, IoT requires a flexible coverage and elastic configuration to address those problems.

With high mobility and easy deployment, UAV can enhance capacity of IoT over much wider range and smarter edge control, giving our opportunities to address the problems IoT in restricted coverage and limited resources. On the one hand, compared to terrestrial networks and satellite remote communications, the wireless network with low-altitude UAVs is in general faster to deploy, more flexibly reconfigured for storage capacity and computing capability, and likely to have better channel gains due to short-range line-of-sight links in UAVs networks. On the other hand, UAVs within a dedicated configuration and control design have already been used in wide applications such as policing, peacekeeping, and surveillance, product deliveries, and drone racing. Flexible deployment and wide applications brings the countless applications of UAV-enabled IoT. UAVs can be applied as aerial base stations and relay nodes for extending the current IoT networks, also be dispatched as the remote data collector, and even be dedicatedly designed as aerial delivery vehicles, etc. Challenges and opportunities are coexisted for UAV-enabled IoT. Technically speaking, opportunities of using UAV in IoT also pose new challenges in dynamic communication connection, flexible network topology and routing, precise control algorithm, and lightweight AI algorithm in local, etc. In front of those challenges, we should design the dedicated communication protocol, the flexible resource allocation mechanism, the trajectory design, and also the local AI design, etc.

1.2 Contribution

In previous literature of applying UAV in IoT, some of opportunities and challenges has been investigated, and even been addressed. This thesis aims to overview related works of UAV in IoT, and make a comprehensive survey. Additionally, this thesis presents a technical work of using UAV as data collector of IoT. Generally speaking, this thesis makes two contributions:

1. An overview of UAV-enabled IoT is provided. In particular, we introduce the IoT

and UAV; the enabling technologies of IoT and UAV are summarized respectively. We then propose the opportunities of using UAV in IoT from four sides: covering everywhere, aerial intelligence, self-maintenance, and power supplying. After that we give the analysis of UAV-enabled IoT from scalability, intelligence, and diverse, respectively. Finally, we list five typical applications of UAV-enabled IoT and conclude the research issues.

2. A UAV-enabled data acquisition scheme with directional WET is presented to overcome the limited battery issues in data acquisition of IoT. The main idea of the proposed scheme is to employ a UAV as both a data collector and an energy supplier. We derive the optimal resource allocation scheme by minimizing the overall energy consumption. We analysis the feasibility of our scheme and investigate the relationship between the optimal allocation value and the values of transmitting data data and channel-fading.

1.3 Outline

The structure of the thesis is organized as follows: Chapter 2 presents overview of UeIoT. Chapter 3 presents the UAV-enabled data acquisition scheme. Finally, conclusion and future work are given in Chapter 4.

Chapter 2

An Overview of UAV-enabled IoT

This chapter aims at giving a survey of UAV-enabled IoT. Particularly, the overview of IoT and UAV is firstly given in Section 2.1 and Section 2.2, respectively. Then in Section 2.3, UAV-enabled IoT are introduces, in which the opportunities, enabling technologies, and applications are discussed.

2.1 Internet of Things

IoT is a global network connecting countless electronic devices related to everything, also is a final ambition of diversity communication networks including WSN, M2M, LPWAN, etc [9, 10]. With the development of current ICT technologies, IoT is potential to supply a large number of various and intelligent services in terms of their different application scenarios, mobile locations, and various communication requirements. In particular, three expectations of IoT and the corresponding enabling technologies are discussed in this section. Meanwhile, an overview of challenges presented in the recent literature is also provided.

2.1.1 Expectations of IoT

The expectations we hold to IoT can be summarized in three points i.e., scalability, intelligence, and diversity as follows:

1. **Scalability**: Scalability is the primary importance of IoT due to the connection requirements from the increasing amount of IoT nodes. To enable scalability, IoT is expected to have wide coverage and massive access to meet the ubiquitous connection of "everything" objects. Thus, the scalable IoT can connect to "everything" in

our daily life such as traffic lights in a city, trees in a park, bathtubs in a house, and even animals in a natural reserve.

2. **Intelligence**: In the context of the scalable IoT with the connection of countless IoT objects, we expect to enable IoT intelligent to further transform 'everything' to be smart and valuable. In particular, the valuable information of decisions can be obtained by the data processing in a global sharing database stored the expected data transmitted from massive objects via IoT. The data storing and processing are conducted in the cloud or local or edge computing plane, thus delivering intelligence to all nodes in IoT containing the cloud control center, the local objects, and the edge nodes.

3. **Diversity**: Diversity of IoT means diverse applications, which is the final ambitions of IoT. These diverse applications are naturally various in terms of different communication demands, computing requirements, security levels, energy consumption levels, and suitable protocols, such as remote tracking for animal behaviours, real-time monitoring of social security and intelligent manufacturing in factory. Relying on the scalable and intelligent IoT, diversity of IoT are easily achieved due to convergence of heterogeneous communication and information technologies.

To achieve the above three expectations, IoT will deploy a great amount of terminal IoT nodes, and in a long-term those nodes will occupy lots of battery capacity, computing capability, storage capacity. However, the available resources in energy, connection, computation, and storage are limited. Hence we meet a trade-off between resource constraints and expectations of IoT. In this context, improving the resource use-efficiency is especially important.

The on-demand principle lies on balancing the demand-and-supply of resources once satisfying requirements of IoT services. The corresponding resource required to be balanced contains hardware cost, storage, battery, spectrum, connectivity, and computing. If all those resources are supplied under the on-demand principle, we can realize a high resource use-efficiency of connections, computing, control, architecture, and communication protocols of IoT. In decades years, the enabling technologies of IoT are also presented for the on-demand principle, as shown in the following sections.

2.1.2 Enabling Technologies of IoT

In terms of the current ICT development, as shown in Fig. 2.1, the enabling technologies of IoT are also categorized into three parts to promote realizing three expectations of IoT i.e., scalability, intelligence, and diversity, respectively.

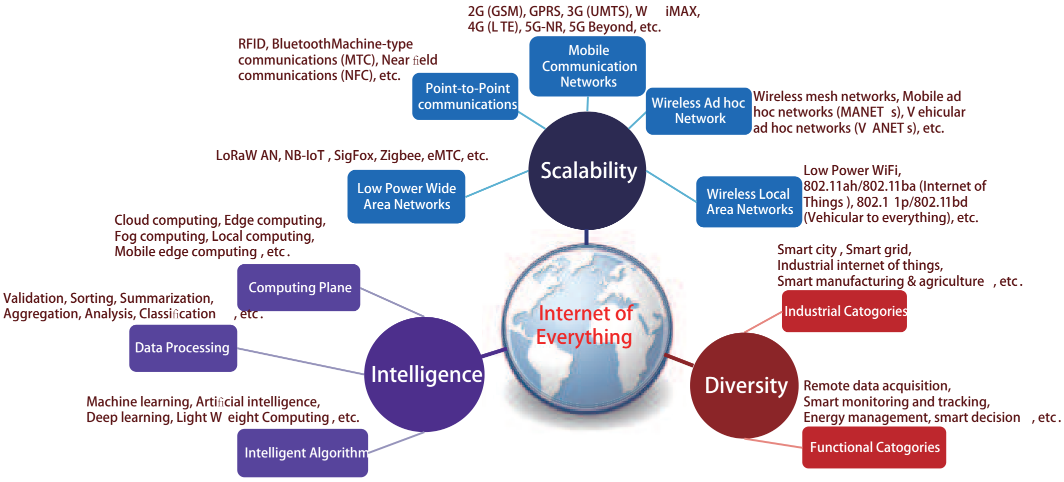


Fig. 2.1 Enabling technologies for three expectations of IoT

Enabling scalability

Scalability for IoT means wide coverage, ubiquitous connection, and massive access, which needs heterogeneous network technologies. Since there is no a single network that can cover everywhere, the goal "wide coverage" of IoT can only rely on the co-operation of the existing communication networks [1, 3, 10]. Those networks play the complementary roles with each other to construct the IoT with global coverage together. According to the previous literature, we can overview the enabling technologies of scalability from the backbone network to the the edge network.

Wireless local area networks (WLAN) and mobile communication networks (MCN) as the mainstream communication networks in our daily life and covering the areas with densely crowd such as business regions, office regions, and urban residential regions, can support the backbone network of IoT. Thus, some indoor and outdoor IoT nodes in dense crowd areas can access to the backbone network via the optional communication protocols such as low-WiFi, 802.11ah, GPRS and 5G-Beyond [1, 11, 12]. In addition, this backbone network conducts global data storing, processing and interaction, and further obtain data reports and smart decisions.

Low power wide area networks (LPWAN) [9] attracting lots of attentions in recent years provide a low-power and also wide coverage solution for IoT, and can give a complementary coverage for the backbone network. Thus, LPWAN can be regarded as the limb network of IoT, paving the way from those power-constrained nodes to the backbone network of IoT. Except for LPWAN, wireless ad hoc networks provide the emergency communication and support dynamic network topology [13, 14], and can be regarded as another limb network of IoT. Additionally, some point-to-point (P2P) communication technologies such as RFID, Bluetooth, NFC, and MTC [15, 16], can be used as the edge network of IoT to accomplish the harsh area of IoT due to their characteristics of easy deployment, low cost, infrastructure-less and short-range.

In consideration of the on-demand design of scalability, all above enabling communication technologies keep the independent developing from low power consumption, low hardware cost, and even low network resource consumption. For example, LPWAN keeps the low power and wide coverage design principle and refer to multiple communication protocols such as LoRaWAN, ZigBee, and NB-IoT [17]. Even a series of WLAN protocols are released to support the specific IoT applications, such as Low power-WiFi, 802.11ah, and 802.11p [18, 19]. Additionally, low hardware cost is also in consideration of communication equipment suppliers. An example is low-cost communication chips and modules with simplified protocols stack and limited storage/battery capacity such as NB-IoT, eMTC [20, 21].

Enabling intelligence

IoT is such a huge network composed by countless end nodes, relay nodes, and the cloud server plane; hence the intelligence of IoT can be divided into three parts i.e., cloud intelligence, edge intelligence, and local intelligence, enabled by three computing technologies i.e., cloud computing, edge computing, and local computing, respectively.

Cloud computing [4] works on the cloud database owned the huge storage and computing resources, usually supplies the centralized management and decision services for the countless end nodes, enabling the global intelligence of IoT. Edge computing [2, 22, 23] owned the matchable resources depending on the particular facilities itself, runs on the edge access nodes such as base stations, gateways, and data collectors, providing edge intelligence services such as pre-processing and compression of collected data packets, security and encryption detection, and edge resource management and decision. Local computing [4] runs on the IoT end nodes with limited storage and computing resources, expected to enable end intelligence by using the local data and limited resources. However, three computing technologies only decide the distribution and amount of computing resources instead of enabling intelligence.

The technology that can enable intelligence to IoT is the big data processing technology as well as light weight computing [24]. Over time, artificial intelligence (AI) algorithm is growing as the most popular technology in the big data processing field, aiming at enabling the computer understanding the meaning of the text, voice, picture, and video just like a human. Particularly, machine learning and deep learning are two main branches of AI algorithm, which can promote as precise intelligence as possible upon giving enough training sequences from the database of IoT. Hence, we can realize cloud intelligence of IoT based on cloud computing plane with the huge big database and AI algorithm. In addition, the edge and local computing plane can only support light weight computing attributed by their limited storage capacity and computing capability, to further enable edge and local intelligence.

Enabling diversity

Actual IoT devices are expected to employ a broad array of applications, from digital sensor tools/interfaces used for remote appliances to smarter and well-connected mobile devices for intelligent and automated scenarios. Those applications are diverse and can be classified by industry and function. For the industrial category, IoT can promote many practical intelligent projects with high efficiencies, such as smart city, industrial internet of thing, smart grid, smart manufacturing, and intelligent agriculture [6, 19, 25, 26]. For the functional category, IoT support series of technical services, such as remote data acquisition [27], energy management system, and smart detection system.

The realization of diverse applications of IoT also relies on various networking protocols, depending on different communication demands. For example, the real-time video monitoring applications require high data transmission rate, short transmission periods, massive access amounts and high-security level and thus is more suitable for the infrastructure-based network such as NB-IoT. Compared with the real-time monitoring projects, another application such as the wearable sensors monitoring body temperature, blood pressure, and heart pulses, fit with lower data transmission rate and longer transmission periods and hence is matching with WSN. Thus, the diversity of IoT also echoes the heterogeneity of communication and network protocols as referred in scalability enabling technologies.

2.1.3 Challenges of IoT

Under the cooperation of those IoT enabling technologies, IoT is expected to realize the scalability with wide coverage, the intelligence with computing plane and AI algorithm, and the diversity with various projects. However, a further vision of IoT- to achieve the ubiquitous connection and intelligence for smart "everything", also introduces many new challenges such as deployment-constraint, battery-constraint, computing-constraint, security issues.

1. **Connection constraint**. The current infrastructure-based communication networks including WLAN, MCN, and parts of LPWANs, cannot be deployed in some geographical areas that are harsh, remote and usually lack of communication infrastructure e.g., construction sites, rural pastures, and mountainous areas. Beside, even though the infrastructure-less communication networks such as wireless ad hoc networks, P2P, have low cost in network nodes, the transportation and deployment of those nodes to massive positions in those remote areas are still a costly mission.

2. **Battery constraint**. Most IoT nodes owns limited battery, except for those nodes attached in the facilities with periodically supplied power, to save the global hardware cost from deployment of countless IoT nodes. We name those nodes *battery constrained nodes*. For this reason, the communication protocols of access networks must be designed with low power to prolong the lifetime of those battery-limited nodes. Upon battery of those nodes is exhausted, they tend to be abandoned, which is a new waste and pollution.

3. **Computing constraint**. Though the cloud plane supports a centralized intelligence for IoT, the edge plane has no enough computing resources to support intelligent algorithms requiring big data processing and big computation capacity. Nevertheless, enabling "everything" intelligence via the edge computing plane is necessary for IoT.

4. **Security constraint**. The existing IoT networks in edge access part simplified the communication protocols for lowering network cost, also weakening the security of the most edge nodes. Then the data emitted from end nodes is easy to be listened by eavesdroppers or pseudo-base-stations that imitate the normal IoT communication links. Especially for end nodes in self-organized networks, they are really far

from the centralized cloud and easy to be stolen once they lost connection with IoT.

Discussion. To address above constraints, we first need to find a cost effective way to built connection with IoT nodes in those deployment-constrained areas, no matter by extending the current infrastructure-based networks or deploying independent nodes self-organized with each other. Furthermore, we expect to achieve the sustainable power-supply by emerging wireless powering transferring and light weight computing algorithms. In addition, a physical security solution is required to protect the data in those ubiquitous end nodes and those end nodes themselves.

Over time, UAVs have enormous potential to provide an attractive solution to address four challenges of IoT, attributed by its flexibility and on-demand deployment. Combining with existing communication network, wireless powering transferring, and edge computing, UAVs can build an extended edge network of IoT with sustainable power, light-weight intelligence, and physical security protection.

2.2 Unmanned Aerial vehicles

UAVs have attracted a lot of attentions from both academic and industrial fields in recent years [28–32]. The current UAV technology covers many interdisciplinary aspects from the aerodynamics, physical manufacture materials, to the circuit boards, chipset and software; an indispensable point of those technologies is the controlling of UAVs by whatever remote control or on-board autonomy. This section will give an overview of previous UAV-based literature. In particular, the design for unmanned aircraft systems is briefly introduced firstly; then two popular UAV-based communication networks are introduced.

2.2.1 Unmanned aircraft system (UAS)

In practical, the unmanned aircraft system (UAS) provides the cooperated services containing flight control, information processing and tasks schedule for achieving UAV-based applications. A typical UAS is composed by three parts: the UAV, the ground-based controller/control station, and a system of communications between the two, in which communications of air-to-air (A2A) and air-to-ground (A2G) play a crucial role for relay of signals and wireless control of UAVs [33–35]. For an autonomous UAV performing tasks in remote areas, the function of the ground controller may be integrated in

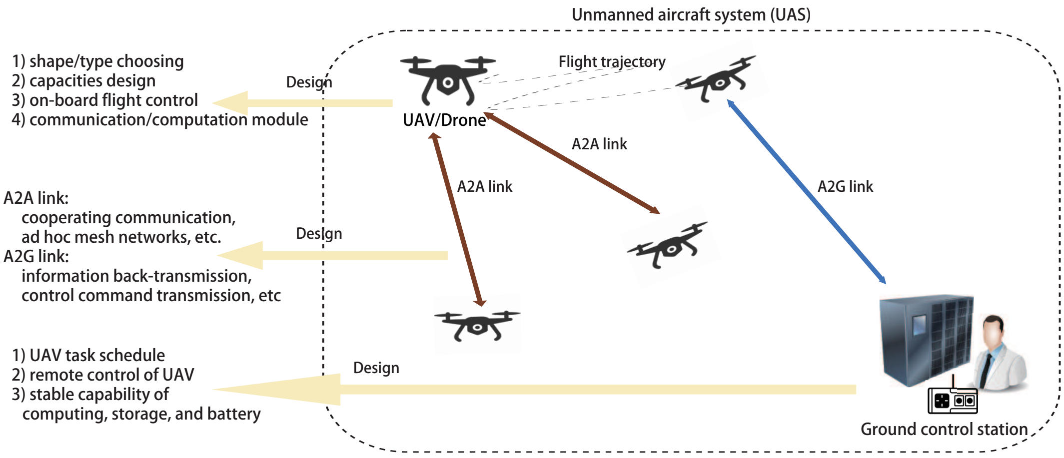


Fig. 2.2 An unmanned aircraft system

on-board, thus the autonomous UAV itself becomes a UAS.

In a particular application, it is necessary to design a dedicated UAS for the specific function such as video monitoring, radar detection, and even automatic localization and tracking. As shown in Fig. 2.2, the design of a dedicated UAS includes three aspects, i.e., design of UAVs, design of the ground controller, and design of communication protocols in the A2A link and the A2G link.

Design of UAVs and the ground controller

UAVs and the ground controller are expected to be designed with functional hardware and software, to support the specified application. In particular, for UAVs - the flexible task performer, below design aspects must be noticed.

1. **Shape/type choosing.** This aspect determines the basic flying requirements of UAVs according to different flying structures (winged craft, rotor-driven craft, etc.), and propulsion systems (engines, thrust-production, etc.).

2. **Capacities design.** This design add practical functions to UAVs, containing carrying capacities, on-board camera, signal transmission, anti-eavesdropping, etc., in terms of the different tasks.

3. **On-board flight control.** This design enables the flexible automatic mobility of UAVs, such as collision avoidance, gesture adjustment, etc., by a dedicated on-board algorithm [36–38].

4. **Communication/computation modules.** This module includes hardware for communication and data analysis, such as wireless transmitter/receiver, data storage units, data processing circle, etc.

Meanwhile, the ground controller is the final commander of all UAV tasks, should pay attention on following design aspects:

1. **UAV task schedule.** This aspect represents the global control of a UAV-based project, determining the performing periodical, the available resources, the work efficiency of all UAV tasks, and referring to the schedule optimization of one UAV with multiple tasks and multiple UAVs [39].

2. **Remote control of UAV.** This aspect aims to receive information from UAVs and also send commands to UAVs, requiring identical communication modules and protocols with UAVs.

3. **Sustainable capability of computing, storage, and energy supply.** This aspect is required to ensure a stable work of the ground controller. The specific design is depending on the practical requirement of data processing and communication links.

Design of communication protocols

The A2G link provides transmissions of both the downlink information and also the uplink control command; the particular design depends on communication requirements and also the wireless channel state in a specific scenario. Specifically, the real-time monitoring by photography requires high data transmitting rate and as short delay as possible, corresponding to a short-range and low-altitude communication, fitting for the small scenario such as home monitoring [40]. Besides, the high altitude UAS can support remote sensing applications while the communication latency is large and can only provide the long-periodic data transmission, as seen in [41–43].

The A2A link provides communications between multiple UAVs, is generally in line-of-sight propagations and thus is easily modelled. For this reason, the mobilities of multiple UAVs are also easily modelled, hence the research direction is transformed from A2A modelling to the collaboration design of multiple UAVs including routing protocols and path planning. The particular design objective of routing protocol and path planning is usually a trade-off between the coverage area and the flying/communication latency, as seen in recent works [44–46].

2.2.2 UAVs communication networks

The previous literature explores two classes of UAV communication networks: independent networks of multi-UAV and UAV-aided edge networks.

Independent networks of multi-UAV

This network is self-organized networks with high autonomy, usually independent with current networks, and thus can be widely applied in the specified occasion requiring mobile connection. Ref. [47] gives such a typical instance, in which a multiple-UAV network assists the vehicular-to-vehicular (V2V) communication in those region with poor connectivity to infrastructure-based networks. Expects for that, multi-UAV networks are also applied to solve the data acquisition problem in large-scale sensor deployed areas [48], the application of which includes disaster management [49], forest monitoring [50].

The research on multi-UAV networks places emphasis on A2A links for collaboration of multiple UAVs. Caused by the intrinsic mobility, the previous research on A2A links is about routing protocol; those works are especially in large amounts of attentions in recent years, as shown in several surveys [28, 51, 52]. For instance, [28] gives a comprehensive summery of routing protocols design principles of multi-UAV communication networks, including self-organization, disruption tolerance, SDN control, seamless handover and energy efficiency. Besides, [51] compares the performance of existing routing protocols that is classified in two categories: single-hop routing and multi-hop routing, in which the comparing options contains multi-path capability, load balancing, loop-free ability, route update method, dynamic robustness, energy efficiency, route metric, and so on.

UAV-aided edge networks

This kind of network is the complementary part of existing networks to extend the coverage areas. Different with independent networks of multi-UAV with self-organized topology and routing protocols, UAV-aided edge networks are infrastructure-based networks and in same communication structure and protocols with the aided edge networks. In this context, the UAV is in general deployed as edge nodes with network functions such as flying base-stations (e.g., [53, 54]) or relay nodes [55, 56], and also as just terminal nodes such as the aerial surveillance camera [57, 58].

Applying UAVs are relay nodes can provide flexible communication services in disconnected areas near to current networks. In particular, the UAV requires to keep both the communication links with the aided network and also the disconnected nodes. Depending on different scenarios, the disconnected nodes are in different distribution and the edge access protocols are also very different, posing the various investigations to flying trajectory/mobility design of UAV. In this case of applying UAVs are terminal nodes, the mobility design depends on the A2G link that is connected to the edge network and also the flying path requirement for the specified task. The investigation methods are similar with UAV-relay/BS works; both two use a large amount of similar metrics to design trajectory, including QoS of communication links, sufficient coverage [59], time-efficiency, energy efficiency [60], outage probability, etc.

2.2.3 Discussion

UAS and UAVs communication networks represent two stresses from mechanical control and telecommunication in academical research of UAVs. Although they focus on different results (UAS aims to global control while UAVs communication networks aim to connection design), they also share a common research point, i.e., mobility design of UAVs. Reviewing the past survey of the UAV (e.g., [46, 60–62]), UAV's mobility design (including *trajectory design* or *path planning*) is in crucial investigated. Attributed by UAVs' mobility and so many related works, we find the opportunities of UAVs enabling IoT in following section.

2.3 UAV-enabled IoT (UeIoT)

In this section, we will first investigate the opportunities of UeIoT in addressing the four constraints of IoT. Then we propose the UAV-enabled IoT (UeIoT), in which UAV-enabled scalability, intelligence, and diverse are introduced, respectively. After that, we list five typical application scenarios as case studies of UeIoT.

2.3.1 Opportunities of UAV bringing to IoT

It is a very fact that UAVs can provide an enhanced IoT solution with extended coverage, flexible intelligence, and more diverse applications. This enhancement is based on employing UAVs as various kinds of edge nodes such as aerial base stations, data collectors, jammers, monitors, edge computing nodes, power suppliers, reclaimers. Hence, UAVs have a huge potential to address some existing constraints of IoT; this potential brings us the corresponding opportunities from four aspects as shown in Fig. **??**.

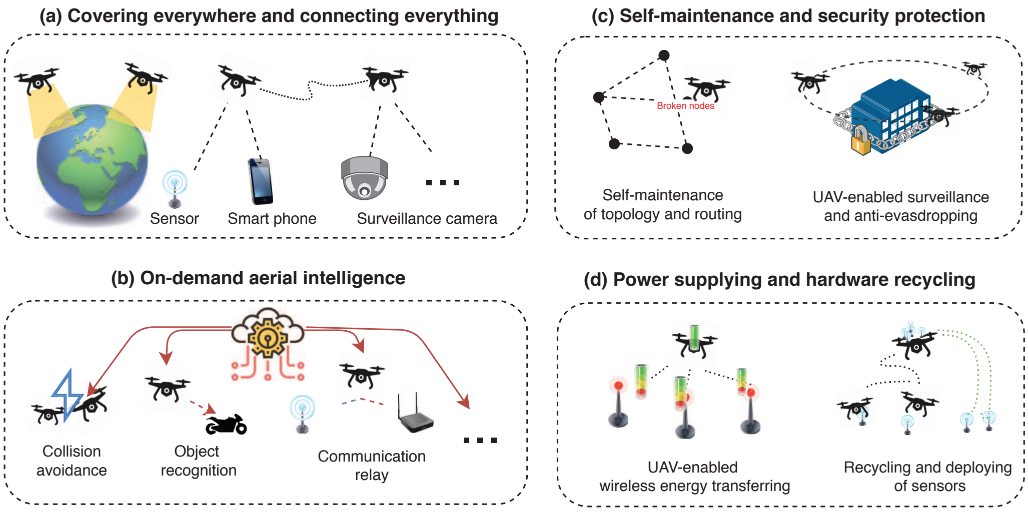


Fig. 2.3 Opportunities of UAV bringing to IoT

Covering “everywhere” and connecting “everything”

Covering *everywhere* is the most fundamental condition to connect *everything*, confirming to the nature requirement of IoT. Applying UAVs to address the *connection constraint* of IoT promote the opportunity to cover *everywhere*. As in section 2.3.2, by using UAV-aided existing networks and building the independent UAVs ad hoc networks, UAV can extend the edge access network to areas with weak-connection and areas without network deployment. Thus, UAVs repair the connection to those uncovered areas of IoT; covering *everywhere* is accordingly achieved.

On-demand aerial intelligence

UAVs can enable an aerial intelligence at the edge side, by using the collected data from the sensors embedded at the UAV itself and also a cluster of IoT nodes along the UAVs' designed trajectory. As in section 2.3.2, this aerial intelligence can be deployed in an on-demand manner according to the specific requirement in the intelligent edge network. The requirements including collision avoidance, communication quality, and trajectory for data collection, form the objective of the aerial intelligence that leads to the on-demand control for UAVs' gesture, position, height, etc. Such as cooperative formation control of tracking a moving target [63]. Besides, UAVs also play as an aerial command-maker to assist producing intelligent perception and decision for IoT nodes with limited computation capacity and also restricted data.

Self-maintenance and security protection

UAVs can support self-maintenance for the communication in edge side of IoT. In more general, the IoT nodes in edge side is easily destroyed and lost attributed by various unstable factors from human or nature environment. For this reason, UAVs can compensate the lost edge communication when employed as a node thrower and placementing IoT nodes in suitable areas. In addition, the edge communication usually adapts the simplified access protocol for reducing cost, such as NB-IoT [17], which causes vulnerable security to IoT, especially for some IoT nodes with high privacy or confidentiality. Such as IoT nodes for malfunction detection in smart manufacturing, and also the nodes for collision avoidance and congest control in intelligent transport system. In this regard, UAVs can form a dedicated edge network to supply physical security such as employing UAVs as jammers to interference the communication of eavesdropping [64] or offer an enhanced encryption security by configuring the dedicated protocols in UAVs [65, 66]. Compared with the previous research on security protection of conventional IoT [67–70], UAVs offer a more flexible protection with adjustable positions and protocols.

Power supplying and hardware recycling

It is worth noting that the general IoT nodes are resource-constrained in both battery, storage, and computation capacity; this phenomenon is especially serious in those weak-connection/no-connection areas. The UAV has the most potential to connect every IoT node in those areas; hence the UAV also is the most suitable facility to supply or update the restricted resource of those IoT nodes. In particular, the UAV can supply energy to those nodes by wireless energy transferring (WET) [46] and even can achieve simultaneously wireless information and power transferring (SWIPT) [71]. Besides, UAVs can recycle the damaged nodes with disabled function and release a new nodes as the replacement.

2.3.2 UAV-enabled IoT: UeIoT

Owning to the opportunities generated by the flexible applying of UAVs on deploying, configuring, and controlling to IoT, we can integrate UAVs in IoT to further enabling three expectations of IoT, i.e., scalability, intelligence, and diversity. Hence, UeIoT introduced in this subsection will be divided into three parts, i.e., UAV-enabled scalability IoT, UAV-enabled intelligent IoT, and UAV-enabled diverse IoT, respectively.

UAV-enabled scalable IoT

Cooperating with existing networks (i.e., WLAN, MCN, LPWAN, P2P, Wireless ad hoc network), UAVs can enable a scalable IoT for maximizing the coverage. In particular, UAVs can maximize the coverage of IoT by mainly extending the edge access network in two kinds of areas as follows.

1. **Areas within weak-connection.** These areas are usually covered by the existing networks such as WLAN, MCN, and LPWAN; but these areas are always in weak-connection state due to the complex geographical environment and serious communication requirements. Four typical areas are *construction sites in urban*, *disaster regions in urban*, *areas-hidden in buildings* and the *the road of transportation*. All these areas naturally suffer from the extremely unstable wireless link connected to the existing network infrastructure; this effect is caused by the movable or various obstructions everywhere. To address this problem, UAVs can aid the existing network to provide a flexible edge access network; UAVs can play as the on-demand relay nodes or base stations or gateways to connect the IoT nodes.

2. **Areas without network deployment.** These areas are in general remote and lack of inhabitants; hence no network infrastructures are deployed in those areas. Four typical areas are *farms, desert, forest*, and *ocean*. To cover those remote areas, what UAVs can do includes two parts: 1) building an independent network for every specific area; 2) designing the access scheme from this independent network to the existing IoT network. To achieve above two goals, the multi-UAV ad hoc network can be applied; this multi-UAV network is self-organized by the wireless ad hoc network protocol and can execute the detail tasks for supporting communications, remote sensing, data acquisition, etc [72]. The ad hoc network comprised by multiple UAVs is an isolated system when UAVs fly to remote areas; meanwhile, the UAVs connect to the terrestrial networks when they fly back to the ground control center along a designed path.

Related works using UAVs to solves the corresponding issues of above areas are shown in Tab. 2.1.

UAV-enabled intelligent IoT

By embedding some lightweight AI algorithms, UAVs can conduct smart decisions or control commands and further enable intelligence to themselves or to the ground IoT

Table 2.1 UAV-based research in two unconnected areas of IoT

Typical areas	**UAV-enabled research**
Areas within weak-connection	
Construction sites in urban areas. • Lack of flexible detection and surveillance.	⋆ Construction project management [73–75]. ⋆ Indoor construction progress monitoring [76]. ⋆ Survey: applications of unmanned vehicles in construction site [77].
Disaster regions in urban areas. • Ruined local network.	⋆ Disaster management and surveillance [49, 78–80]. ⋆ Emergency networks construction [81–84].
Areas-hidden in building obstructions. • E.g., warehouse, basement, bazaar.	⋆ This area is usually included in the convergence scheme of UAV and the current networks (such as 5G, IoT) [11, 49, 85–88]. ⋆ Patrolling and surveillance [89–94].
The road of transportation. • Non-uniformly distributed networks along the road.	⋆ Intelligent transportation systems in city [95–98]. ⋆ supporting connectivity to ground vehicles [13, 99–101].
Areas without network deployment	
Farms • Repetitive operations and periodical surveillance.	⋆ Survey of UAV in agriculture [102, 103]. ⋆ Patents of agricultural UAV [104]. ⋆ Imagery analysis of crops [43, 105–108].
Desert • Arid and sizzling weather.	⋆ Disaster monitoring in desert [109–111]. ⋆ Geomorphological analysis [112–114]. ⋆ Military detection in desert [115].
Forest • Various flora and fauna.	⋆ Trees and plants monitoring [42, 116–118]. ⋆ Growing stock volume prediction [119, 120].
Ocean • Stormy and violent weather.	⋆ Coastal environment analysis [121–124]. ⋆ Ocean environment monitoring [79, 125–127]. ⋆ Marine science and observation [128–131].

nodes. In this way, UAVs can help fill the gaps to the edge intelligence in IoT. Specifically, we will introduce the UAV-enabled intelligent IoT via two following respects.

1. **The intelligent edge network.** In this case, UAVs are employed as network nodes and aim at enabling the intelligence of network functions. In terms of the bottom up sight, we introduce three layers of intelligent network functions: the physical layer, the network layer, and the application layer.

   - The bottom function is the physical layer; the primary matrix of this layer is the wireless connectivity of the UAV to its surround nodes. An intelligent connectivity requires the good channel state; this can be achieved by deploying the UAV in optimal aerial positions. The related optimization research are summarized in section 2.2.2 designed the optimal path trajectory and also the topology for self-organized networks or just relay-based edge networks.
   - The middle network function - the network layer refers to routing choosing of the packet; the routing function relies on recognizing the source address and the destination address of every packet. In self-organized networks, the routing choosing has dynamic solution with the changed topology (e.g., [51]). Besides, in edge networks, the routing function contains recognition of the multiple access and controlling the congestion from massive ground nodes to the UAV or from multiple UAVs to the ground access point. Therefore, the intelligent routing function to UAV should include dynamic routing, smart access, congestion control. Without loss of generality, security control should also be considered in this layer.
   - The top network function - the application layer needs to satisfy requirements of the specified application; this function is usually achieved by the high-level interface to send the intelligent commands. The high-level commands further guide UAVs performing data operations, such as data compression, data aggregation.

   In general, UAVs owns limited hardware resources and cannot support the network functions above that require many global storage and computation. Fortunately, the concepts of network functional virtualization (NFV) and mobile edge computing (MEC) give us solution to enable above three layers of network functions at UAVs. NFV can virtualize the network function to the program; MEC can dispersing the virtual function into the specific hardware at every mobile UAV. Thus, multiple UAVs enables dynamic, programmatically efficient network configurations consisting of accessing, routing, switching, and firewall supports; this NFV/MEC-driven UAVs network is similar with a mobile software defined network (SDN), and practically the network functions can be managed by SDN technologies (e.g., [132]).

2. **The intelligent terminal service.** In this case, the UAV plays the role of a terminal node in IoT, and usually conduct the task with strong maneuverability and quick response such as real-time monitoring, tracking, and surveillance. The terminal services supported at UAVs are intelligent via a controlling algorithm. This algorithm guides UAV the controllable motions including gesture adjustment in the air, the flying height, and other manoeuvrable actions, depending on the specific IoT task.

   The algorithm controlling motions of the UAV can be conducted in the local computing plane, the edge computing plane, and the cloud computing planes. The practical choice of the computing plane relies on the particular intelligence requirement.

   - Choosing the local computing means the UAV entirely control the motion by its own computing resources, in which a pre-designed AI program is embedded. The local controlling has the merit of quick response without delay but restricted by limited computing resources. Hence the controlling algorithm running on the local plane must be lightweight.
   - In contrast, the edge computing plane in general lies on the near ground access stations of UAVs; this plane has more computing resources than the local computing plane but also leads to the delay of the transmission of the controlling commands.
   - Furthermore, the cloud computing plane has the huge computing resources but the delay of the controlling commands is very long.

   Therefore, we can choose the local controlling for immediate and simple intelligence such as ; we can choose the edge/cloud controlling for time-tolerate and complicated intelligence such as .

Related works of UAV-enabled intelligence are summarized as Tab. 2.2.

Table 2.2 UAV-based research to enable intelligent IoT

Intelligent sides	**UAV-enabled research**
The intelligent edge network	
Intelligent physical layer • Optimizing the position and trajectory.	⋆ Connectivity of multi-UAV networks [80–83, 99]. ⋆ Connectivity of UAV-based edge networks [13, 55, 88, 133, 134]. ⋆ MEC-aided intelligent trajectory [135–139].
Intelligent network layer • Routing choosing, • Smart access • Congestion control • Security control	⋆ Routing protocols of multi-UAV networks [28, 51, 52]. ⋆ SDN-driven network management [132, 140–143] ⋆ MEC-aided secure control [144, 145].
Intelligent application layer • High-level control	⋆ Application-driven UAV systems: disaster sensing, policing enhancement, manufacturing management [146–149].
The intelligent terminal service	
Local computing plane • Zero transmission delay • Lightweight intelligence	⋆ Lightweight target tracking algorithms [150, 151]. ⋆ Real-time AI algorithms [152]. ⋆ Real-time flying control [153].
Edge computing plane • Little transmission delay • Mediate intelligence	⋆ MEC-enabled computing resource offloading of users [154–158]. ⋆ MEC aided UAVs' computing [135, 137, 138, 145, 159].
Cloud computing plane • Longest transmission delay • Strongest intelligence	⋆ Cloud-supported UAV applications: monitoring and management [148, 160–164].

UAV-enabled diverse IoT

Applying UAVs in different scenarios of IoT, such as smart manufacturing and smart traffic, will bring more diverse applications for IoT. In recent decades, UAVs have attracted a large number of attention of scenarists and businessmen due to its basically boundless extent of UAV services. At the civilian-use level, the small-scale UAV, usually known as the drone, is used as flying cameras to expand the vision and really popular for amateurs and ventures. In addition, at the business-use level, the UAV with dedicated design has various configurations for different applications such as delivering products to clients, delivering urgent medical supplies, and serving as the urgent aerial base stations. Once integrating UAVs in IoT, the application of UAVs just becomes more diverse due to the wide network coverage, big sharing database, and ubiquitous intelligence. Thus, we will achieve very high efficiency in every aspect of our daily life. The high-efficient aspect will include security surveillance, jogging accompany, military detection, natural science research, crime tracking, and assault, etc. The potential applications of UAV to seismic risk assessment, transportation, disaster response, construction management, surveying and mapping, and flood monitoring and assessment.

2.3.3 Applications of UeIoT

This section will introduce several applications of UeIoT as case studies, referring to the current mainstream of the UAV-enabled IoT applications (e.g., intelligent transportation system, automatic package delivery, aerial surveillance) and also discussing the potential direction of the future development for green and sustainable requirement (e.g., unmanned trash recycling, aerial power supply).

Intelligent transportation system

Intelligent transportation system (ITS) as one of the major components of smart city, is expected to be automated transportation decision and security through inter-connected vehicles. The conventional transportation system is quite time-consuming and manpower-consuming, in which the decision and execution mainly rely on the coordination of a large number of components such as the field support team, traffic police, road surveys, and rescue teams. ITS aims to achieve automation of components of the conventional system, to make the decision and execution more efficient.

Considering the application of UeIoT in ITS (UeIoT-ITS), we can employ the smart and reliable UAV as the transportation information collector, the information transmitter, and even the executer for traffic schedule [95]. For example, a road support team can be replaced or supported by a set of UAVs that could fly around the location of an incident to provide basic support, or at least to send back a survey report about the situation. Moreover, a traffic police officer can also be replaced or supported by UAVs, which can fly over vehicles on a highway to monitor and report possible traffic violations. In such an UeIoT-ITS scenario, internet connection of the real-time transportation information can be offered by UAVs communication networks; a fast decision and execution to enforce traffic rules and support traffic police on the ground can also be provided by running a dedicated AI algorithm in local/edge computing plane; intelligent information services can also be supported by conveying efficient information on traffic or other real-time messages from internet to road users.

Automatic package delivery

There are always shortages of living material in underdeveloped and hard to reach areas; the shortage is especially urgent for those areas under natural disaster and plague. Due to the disconnected road, applying UAVs as the flying transportation vehicle becomes an effective method to achieve the automatic package delivery of some important materials such as medicines, foods, and clothes [40, 165–168]. Besides, using UAVs for ordinary express delivery in urban areas is also attracted the attention of the businessman, attributed by its flexible deployment and high cost-efficiency.

To make the automatic delivery practical, we can use UeIoT to achieve on-line designs of hardware of UAV, navigation, path, positioning, and delivery cost-efficiency by enabling communication ability and computing ability to the delivery UAV. Specifically, the previous research has done partial of those design for delivery UAVs. For example, [169] developed a long-range and energy-efficient communication system for UAVs delivery application assisted by LoRaWAN, in which the use of LoRaWAN protocol is evaluated to achieve a semi-real-time telemetry purpose. Besides, [170] propose two multi-trip vehicle routing designs for the cost-efficient drone delivery, in which the effect of battery and payload weight on energy consumption is considered. The further research encompasses hardware structure design [171] and also the supplier cooperation [172].

Aerial surveillance intelligence

Since fixed surveillance cameras placed in specific occasions can only offer inflexible views, we expect to develop an aerial surveillance devices for a flexible and multi-view detection in both military and civil applications. Over the last decades there has been growing research of UAVs for aerial surveillance system (ASS) [57, 58, 79], in which UAVs embedded with the surveillance camera can employ sufficient aerial assets for ongoing collection of information from a specified area. In particular, lots of work examines the autonomous UAVs for surveillance, including the detection of surveillance regions [173, 174], the locking of surveillance objects [105], and the adjustment of surveillance paths [25, 175, 176]. Those autonomies further enabling intelligence of UAV-enabled aerial surveillance.

In addition, there is a strong demand to design an interface for connecting to the ground control nodes in internet; this connection enable the internet to monitor the record at UAVs and hence the internet can exploit the AI algorithm in cloud/edge computing plane to store and analyze the surveillance photographs and videos. Some work investigates the dedicated AI algorithms for rangeland inventory monitoring [108], emergent trees detections in tropical rainforests [116], soil erosion monitoring [177], forest phenology monitoring [117].

Unmanned military missions

In previous literature, UAVs are frequently used to perform many military missions under highly chaotic situations [178]. In particular, UAVs can be employed as the aerial detective in chaos battlefield, to detect the movements of enemy's troops and also monitor the global battle situation [179]. Besides, UAVs can also periodically spy the suspicious region such as border surveillance [115]. The UAV-based relay communication in military also be widely investigated in existing works, e.g., [180, 181].

Obviously, UAV-enabled military missions (we name it unmanned military missions) will save a lot operating costs in manpower, and fixed network infrastructures. The efficiency of this unmanned mission works under reliable control for exposure avoidance and strict trajectory design. Especially for some missions in inaccessible areas (mountains, ice roads, desert, etc.), the reliability of remote control is quite significant. Due to scalable coverage and intelligent computing resources, UeIoT is definitely qualified to support the wireless connectivity and also the intelligence of anti-detection, further enable a reliable remote control of UAV-enabled military missions.

Unmanned trash detection and gathering

With human's economy and society developing, we create the growing quantity of trash. Those trash is composed by various things that we throw away, such as empty bottles, used papers, and building waste. There are substantial part of those trash that is recyclable such as plastic trash, metal trash, and paper trash. However, in real life, most of trash is processed together without reasonable classification via incineration or landfill ways. Those trash process ways cause undetermined physic-chemical reactions and further bring a large amount of environment pollution to our sky, ocean, soil, and forest.

One valid to address the above pollution problem is making a good classification at the beginning throw of those trash. So far, the standard regulators of trash throwing is effective in urban residential area. Except for that, many other areas are not in a good regulation of trash recycle; those areas usually lack of human management such as some remote natural regions (lake, river, mountain), the underdevelopment industrial regions, remote villages and towns. UeIoT with its scalable coverage, can easily fly to those areas to perform trash gathering. Meanwhile, a trash detection algorithm can be enabled by UeIoT to guide the flying trajectory of UAVs.

Discussion: this section gives five typical representatives for UeIoT applications. In additions, there are more applications of UeIoT such as UAV-enabled power supply [46], social internet of vehicles [158], waiting for future research.

Chapter 3

UAV-enabled Data Acquisition Scheme with Directional Wireless Energy Transferring

This chapter considers UAV's using as wireless energy supplier and also data collector in a IoT scenario. Section 3.1 introduces the motivation, the basic idea of the proposed data acquisition scheme. Sections 3.2 - 3.5 give the details of the proposed schemes, containing system model, problem formulation, scheme design and numerical results. We summary and discuss the future work in Section 3.6.

3.1 Introduction of UAV-enabled data acquisition scheme

As in Chapter 2, IoT is widely used in various applications, resulting in the upsurge of massive data generated from a diversity of IoT devices, such as sensors, RFIDs tags, and smart meters. Analysis on big volume of IoT data is bringing numerous values including forecasting disastrous events, reducing factory machine downtime, enhancing product quality and improving supply chain efficiency [8]. Data acquisition is a crucial step during the whole procedure of IoT data analytics while it is also challenging due to the *diversity* of IoT devices and the *heterogeneity* of IoT networks.

The conventional data acquisition tasks of IoT rely on LPWAN technologies to support wide coverage and low cost [9, 182, 183]. Meanwhile, as in section 2.1.3, we notice that two intrinsic problems presented in this context: 1) the limited battery storage of IoT nodes and 2) the inflexible connection of existing networks.

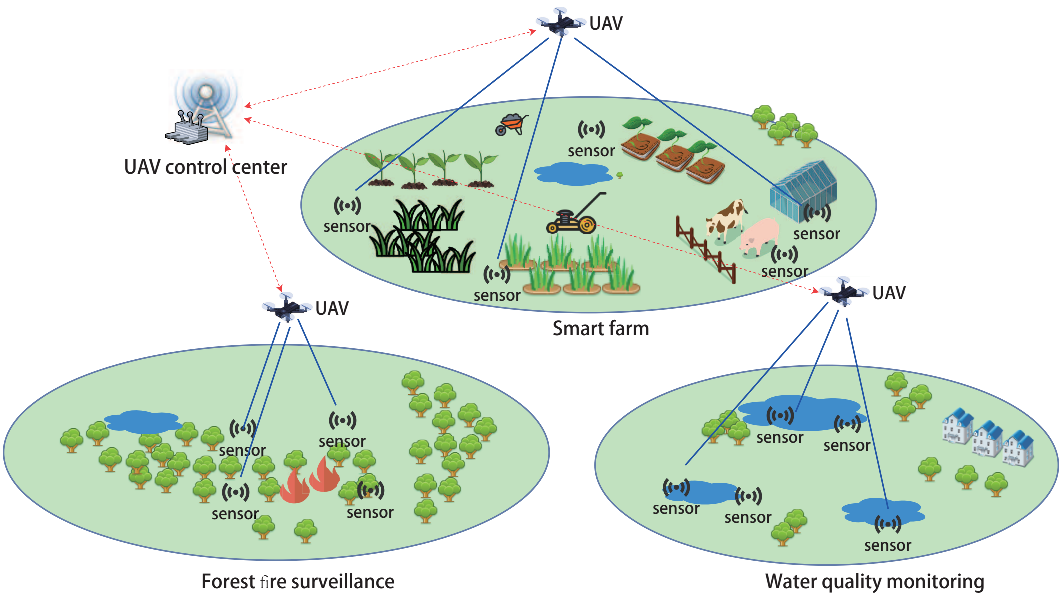


Fig. 3.1 Application scenarios of UAV-enabled data acquisition with WET

1. Regarding 1), an IoT node typically has a limited battery storage and some of IoT nodes may even have no battery (e.g., passive RFID) [184]. IoT nodes often turn off to save energy when there is no data transmission demand.

2. Regarding 2), the infrastructure nodes in current IoT networks usually result in the high expenditure and the inflexible connection. This problem is especially serious in areas within weak connection or without network deployment.

Above two problems always occur in the scenarios like rural pastures, mountainous areas and ruins after a disaster [185].

WET technologies can be used to address the limited-battery problem, by transferring radio energy to wireless nodes so as to prolong the life-span of IoT nodes [186, 187]. Moreover, it is shown in recent studies such as [188–191] that directional WET technology based on beamforming (BF) can further improve energy-transferring efficiency. In particular, directional WET is achieved by directional BF via a multi-antenna array mounted at the energy transmitter. In addition, as discussion in section **??**, UAVs can be used to address the inflexible-connection problem due to its high mobility and deployment flexibility[192]. There are many studies employing UAVs as relay nodes to extend the coverage of communications networks [14, 99, 193]. The studies such as [27, 44, 48, 194] exploit UAVs as the data collectors hovering over the area with IoT nodes to obtain the IoT data.

Therefore, the integration of UAV and WET technologies can potentially overcome the aforementioned two problems of IoT data acquisition. In particular, UAVs can transfer radio energy to IoT nodes which can then have enough energy to transmit data back to UAVs. During this procedure, a UAV plays a role of both an energy supplier and a data collector in IoT. Some recent studies exploit the integration of UAVs with WET technology. For example, the work of [46] investigates the optimal UAV trajectory when using UAVs as energy suppliers to IoT nodes. In contrast to these prior studies, this paper mainly concentrates on designing UAV-enabled data acquisition scheme with directional WET for IoT.

Particularly, we propose a UAV-enabled data acquisition scheme with directional WET, in which a UAV serves as both energy supplier and data collector for IoT nodes. Without loss of generality, we assume that there must be an IoT control center responsible for UAV's dispatching, path planning, and the resource pre-allocation. In addition, we also mount a multi-antenna at the UAV to generate BF energy signal so as to improve the energy transfer efficiency. After the IoT node harvests enough energy, it will then send back the data to the UAV. Our scheme can be used in a number of IoT application scenarios, such as forest fire surveillance, smart farms, water-quality monitoring in rural areas.

Based on our idea, we make the following contributions:

- We design a 4-step communication process consisting of 1) IoT-node activation, 2) IoT-node localization, 3) wireless energy transferring, 4) data transmission. It is worth mentioning that IoT nodes can be activated via a wake-up signal sent from the UAV. UAV can then accurately localize the IoT nodes via the feedback signal sent from IoT nodes. After the activation and positioning process, the UAV next transfers the wireless energy to IoT node, which can send back the data with the harvested energy.

- To improve the overall energy efficiency during WET and data transmission, we construct an energy minimization problem, which is subjected to two constraints: balanced energy supply and limited overall time. We then obtain closed-form expressions of the optimal WET time and data transmission power via solving the optimization problem.

- We design an allocation scheme based on the optimal solution in the energy minimization problem. We also demonstrate that the allocation scheme is feasible since the allocation parameters fall into the feasible ranges of system parameters.

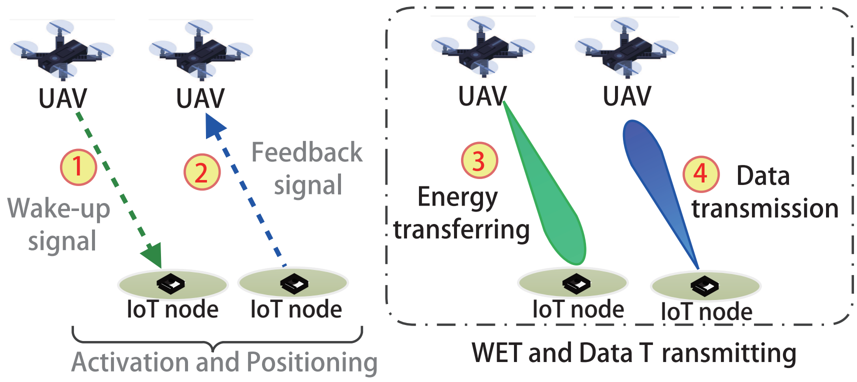


Fig. 3.2 A UAV-enabled data acquisition including 4-step communication process

We also show that the allocation parameters are adjustable with the varied values of system parameters.

3.2 UAV-enabled data acquisition

Our system design includes two parts: Section 3.2.1 gives communication design of a data acquisition; Section 3.2.2 shows the mathematical model in data acquisition.

3.2.1 Communications design

We assume that every UAV is pre-allocated with special path planning and battery storage; the preallocation is usually conducted at a ground control node [195]. In the data acquisition scenario, we assume that the ground control node is an IoT control center supporting that pre-allocation of UAVs by some prior knowledge such as the distribution of sensors, location of sensors and size of sensed data. Thus, one dispatched UAV can hover in the location of the IoT node one by one to conduct WET and data transmission along the designed path, in which the UAV is mounted with multiple antennas and an IoT node is mounted with a single antenna.

Although the general communication networks (such as LPWAN) provides reliable and periodical communication, the IoT nodes may not have data to send all the time. This phenomenon is especially serious for those nodes constrained by battery and coverage since those nodes have neither enough energy nor the available receiver. Hence, we use a simple radio frequency (RF) wake-up mechanism to provide an on-demand data acquisition, in which the UAV transmits a wake-up signal to the IoT node and then the IoT node is activated upon detecting enough power from the wake-up signal [196]. Compared with periodic-based communications in conventional LPWAN, RF wake-up mechanism is more flexible and more suitable for data acquisition applications with sporadic transmissions especially for those sensors in deployment-constrained areas.

Combining the wake-up mechanism with WET and data transmission, we design a 4-step communication process in one data acquisition task (we call it *one task* for simplicity in rest of this paper) as shown in Fig. 3.2. Table I summarizes the four steps. We next describe them in details. In *Step* 1, the IoT node can be woke up upon detecting enough

Table 3.1 4-step communication process in one task

Step 1	The UAV broadcasts a wake-up signal to the IoT node.
Step 2	The IoT node transmits a feedback signal to the UAV.
Step 3	The UAV transmits the BF energy signal to the IoT node along its orientation.
Step 4	The IoT node uses harvested energy transmit its sensed data.

power from the wake-up signal [196]. In a general case, given a certain height, the received power at sensors depends on the power of the wake-up signal. For simplicity, we assume that the power of the wake-up signal is large enough to activate sensors. This *large-enough* power value is computable and designed by IoT control center. After *Step* 1, the IoT node is activated and then conduct *Step* 2, i.e., transmitting a feedback signal to UAV. *Step* 2 is necessary for UAV to estimate the orientation of sensors by analysing the received feedback signal via the multi-antenna array as assumed in [197–199]. We assume that the IoT node keeps a static position after been woke up; then the UAV can estimate the precise orientation of the IoT node. After that, the UAV can obtain the BF vector including the orientation of one IoT node and the energy supply is accordingly controllable by allocating WET time and power. In conclusion, the first two steps are designed for activation and positioning of the IoT node, paving the way for WET and data transmission. The last two steps are more crucial to accomplish data acquisition than the first two steps. This is because, in last two steps, it is necessary to fulfil two goals: 1) achieving the balance between the energy supply and demand; 2) limiting the overall time of WET and data transmission. These two goals can be mapped to the following two conditions, respectively:

- **Balanced Energy Supply**. The harvested energy at the IoT node is equal to the consumed energy in data transmission. This condition can help to achieve the highest energy efficiency because the entire harvested energy is used for data transmission without waste. Note that energy supply being higher than energy consumption is a more general consideration to ensure sufficient and reliable energy supply.

- **Limited Overall Time**. The overall time spent at one task must be smaller than a maximum threshold value to ensure time efficiency. Since time spending on activation process is negligible, the overall time is equal to the sum of WET time and data transmission time.

3.2.2 Communication Model

The wireless link

The wireless link between a UAV with N antennas and an IoT node with single antenna can be characterized by a vector $h \in \mathbb{C}^{N\times 1}$, where $\mathbb{C}^{N\times 1}$ denotes the space of $N \times 1$ complex matrices. We assume that the UAV hovers at a fixed position for one task. Then we can assume that the wireless channel of WET is identical to that of data transmission.

The BF energy signal

We denote the normalized BF vector by $\mathbf{w} \in \mathbb{C}^{N\times 1}$ and denote the normalized energy signal by x. Let P be a fixed energy transmitting power. Then the BF energy signal is given by $s = \sqrt{P}\mathbf{w}x$. To ensure a high energy efficiency in WET, we use an optimal BF vector given by

$$\mathbf{w}^* = \frac{\mathbf{v}_1}{\|\mathbf{v}_1\|},$$

where $\mathbf{v}_1$ is an eigenvector that matches with the maximum eigenvalue λ_1 of matrix H being the covariance matrix of h, i.e., $H = hh^H$. The derivation for expression $\mathbf{w}^*$ is given in Appendix A.

The optimal BF vector leads to the maximum harvested power $\lambda_1 P/\|\mathbf{v}_1\|$ at the IoT node. Herein $\mathbf{v}_1$ also represents the orientation of the IoT node because it corresponds to the maximum orientation gain. Hence, in rest of this paper, we use $\mathbf{v}_1/\|\mathbf{v}_1\|$ to represent the BF vector.

Two portions of the overall time

Let T be the overall time of one task and $T^{\max}$ be the upper limit of T (i.e., $T \leq T^{\max}$). We ignore both the time and energy consumption during the first two steps since the packet size during the activation process is so small that it can be ignored. Hence we consider that the overall time consists of two portions: the time for WET and the time for data transmission. Let α denote the portion part of WET time where $0 < \alpha < 1$. Then αT represents the time for WET and $(1-\alpha)T$ represents the time for data transmission. Note that the time of signal conversion in energy harvesting and the time in data processing are also negligible because they are much smaller than the overall time T.

The harvested energy

The harvested energy of one IoT node in a task is denoted by e_{EH}. Combining the WET time αT with the energy harvested power $\lambda_1 P / \|\mathbf{v}_1\|$, we derive the expression of e_{EH} as follows

$$e_{EH} = \zeta \alpha T \frac{\lambda_1 P}{\|\mathbf{v}_1\|}, \tag{3.1}$$

where $0 < \zeta \leq 1$ denotes the constant energy conversion efficiency similar to [189, 200].

The data transmission

We denote the data transmission power by p and denote the data transmission size by l. We assume that p can be controlled by the UAV. This assumption can be achieved by using the downlink energy signal carrying the power control command with the value of p; this control command only needs to occupy a very small part of the energy signal and thus the impact is ignorable to the WET process. In addition, we assume l is fixed as a prior-knowledge in IoT control center. According to Shannon–Hartley theorem [201], we can construct the achievable data transmission rate, which is $r = B\log_2\left(1 + \frac{p\mathrm{tr}(H)}{N_{noise}}\right)$, where B is the transmission bandwidth and N_{noise} is the noise power. The data transmission time is equal to l/r. We then have the time equality $l/r = (1-\alpha)T$ and further derive the expression of T

$$T = \frac{l}{(1-\alpha)r}. \tag{3.2}$$

We next have the consumed energy at sensors during data transmission, denoted by e_{DT} as follows

$$e_{DT} = p(1-\alpha)T. \tag{3.3}$$

Overall Energy Consumption

Let $e_{overall}$ be the overall energy consumption in one data acquisition task. We have

$$e_{overall} = \mathrm{tr}(\mathbf{s}\mathbf{s}^H)\alpha T = P\mathrm{tr}(\mathbf{w}\mathbf{w}^H)\alpha T = P\alpha T. \tag{3.4}$$

where $\mathbf{w}\mathbf{w}^H = \mathbf{v}_1\mathbf{v}_1^H / \|\mathbf{v}_1\|^2 = \mathbf{I}$ is the covariance matrix of $\mathbf{w}$. Obviously, the overall energy consumption in one task is equal to WET energy consumption at the UAV.

3.3 Problem Formulation

In this section, to further improve energy efficiency, we minimize the overall energy consumption in a task and find out an optimal energy supply solution.

3.3.1 Problem Formulation

To find out the optimal energy supply solution while maintaining high energy efficiency, we use the minimization of the overall energy consumption in a task as the objective and both the balanced energy supply and limited overall time as the constraints. We choose three controllable system parameters as the variables i.e., overall time T, WET time factor α and data transmission power p. The other system parameters are either fixed as prior knowledge (such as WET power, size of sensed data, communication bandwidth) or uncontrollable parameters (such as channel fading, noise, and energy conversion efficiency). We then construct the object function, constraints and optimal solutions based on these system parameters. In particular, we construct an overall energy minimization problem by optimizing p, α and T as follows:

$$(\mathscr{P}1): \quad \min_{p,T,\alpha \in (0,1)} \quad e_{overall} \tag{3.5}$$

$$\text{s.t.} \quad e_{EH} = e_{DT}, T \in (0, T^{\max}], \tag{3.6}$$

where $e_{EH} = e_{DT}$ represents a balanced energy supply for a generally consideration and $T \leq T^{\max}$ is the condition of *Limited Overall Time*. The optimal solution in $\mathscr{P}1$ can be used to adjust the data acquisition task in an optimal energy supply-and-demand. For example, multiplying the optimal data transmission power p^* by the optimal data transmission time $(1-\alpha^*)T^*$, we get the optimal energy consumption for data transmission demand; multiplying the WET power P by the optimal WET time $\alpha^* T^*$, we get the optimal energy supply in WET.

3.3.2 Optimal Solution

Due to fading characteristics of the wireless channel, both WET and data transmission processes are sensitive to the diverse channel fading effects, leading to unstable energy supply-and-demand in a task. Hence, we find that the optimal solution of energy supply-and-demand is related to the channel fading and also constrained by the feasible range of the channel-fading. In order to simplify the analysis of our solution, we define $\kappa \triangleq \frac{N_{noise}}{\zeta \lambda_1 P \frac{\mathrm{tr}(H)}{\|\mathbf{v}_1\|}}$ as a joint channel-fading degree that will be used to represent the feasible condition of our optimal solution. Obviously, κ represents a system-fading degree in terms of the wireless channel, noise and also energy conversion. We observe that, the smaller value of κ indicates a better communication condition.

Solving $\mathscr{P}1$, we derive the optimal solution as shown in Theorem 1.

Theorem 1 $\mathscr{P}1$ *has two optimal solutions for two cases:*

Case 1 If channel-fading degree κ is in the range specified as follows,

$$0 < \kappa \le \frac{T^{\max} B}{3l} - \frac{1}{2}, \tag{3.6}$$

then the optimal solution is

$$T_1^{opt} = \frac{3l(2\frac{\sigma^2}{tr(H)} + \zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|})}{2B\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|}}, \tag{3.7a}$$

$$p_1^{opt} = 2\frac{\sigma^2}{tr(H)}, \tag{3.7b}$$

$$\alpha_1^{opt} = \frac{2\sigma^2}{\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|} tr(H) + 2\sigma^2}, \tag{3.7c}$$

In this case, $T_1^{opt} < T^{\max}$ always holds (i.e., the overall time is smaller than the upper limit $T^{\max}$).

Case 2 If channel-fading degree κ is in the range specified as follows

$$0 < \kappa < 2\left(1 + \frac{T^{\max} B}{l}\right), \tag{3.8}$$

then the optimal solution is

$$T_2^{opt} = T^{\max}, \tag{3.9a}$$

$$p_2^{opt} = -\frac{\zeta T^{\max} B}{l \ln(2)} \frac{\lambda_1 P}{\|\boldsymbol{v}_1\|} W(\tau) - \frac{N_{noise}}{tr(H)}, \tag{3.9b}$$

$$\alpha_2^{opt} = \frac{-\frac{\zeta T^{\max} B}{l \ln(2)} \frac{\lambda_1 P}{\|\boldsymbol{v}_1\|} W(\tau) - \frac{N_{noise}}{tr(H)}}{\zeta \frac{\lambda_1 P}{\|\boldsymbol{v}_1\|} - \frac{\zeta T^{\max} B}{l \ln(2)} \frac{\lambda_1 P}{\|\boldsymbol{v}_1\|} W(\tau) - \frac{N_{noise}}{tr(H)}}, \tag{3.9c}$$

where $W(\tau)$ is Lambert Function [202] and τ is given by

$$\tau = -\frac{N_{noise}}{tr(H)} \frac{l \ln(2)}{\zeta T^{\max} B \frac{\lambda_1 P}{\|\boldsymbol{v}_1\|}} \times 2^{\frac{l}{T^{\max} B}\left(1 - \frac{N_{noise}}{\zeta tr(H) \frac{\lambda_1 P}{\|\boldsymbol{v}_1\|}}\right)}.$$

In this case, $T_2^{opt} = T^{\max}$ always holds (i.e., the overall time is equal to $T^{\max}$).

Proof: The proof for Theorem 1 is shown in Appendix B. ■

Remark 1: The derivation of Theorem 1 comes from inequality of limited time condition (i.e., $T \leq T^{\max}$) and equality of energy-supply condition (i.e., $e_{EH} = e_{DT}$). In particular, there are two cases for the condition $T \leq T^{\max}$: *Case 1* for $T < T^{\max}$ and *Case 2* for $T = T^{\max}$. In addition, $e_{EH} = e_{DT}$ holds to avoid unnecessary energy consumption from UAV and also satisfy the minimized overall energy consumption. Caused by energy-supply equality $\alpha^{opt} T^{opt} \zeta \lambda_1 P / \|\mathbf{v}_1\| = (1 - \alpha^{opt}) T^{opt} p^{opt}$, a general expression between the optimal WET time factor and the optimal data transmission power denoted by

$$\alpha^{opt} = \frac{p^{opt}}{\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|} + p^{opt}}$$

always holds in two cases. We observe that the optimal WET time factor is also related to the optimal data transmission power.

3.4 The Allocation Design

In this section, we will first analyse the feasibility of these optimal solutions and then design our allocation scheme.

3.4.1 Feasibility analysis

Since the overall time and the WET time factor are essentially determined by $\alpha \in (0,1)$ and $T \leq T^{\max}$, their optimal values in Theorem 1 are thereby feasible. However, no limitation on data transmission power p leads to that the optimal value of p may not be feasible. To ensure the feasibility of p^{opt}, we set a limit on p^{opt}. We denote the upper bound of p^{opt} by $p^{\max}$. Then both the optimal data transmission power in two cases (p_1^{opt} and p_2^{opt}) are limited by $p_1^{opt} \leq p^{\max}$ and $p_2^{opt} \leq p^{\max}$, respectively. Solving two above inequalities, we derive two constraints on channel fading degree corresponding to *Case 1* and *Case 2* in Theorem 1 as follows:

$$0 < \kappa \leq \frac{p^{\max}}{2\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|}} \textit{ (for Case 1)}; \tag{3.10}$$

$$0 < \kappa \leq \frac{1}{\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|}} \cdot \frac{p^{\max}}{2^{\frac{l}{T^{\max}B}(1+\frac{p^{\max}}{\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|}})} - 1} \textit{ (for Case 2)}. \tag{3.11}$$

Merging Eq. (10) with the previous constraint Eq. (6), we update the feasible channel-fading range for *Case 1* as

$$0 < \kappa \leq \min\left(\frac{T^{\max}B}{3l} - \frac{1}{2}, \frac{p^{\max}}{2\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|}}\right). \tag{3.12}$$

Meanwhile, merging Eq. (11) with Eq. (8), we get the feasible channel-fading range for *Case 2* as

$$0 < \kappa < \min\left(2 + \frac{2T^{\max}B}{l}, \frac{1}{\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|}} \times \frac{p^{\max}}{2^{\frac{l}{T^{\max}B}(1+\frac{p^{\max}}{\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|}})} - 1}\right). \tag{3.13}$$

Up to now, we have obtained two optimal solutions in Theorem 1 and two updated feasible ranges of channel-fading degree κ. We can allocate the optimal values of WET time and data transmission power as long as the practical channel-fading degree is within the feasible ranges. However, it is non-trivial to design the appropriate allocation scheme due to the following two difficulties:

- First, we cannot handle the numerical variations of the optimal solutions influenced by multiple system parameters. In this context, it is difficult to determine the ranges of allocation values. The solution to this problem is to use system parameters to estimate the numerical range of the allocation values.

- Second, as in Eq. (12) and Eq. (13), there is an intersection between two feasible ranges of channel-fading degree κ. To ensure the global efficiency, we choose the solution of *Case 1* as the allocation value if the practical channel-fading degree is within the intersection of two feasible ranges because the overall time in *Case 1* is less than that in *Case 2*. So we need to find out the intersection range and separate two feasible channel-fading ranges corresponding to two cases.

To overcome the above difficulties, we make the following analysis.

Define three joint system parameters

According to Theorem 1, we observe that all of the optimal solutions are determined by three joint expressions (i.e., $l/T^{\max}B$, $\zeta\lambda_1 P/\|\mathbf{v}_1\|$ and $\sigma^2/\mathrm{tr}(H)$). It means that a single system-parameter such as l, $T^{\max}$, B, ζ, $\lambda_1, P, \|\mathbf{v}_1\|$, σ^2 and $\mathrm{tr}(H)$ has no conclusive effect on optimal solutions. In the same joint expression, two or more system-parameters have joint impacts the optimal value. For instance, increasing l to 3 times and reducing $T^{\max}$ to 3 times have the same impact on value of the optimal solution because l and $T^{\max}$ are in expression $l/T^{\max}B$. Therefore, we can analyse the numerical variation of the optimal solutions based on the above three joint expressions. For simplicity, we define these three joint expressions as new parameters in Table II.

Particularly, the expressions of all optimal solutions composed by the above three parameters are shown in Corollary 1.

Reallocate channel-fading range

Substituting the corresponding expressions in Eq. (12) and Eq. (13) with R, P_{EH} and κ, we have the following updated ranges of κ for Case 1 and Case 2, respectively:

- As in Eq. (12), the feasible channel-fading range for *Case 1* is $(0, \kappa_1]$, where

$$\begin{aligned}\kappa_1 &= \min\left(\frac{1}{3R} - \frac{1}{2}, \frac{p^{\max}}{2P_{EH}}\right) \\ &= \begin{cases} \frac{p^{\max}}{2P_{EH}}, \text{when} R < \frac{1}{3\left(\frac{p^{\max}}{2P_{EH}} + \frac{1}{2}\right)} \\ \frac{1}{3R} - \frac{1}{2}, \text{when} R > \frac{1}{3\left(\frac{p^{\max}}{2P_{EH}} + \frac{1}{2}\right)} \end{cases};\end{aligned} \tag{3.14}$$

Table 3.2 Definition of joint system parameters

Definition	Meaning
$R \triangleq \frac{l}{T^{\max}B}$	The term R represents data size level of the amount of transmitting data compared with $T^{\max}B$. Given the fixed value of maximum threshold $T^{\max}$ and bandwidth B, the larger data transmission size l leads to larger data size level R. In this paper, we set $R \in (0,1)$.
$P_{EH} \triangleq \frac{\zeta\lambda_1 P}{\\|\mathbf{v}_1\\|}$	The term P_{EH} represents the received power at sensors; it depends on the energy conversion efficiency, the upper limit of WET power and the maximum orientation gain between UAV and the IoT node.
$\frac{\sigma^2}{\mathrm{tr}(H)} \triangleq \kappa P_{EH}$	This joint parameter represents the channel-fading degree of the up-link channel. For simplicity, we use the pre-defined channel-fading degree κ and P_{EH} to replace $\sigma^2/\mathrm{tr}(H)$, i.e., κP_{EH}.

- As in Eq. (13), the feasible channel-fading range for *Case 2* is $(0,\kappa_2)$, where

$$\begin{aligned}\kappa_2 =& \min\left(2+\frac{2}{R}, \frac{1}{P_{EH}}\frac{p^{\max}}{2^{R(1+\frac{p^{\max}}{P_{EH}}}-1}\right)\\ \approx& \frac{1}{P_{EH}}\frac{p^{\max}}{2^{R(1+\frac{p^{\max}}{P_{EH}}}-1}.\end{aligned} \tag{3.15}$$

  Note that $\approx$ we used in above expression is valid in a general case when $P_{EH} \in [0,10]$ and $p^{\max} \in [0,1]$.

To separate two channel-fading ranges, we first analyse the relationship between them $(0,\kappa_1]$ and $(0,\kappa_2)$.

As shown in Fig. 3.3, both κ_1 and κ_2 increase with the larger value of $p^{\max}$ and the smaller value of P_{EH}; this indicates that we can either increase the threshold of the data transmission power or decrease the received-energy power to endure the higher channel-fading degree. This phenomenon can be explained by the upper limit of p^{opt}. In two schemes, p^{opt} is proportional to κ and P_{EH}. As shown in Eq. (14) and Eq. (15), κ_1 and κ_2 are inversely proportional to P_{EH} and directly proportional to $p^{\max}$. In addition, both κ_1 and κ_2 decrease exponentially with the increment of R, meaning that the system with smaller data size level can tolerate larger channel-fading. Moreover, κ_1 decreases to zero when $R = 2/3$. Hence, κ_1 is valid only when $R \in (0,2/3)$. As a consequence, the

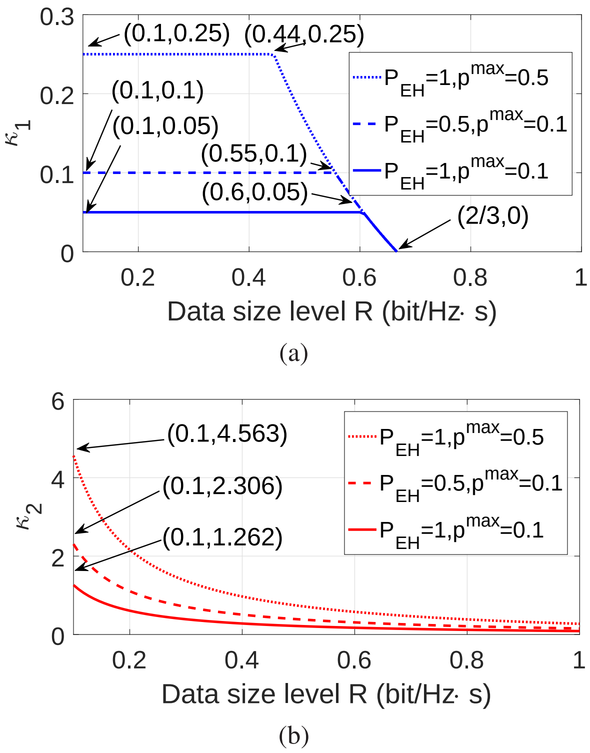


Fig. 3.3 The upper bound (i.e., κ_1 and κ_2) of two feasible channel-fading ranges (i.e., $(0,\kappa_1]$ and $(0,\kappa_2)$) versus R, where $R \in (0,1)$.

supportable range of R in *Case 1* is $(0,2/3)$. Meanwhile, the supportable range of R in *Case 2* is $(0,1)$.

Comparing the value of κ in Fig. 3.3a with that in Fig. 3.3b, we observe that $\kappa_2 > \kappa_1$ always holds when fixing R at any valid value. Hence we get the relationship of two feasible channel-fading ranges, i.e., $(0,\kappa_1] \subseteq (0,\kappa_2)$ when $R \in (0,2/3]$. In particular, $(0,\kappa_1]$ is invalid but $(0,\kappa_2)$ is valid when $R \in (2/3,1)$. When $R \in (0,1)$, a unified relationship of two feasible channel-fading ranges is

$$(0,\max(\kappa_1,0)] \subseteq (0,\kappa_2).$$

It implies that the intersection of two feasible channel-fading ranges (i.e., Eq. (12) and Eq. (13)) is $(0,\max(\kappa_1,0)]$. Adding the intersection range as the feasible channel-fading in *Case 1* because the overall time in *Case 1* is less than that in *Case 2*. Accordingly, we can reallocate the separate channel-fading ranges for two cases, i.e., $(0,\max(\kappa_1,0)]$ as the applicable channel-fading range in *Case 1* and $(\max(\kappa_1,0),\kappa_2)$ as the applicable channel-fading range in *Case 2*, respectively.

3.4.2 The Allocation Scheme

Substituting three aforementioned joint parameters and applying two separated channel-fading ranges, we design the allocation scheme as given in *Corollary 1*.

Corollary 1 *The allocation schemes for a data acquisition task:*

***Scheme** (1) If the estimation value of channel-fading degree* $\kappa \in (0, \kappa_1]$ *(where* $\kappa_1 = \min(1/(3R) - 1/2, p^{\max}/(2P_{EH}))$*) and data size level* $R \in (0, 2/3)$*, we allocate*

$$T_1^{alo} = \frac{3R(2\kappa+1)T^{\max}}{2}, \tag{16a}$$

$$p_1^{alo} = 2\kappa P_{EH}, \tag{16b}$$

$$\alpha_1^{alo} = \frac{2\kappa}{1+2\kappa}. \tag{16c}$$

***Scheme** (2) If the estimation value of channel-fading degree* $\kappa \in (\max(\kappa_1, 0), \kappa_2)$ *(where* $\kappa_2 = \min(2(1+1/R), 1/P_{EH}p^{\max}/(2^{R(1+p^{\max}/P_{EH})} - 1))$*) and data size level* $R \in (0,1)$*, we allocate the maximum value of the overall time (i.e.,* $T_2^{alo} = T^{\max}$*) and*

$$p_2^{alo} = P_{EH}\left(-\frac{W(\tau)}{R\ln(2)} - \kappa\right), \tag{17a}$$

$$\alpha_2^{alo} = \frac{-\frac{W(\tau)}{R\ln(2)} - \kappa}{1 - \frac{W(\tau)}{R\ln(2)} - \kappa}, \tag{17b}$$

where

$$\tau = -\kappa R\ln(2) \times 2^{R(1-\kappa)}.$$

Remark 2: Two allocation schemes in *Corollary 1* are based on the constrained range of data size level R and channel-fading degree κ. The two constraints come from the limited system resources (i.e., energy transferring power, bandwidth, energy conversion efficiency and the overall time). Both values of R and κ have the influence on the choice of two allocation schemes.

It is worth mentioning that our scheme can perform well in practical scenarios because of the following two reasons.

- First, three joint parameters R, P_{EH} and κ are available in practical scenarios. In practice, we can compute the value of R when the value of l is predictable and values of

$T^{\max}, B$ are given. Meanwhile, P_{EH} and κ can be computed at UAV by precise channel estimation via multi-antenna array when ζ and P are given as prior-knowledge.

- Second, the proposed schemes are adjustable with varied value of system parameters. In particular, for *Scheme* (1), we have the adjustable allocation of T_1^{alo} with the varied value of R; this effect leads to the stable allocation of α_1^{alo} and p_1^{alo} with the varied value of R. In contrast, *Scheme* (2) keeps the fixed allocation of T_2^{alo} at the maximum value (i.e., $T^{\max}$); this effect leads to the susceptible allocation of α_2^{alo} and p_2^{alo} with both varied values of R and κ.

3.5 Numerical results

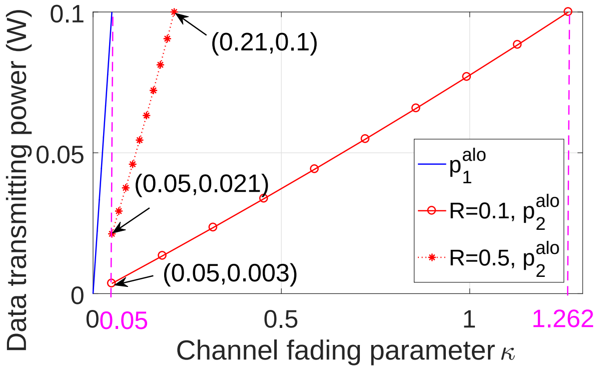
This section shows the numerical results of the allocation values and performance of two schemes. Since the received-energy power P_{EH} is linearly related to our allocation values as in Eq. (14a) and Eq. (15a), we focus on analysing the impact of channel-fading degree κ and data size level R on our results. In all the following figures, we use the blue line and the red line with markers to denote *Scheme (1)* and *Scheme (2)*, respectively. Moreover, the solid and dotted line denote the results corresponding to $R = 0.1, 0.5$, respectively.

3.5.1 Allocation Value

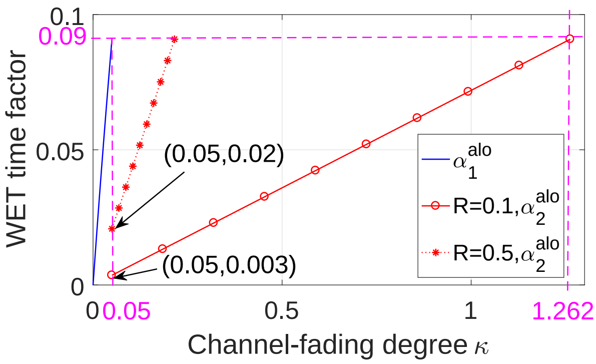
We conduct a comparative analysis for allocation values of two schemes in Fig. 3.4. Since the inequality $T_1^{alo} < T_2^{alo}$ always holds, we ignore the numerical analysis of the overall time in two schemes. Instead, we give a comparative analysis of data transmission power, WET time factor and WET time of two schemes in Fig. 3.4a, Fig. 3.4b and Fig. 3.4c, respectively.

As shown in Fig. 3.4a, data transmission power allocated in two schemes (i.e., p_1^{alo} and p_1^{alo}) increases with larger channel-fading degree to adapt the deteriorated channel. Obviously, both p_1^{alo} and p_1^{alo} keep in the same range $(0, p^{\max} = 0.1)$, conforming to the feasible constraint of p^{alo}.

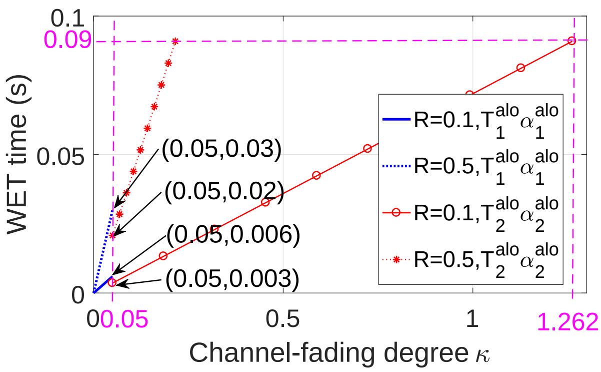
The difference between p_1^{alo} and p_1^{alo} lies in the impact of data size level R and channel fading degree κ. In *Scheme (1)*, p_1^{alo} keeps stable allocation with the varied value of R. This is because the upper bound of feasible channel fading range κ_1 keeps at a fixed value $p^{\max}/(2P_{EH}) = 0.05$ when R is smaller than the critical value 0.6 as in Fig. 3.3a. Hence, in Fig. 3.4a, p_1^{alo} keeps the same linear growth with varied value of channel fading factor when $R = 0.1, 0.5$. In contrast, p_2^{alo} always keeps increasing with larger



(a)



(b)



(c)

Fig. 3.4 WET time factor α, WET time αT and data transmission power p versus channel-fading degree κ with varied size level R, where $T^{\max} = 1$, $P_{EH} = 1$, $B = 15 \times 10^6$ bit/s and $p^{\max} = 0.1$.

value of R or κ. Herein, R cannot only influence κ_2 but also the value of p_2^{alo}. As in Fig. 3.3b, κ_2 is decreasing and p_2^{alo} is increasing with the increased value of R. This impact of R on p_2^{alo} can be explained by the second reason of *Remark 2*.

Fig. 3.4b shows the increased allocation value of WET time factor (i.e., α_1^{alo} and α_2^{alo}) versus κ and R. Due to energy-supply equality as in *Remark 1*, both α_1^{alo} and α_2^{alo} share a general expression related with data transmission power (i.e., $\alpha^{opt} = p^{opt}/(P_{EH} + p^{opt})$). Consequently, the value of WET time factor in two schemes is susceptible to the corresponding data transmission power in Fig. 3.4a. Thus, α_1^{alo} is unchanged with varied value of R, which is similar to p_1^{alo}. In addition, α_2^{alo} keeps increasing when R increases from 0 to 0.5.

We show WET time versus channel-fading and data size level in Fig. 3.4c. Herein we set the threshold of overall time $T^{\max}$ is 1. Then $T_2^{alo} = T^{\max} = 1$. Consequently, WET time of *Scheme (2)* is equal to WET time factor of *Scheme (2)*. Meanwhile, WET time of *Scheme (1)* is smaller than WET time factor of *Scheme (1)* because $T_1^{alo} < T^{\max} = 1$. Furthermore, WET time of *Scheme (1)* increases with the larger value of R because T_1^{alo} is directly proportional with R.

3.5.2 Performance Analysis

We then analyse the performance of our data acquisition scheme via three metrics (i.e., overall time, overall energy consumption and data transmission rate). The overall time is optimized in Corollary 1 and we accordingly get T_1^{alo} and T_2^{alo} for *Scheme (1)* and *Scheme (2)*, respectively. Undoubtedly, the overall time in *Scheme (1)* is smaller than that in *Scheme (2)*. The overall energy consumption is equal to $P\alpha T$ in (3.4). Since P is fixed at first, numerical results of WET time in Fig. 3.4c represent the upper bound of overall energy consumption. As in Fig. 3.4c, the overall energy consumption achieves the largest value when the channel-fading degree is the upper boundary of the feasible range. Accordingly, the largest overall energy consumption in *Scheme (1)* is always much smaller than the largest overall energy consumption in *Scheme (2)*.

Substituting allocation value of data transmission power into r, we can draw the result of the data transmission rate r versus channel-fading degree κ and data size level R in Fig. 5. For *Scheme (1)*, since multiplying p_1^{alo} with $\frac{\mathrm{tr}(H)}{N_{noise}}$ is just reduced to a constant number, we get a steady data transmission rate. In contrast, for *Scheme (2)*, data transmission rate increases with the increased value of κ and also increases with the increased value of R.

In summary, we find the performance of *Scheme (1)* is more stable versus R and κ

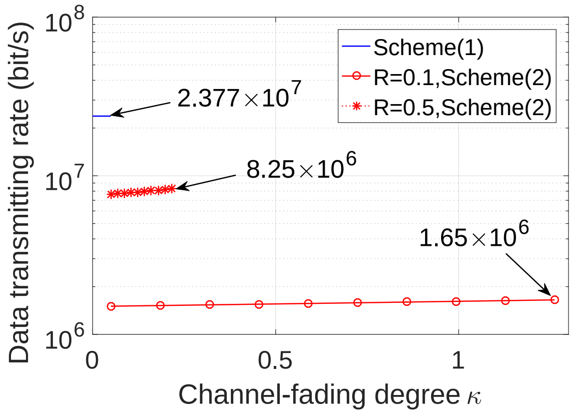


Fig. 3.5 Data transmission rate r versus channel-fading degree κ with varied size level R, where $T^{\max} = 1$, $P_{EH} = 1$, $B = 15 \times 10^6$ bit/s and $p^{\max} = 0.1$.

than that of *Scheme (2)*. This is because of the adjustable overall time in *Scheme (1)* and non-adjustable overall time in *Scheme (2)* against R and κ. In other words, *Scheme (1)* and *Scheme (2)* are complementary with each other to achieve an overall allocation in feasible channel-fading range.

3.6 Summary

We proposes a UAV-enabled data acquisition scheme with directional WET for IoT. In particular, we investigate an overall energy minimization problem for a single UAV-enabled data acquisition task. Accordingly, we design two allocation schemes for the optimal and feasible values of WET time and data transmission power. The numerical results show our allocation schemes are complementary with each other and are also adaptable for varied system parameters such as channel-fading factor and data size level. The proposed scheme is promising to support various IoT applications especially in rural pastures, mountainous areas and reconstructions after a disaster.

Chapter 4

Conclusion and Future Works

4.1 Conclusion

In this thesis, we overview the related work and technologies of applying UAV in IoT, and summary a general solution called UeIoT. We introduce enabling technologies of UeIoT from three sides: scalability, intelligence, and diversity, which can offer a roadmap for related research in UAV and IoT. Furthermore, we analyze a communication system of UAV-enabled data acquisition with WET and propose an optimal resource allocation scheme under balanced energy supply and consumption in a limited overall time. Though our scheme places emphasis on only the investigation on point-to-point communication, it deserves a practice when combining with previous works on the availability of UAV-enabled energy harvesting and the mobility of UAV-enable data acquisition.

4.2 Future Works

The practical deployment of UeIoT still faces lots of technical gaps requiring dedicated research. Those gaps usually come from 4 open research issues: 1) restricted resources of UAVs such as battery capacity to support long-distance flying and long-time communication and computation; 2) no security protocols to limit the illegal action and communication of UAVs; 3) lack of light-weight AI algorithm for autonomously mobility of UAVs; 4) no general framework of UeIoT to make heterogeneous applications compatible. The future works following this thesis can reference the four issues, respectively. Specific research directions can be briefly introduced as follows.

4.2.1 Resource allocation in UeIoT

An rational resource allocation of energy supply, data storage, and computation capacity in every nodes at UeIoT, including IoT nodes, UAVs, ground access nodes, can bring the most efficiency to UeIoT. The particular research directions of the resource allocation are divided into two categories: the global resource allocation (i.e., the number and the distribution of deployment of every nodes in UeIoT); the local resource allocation (i.e., the dedicated hardware design of every nodes in UeIoT). The global resource allocation focuses on the global high-efficiency of costs in time, energy, and the equipment; this global high-efficiency decides the distribution of IoT nodes and also the trajectory of UAVs. The local resource allocation places emphasis on the dedicated efficiency in every task such as communication, computing, and data storage; this local efficiency decides the specified resource allocation in power, data rate, communication time, data storage, computation complexity, computing time for communication tasks and computing tasks (e.g. [203]). Whatever the resource allocation is varied, it always keeps the unique design philosophy i.e., the on-demand principle to coordinate the demand of tasks and the resource consumption.

4.2.2 Security protocols in UeIoT

With the deployment of UAVs for various IoT applications, UAVs' flexible communication and action meanwhile pose various threats of safety, security, and privacy. So far, these are some works giving overview of UAVs' security in some specified scenarios (e.g., UAVs' security in industrial internet of things [204]) and another works presenting analysis of security [205]. However, these works are not enough to solve threat issues in UeIoT.

Hence, it is a strong demand for making security protocols to address those threats. The first research direction is to enhance the security level of the communication interfaces of UAVs; the interfaces are used to connect IoT nodes, other UAVs, and ground access nodes. The authentication mechanism for access to these interfaces is required to be enhanced in case that the hacker or eavesdropper illegally accesses to UAVs, eavesdropping the legal communication and even sending high-level commands as the pseudo ground control nodes. The second research direction is the anti-access of pseudo UAVs to IoT nodes and also the ground nodes. Particularly, the recognition mechanism of illegal access of UAVs and also the identification of legal UAVs (i.e., [206–208]) are required.

4.2.3 Light-weight AI algorithm

The local computing with a quick and precise response at UAVs is an expected objective for enhancing the intelligence of UeIoT. The light-weight AI algorithm must be required to enable the quick and precise response based on limited resources of computation, storage and data base. On one hand, *AI* is required to obtain the precise and intelligence result; on the other hand, *light-weight* is necessary to gain the as low computing complexity as possible.

The existing work using AI algorithms in UAVs-based applications are more run on the cloud side instead of on local. For example, some papers present the AI algorithms to detect and count cars by using images and combining with different AI technologies such as deep convolutional neural network (CNN) [209], and Faster R-CNN [210]. Besides, other similar UAV-based AI algorithms are also proposed with various applications such as human detection (i.e., finding pedestrians) [211], weed mapping [212]. Even though those AI algorithms use the imagery recording by UAVs to conduct the mobile object recognition, the computation is either too complex or needing too many data base, not fitting for local processing at UAVs. For local running, there are few works that investigate low-complex algorithms for UAVs' navigation [213], path finding [214], moving-targets' tracking [150]. The future applications on local processing at UAVs need more light-weight AI algorithms to support a really autonomous intelligence with a quick and precise response.

4.2.4 Generality design of UeIoT

Generality design of UeIoT is necessary for coordinating so many heterogeneous ICT technologies in so many diverse applications; the generality can also help reduce the hardware cost and increase the running efficiency of the UeIoT. Specifically speaking, every network layer (containing physical layer, network layer, and application layer) should be restricted by a universal standard. For the physical layer, the generality should support the universal identification of various nodes (IoT nodes, UAVs) and the universal access by multiple communication protocols. The generality design in the network layer should aim at designing a universal network control protocol; this protocol can be run on current network infrastructures and perform the IoT network functions such as security control, routing design, data fusion and de-fusion. For the application layer, the generality design should be reflected in a universal computing plane; this plane can be either cloud or edge or local side, and provide a sharing storage and computing resources.

In our opinion, the practical generality designs of above three layers are referring to the universal communication chips for end nodes, the universal network control protocols, and the universal computing plane, respectively. Reviewing the related works, the communication chip for end nodes are only designed for particular communication protocols such as NB-IoT, MTC, LoRa-WAN [215]. Besides, the universal network protocols can be achieved by integrating SDN for UAVs, but no global scheme was presented. The universal computing plane can be achieved by integrating local, edge, and cloud computing planes together; this integration is feasible by designing a high-level interface for connecting computing services between three computing planes.

References

[1] M. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel, and L. Ladid, "Internet of things in the 5g era: Enablers, architecture, and business models," *Ieee Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 510–527, 2016.

[2] G. Premsankar, M. Di Francesco, and T. Taleb, "Edge computing for the internet of things: A case study," *Ieee Internet of Things Journal*, vol. 5, no. 2, pp. 1275–1284, 2018.

[3] T. Qiu, N. Chen, K. Li, M. Atiquzzaman, and W. Zhao, "How can heterogeneous internet of things build our future: A survey," *Ieee Communications Surveys and Tutorials*, vol. 20, no. 3, pp. 2011–2027, 2018.

[4] O. Sezer, E. Dogdu, and A. Ozbayoglu, "Context-aware computing, learning, and big data in internet of things: A survey," *Ieee Internet of Things Journal*, vol. 5, no. 1, pp. 1–27, 2018.

[5] L. Xu, W. He, and S. Li, "Internet of things in industries: A survey," *Ieee Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2233–2243, 2014.

[6] C. Zhu, V. Leung, L. Shu, and E. Ngai, "Green internet of things for smart world," *Ieee Access*, vol. 3, pp. 2151–2162, 2015.

[7] G. Bedi, G. Venayagamoorthy, R. Singh, R. Brooks, and K. Wang, "Review of internet of things (iot) in electric power and energy systems," *Ieee Internet of Things Journal*, vol. 5, no. 2, pp. 847–870, 2018.

[8] E. Ahmed, I. Yaqoob, I. A. T. Hashem, I. Khan, A. I. A. Ahmed, M. Imran, and A. V. Vasilakos, "The role of big data analytics in internet of things," *Computer Networks*, vol. 129, pp. 459–471, 2017.

[9] J. P. Bardyn, T. Melly, O. Seller, and N. Sornin, "IoT, The era of LPWAN is starting now," in *European Solid-State Circuits Conference, Esscirc Conference 2016:*, 2016, pp. 25–30.

[10] F. Javed, M. Afzal, M. Sharif, and B. Kim, "Internet of things (iot) operating systems support, networking technologies, applications, and challenges: A comparative review," *Ieee Communications Surveys and Tutorials*, vol. 20, no. 3, pp. 2062–2100, 2018.

[11] S. Andreev, V. Petrov, M. Dohler, and H. Yanikomeroglu, "Future of ultra-dense networks beyond 5g: harnessing heterogeneous moving cells," *IEEE Communications Magazine*, 2019.

[12] T. Qiu, N. Chen, K. Li, M. Atiquzzaman, and W. Zhao, "How can heterogeneous internet of things build our future: A survey," *IEEE Communications Surveys Tutorials*, vol. 20, no. 3, pp. 2011–2027, thirdquarter 2018.

[13] O. S. Oubbati, N. Chaib, A. Lakas, P. Lorenz, and A. Rachedi, "Uav-assisted supporting services connectivity in urban vanets," *IEEE Transactions on Vehicular Technology*, 2019.

[14] ilker Bekmezci, O. K. Sahingoz, and Şamil Temel, "Flying Ad-Hoc Networks (FANETs): A survey," *Ad Hoc Networks*, vol. 11, no. 3, pp. 1254–1270, 2013.

[15] Y.-S. Kang, I.-H. Park, J. Rhee, and Y.-H. Lee, "Mongodb-based repository design for iot-generated rfid/sensor big data," *IEEE Sensors Journal*, vol. 16, no. 2, pp. 485–497, 2015.

[16] M. Ojo, D. Adami, and S. Giordano, "A sdn-iot architecture with nfv implementation," in *2016 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2016, pp. 1–6.

[17] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low power wide area networks: An overview," *Ieee Communications Surveys and Tutorials*, vol. 19, no. 2, pp. 855–873, 2017.

[18] F. Samie, V. Tsoutsouras, L. Bauer, S. Xydis, D. Soudris, and J. Henkel, "Computation offloading and resource allocation for low-power iot edge devices," in *2016 IEEE 3rd World Forum on Internet of Things (WF-IoT)*. IEEE, 2016, pp. 7–12.

[19] E. Khorov, A. Lyakhov, A. Krotov, and A. Guschin, "A survey on ieee 802.11 ah: An enabling networking technology for smart cities," *Computer Communications*, vol. 58, pp. 53–69, 2015.

[20] Z. Song, X. Liu, X. Zhao, Q. Liu, Z. Jin, and B. Chi, "A low-power nb-iot transceiver with digital-polar transmitter in 180-nm cmos," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 64, no. 9, pp. 2569–2581, 2017.

[21] E. Bechthum, M. El Soussi, J. F. Dijkhuis, P. Mateman, G.-J. van Schaik, A. Breeschoten, Y.-H. Liu, and C. Bachmann, "A cmos polar class-g switched-capacitor pa with a single high-current supply, for lte nb-iot and emtc," *IEEE Journal of Solid-State Circuits*, 2019.

[22] W. Yu, F. Liang, X. He, W. Hatcher, C. Lu, J. Lin, and X. Yang, "A survey on the edge computing for the internet of things," *Ieee Access*, vol. 6, pp. 6900–6919, 2018.

[23] H. El-Sayed, S. Sankar, M. Prasad, D. Puthal, A. Gupta, M. Mohanty, and C. Lin, "Edge of things: The big picture on the integration of edge, iot and the cloud in a distributed computing environment," *Ieee Access*, vol. 6, pp. 1706–1717, 2018.

[24] M. Marjani, F. Nasaruddin, A. Gani, A. Karim, I. Hashem, A. Siddiqa, and I. Yaqoob, "Big iot data analytics: Architecture, opportunities, and open research challenges," *Ieee Access*, vol. 5, pp. 5247–5261, 2017.

[25] H. Kim and J. Ben-Othman, "A collision-free surveillance system using smart uavs in multi domain iot," *IEEE Communications Letters*, vol. 22, no. 12, pp. 2587–2590, 2018.

[26] F. Tao, Q. Qi, A. Liu, and A. Kusiak, "Data-driven smart manufacturing," *Journal of Manufacturing Systems*, vol. 48, pp. 157–169, 2018.

[27] D. Ho, E. Grotli, P. Sujit, T. Johansen, and J. Sousa, "Optimization of wireless sensor network and uav data acquisition," *Journal of Intelligent & Robotic Systems*, vol. 78, no. 1, pp. 159–179, 2015.

[28] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in uav communication networks," *Ieee Communications Surveys and Tutorials*, vol. 18, no. 2, pp. 1123–1152, 2016.

[29] A. Jamalipour, Z. Kaleem, P. Lorenz, and W. Choi, "Special issue on amateur drone and uav communications and networks," *Journal of Communications and Networks*, vol. 20, no. 5, pp. 429–433, 2018.

[30] P. Liu, A. Chen, Y. Huang, J. Han, J. Lai, S. Kang, T. Wu, M. Wen, and M. Tsai, "A review of rotorcraft unmanned aerial vehicle (uav) developments and applications in civil engineering," *Smart Structures and Systems*, vol. 13, no. 6, pp. 1065–1094, 2014.

[31] C. Zhang and W. Zhang, "Spectrum sharing for drone networks," *Ieee Journal on Selected Areas in Communications*, vol. 35, no. 1, pp. 136–144, 2017.

[32] S. Granshaw, "Rpv, uav, uas, rpas ... or just drone?" *Photogrammetric Record*, vol. 33, no. 162, pp. 160–170, 2018.

[33] S. G. Gupta, M. M. Ghonge, and P. Jawandhiya, "Review of unmanned aircraft system (uas)," *International journal of advanced research in computer engineering & technology (IJARCET)*, vol. 2, no. 4, pp. 1646–1658, 2013.

[34] S. Manitta, "Unmanned aircraft systems ground support platform," Mar. 10 2016, uS Patent App. 14/793,708.

[35] A. K. Chan, J. R. Cheatham III, H. W. Chin, W. D. Duncan, R. A. Hyde, M. Y. Ishikawa, J. T. Kare, T. S. Pan, R. C. Petroski, C. T. Tegreene *et al.*, "Reconfigurable unmanned aircraft system," Feb. 27 2018, uS Patent 9,902,491.

[36] H. Li, C. Li, Y. Li, and Z. Xing, "An integrated altitude control design for a tail-sitter uav equipped with turbine engines," *Ieee Access*, vol. 5, pp. 10 941–10 952, 2017.

[37] M. Orsag, C. Korpela, and P. Oh, "Modeling and control of mm-uav: Mobile manipulating unmanned aerial vehicle," *Journal of Intelligent & Robotic Systems*, vol. 69, no. 1-4, pp. 227–240, 2013.

[38] W. Lee, Y. Hong, J. Lee, D. Gillespie, K. Ricks, F. Hu, and J. Abu-Qahouq, "Dual-polarized hexaferrite antenna for unmanned aerial vehicle (uav) applications," *Ieee Antennas and Wireless Propagation Letters*, vol. 12, pp. 765–768, 2013.

[39] A. Crane, "From startup to empire: The evolution of dji drones," https://dronelife.com/2018/05/14/from-startup-to-empire-the-evolution-of-dji-drones/, accessed May 14, 2018.

[40] R. D'Andrea, "Can drones deliver?" *Ieee Transactions on Automation Science and Engineering*, vol. 11, no. 3, pp. 647–648, 2014.

[41] H. Xiang and L. Tian, "Method for automatic georeferencing aerial remote sensing (rs) images from an unmanned aerial vehicle (uav) platform," *Biosystems Engineering*, vol. 108, no. 2, pp. 104–113, 2011.

[42] C. Carl, D. Landgraf, M. van der Maaten-Theunissen, P. Biber, and H. Pretzsch, "Robinia pseudoacacia l. flowers analyzed by using an unmanned aerial vehicle (uav)," *Remote Sensing*, vol. 9, no. 11, 2017.

[43] D. Cramp, "The use of an unmanned aerial vehicle (uav) to investigate aspects of honey bee drone congregation areas (dcas)," *Journal of Apicultural Research*, vol. 56, no. 2, 2017.

[44] Q. Yang and S. Yoo, "Optimal uav path planning: Sensing data acquisition over iot sensor networks using multi-objective bio-inspired algorithms," *Ieee Access*, vol. 6, pp. 13 671–13 684, 2018.

[45] Z. Wu, J. Li, J. Zuo, and S. Li, "Path planning of uavs based on collision probability and kalman filter," *Ieee Access*, vol. 6, pp. 34 237–34 245, 2018.

[46] J. Xu, Y. Zeng, and R. Zhang, "UAV-Enabled Wireless Power Transfer: Trajectory Design and Energy Optimization," *Ieee Transactions on Wireless Communications*, vol. 17, no. 8, pp. 5092–5106, 2018.

[47] Y. Zhou, N. Cheng, N. Lu, and X. Shen, "Multi-uav-aided networks aerial-ground cooperative vehicular networking architecture," *Ieee Vehicular Technology Magazine*, vol. 10, no. 4, pp. 36–44, 2015.

[48] P. Sujit, D. Lucani, and J. Sousa, "Bridging cooperative sensing and route planning of autonomous vehicles," *Ieee Journal on Selected Areas in Communications*, vol. 30, no. 5, pp. 912–922, 2012.

[49] M. Erdelj, M. Krol, and E. Natalizio, "Wireless sensor networks and multi-uav systems for natural disaster management," *Computer Networks*, vol. 124, pp. 72–86, 2017.

[50] C. M. de A. Lima, E. A. da Silva, and P. B. Velloso, "Performance evaluation of 802.11 iot devices for data collection in the forest with drones," in *2018 IEEE Global Communications Conference (GLOBECOM)*, Dec 2018, pp. 1–7.

[51] J. Jiang and G. Han, "Routing protocols for unmanned aerial vehicles," *Ieee Communications Magazine*, vol. 56, no. 1, pp. 58–63, 2018.

[52] M. Arafat and S. Moh, "A survey on cluster-based routing protocols for unmanned aerial vehicle networks," *Ieee Access*, vol. 7, pp. 498–516, 2019.

[53] M. Alzenad, A. El-Keyi, F. Lagum, and H. Yanikomeroglu, "3-d placement of an unmanned aerial vehicle base station (uav-bs) for energy-efficient maximal coverage," *IEEE Wireless Communications Letters*, vol. 6, no. 4, pp. 434–437, 2017.

[54] J. Lyu, Y. Zeng, R. Zhang, and T. J. Lim, "Placement optimization of uav-mounted mobile base stations," *IEEE Communications Letters*, vol. 21, no. 3, pp. 604–607, 2016.

[55] S. Zhang, H. Zhang, Q. He, K. Bian, and L. Song, "Joint trajectory and power optimization for uav relay networks," *IEEE Communications Letters*, vol. 22, no. 1, pp. 161–164, 2017.

[56] D. H. Choi, S. H. Kim, and D. K. Sung, "Energy-efficient maneuvering and communication of a single uav-based relay," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 50, no. 3, pp. 2320–2327, July 2014.

[57] E. Semsch, M. Jakob, D. Pavlicek, and M. Pechoucek, "Autonomous uav surveillance in complex urban environments," in *Proceedings of the 2009 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology-Volume 02*. IEEE Computer Society, 2009, pp. 82–85.

[58] N. H. Motlagh, M. Bagaa, and T. Taleb, "Uav-based iot platform: A crowd surveillance use case," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 128–134, 2017.

[59] Z. M. Fadlullah, D. Takaishi, H. Nishiyama, N. Kato, and R. Miura, "A dynamic trajectory control algorithm for improving the communication throughput and delay in uav-aided networks," *IEEE Network*, vol. 30, no. 1, pp. 100–105, January 2016.

[60] Y. Zeng and R. Zhang, "Energy-Efficient UAV Communication With Trajectory Optimization," *Ieee Transactions on Wireless Communications*, vol. 16, no. 6, pp. 3747–3760, 2017.

[61] G. Zhang, H. Yan, Y. Zeng, M. Cui, and Y. Liu, "Trajectory optimization and power allocation for multi-hop uav relaying communications," *Ieee Access*, vol. 6, pp. 48 566–48 576, 2018.

[62] Q. Wu, Y. Zeng, and R. Zhang, "Joint trajectory and communication design for multi-uav enabled wireless networks," *Ieee Transactions on Wireless Communications*, vol. 17, no. 3, pp. 2109–2121, 2018.

[63] J. Zhang, J. Yan, P. Zhang, and X. Kong, "Design and information architectures for an unmanned aerial vehicle cooperative formation tracking controller," *Ieee Access*, vol. 6, pp. 45 821–45 833, 2018.

[64] Q. Wang, "A novel anti-eavesdropping scheme in wireless networks: Fri-uj," in *Proceedings of the 2019 International Conference on Embedded Wireless Systems and Networks*. Junction Publishing, 2019, pp. 316–317.

[65] V. Kharchenko and V. Torianyk, “Cybersecurity of the internet of drones: Vulnerabilities analysis and imeca based assessment,” in *2018 IEEE 9th International Conference on Dependable Systems, Services and Technologies (DESSERT)*. IEEE, 2018, pp. 364–369.

[66] D. He, Y. Qiao, S. Chan, and N. Guizani, “Flight security and safety of drones in airborne fog computing systems,” *IEEE Communications Magazine*, vol. 56, no. 5, pp. 66–71, 2018.

[67] N. Neshenko, E. Bou-Harb, J. Crichigno, G. Kaddoum, and N. Ghani, “Demystifying iot security: An exhaustive survey on iot vulnerabilities and a first empirical look on internet-scale iot exploitations,” *IEEE Communications Surveys & Tutorials*, 2019.

[68] M. A. Khan and K. Salah, “Iot security: Review, blockchain solutions, and open challenges,” *Future Generation Computer Systems*, vol. 82, pp. 395–411, 2018.

[69] C. Stergiou, K. E. Psannis, B.-G. Kim, and B. Gupta, “Secure integration of iot and cloud computing,” *Future Generation Computer Systems*, vol. 78, pp. 964–975, 2018.

[70] J. Zhou, Z. Cao, X. Dong, and A. V. Vasilakos, “Security and privacy for cloud-based iot: Challenges,” *IEEE Communications Magazine*, vol. 55, no. 1, pp. 26–33, 2017.

[71] J. Xu and R. Zhang, “A general design framework for mimo wireless energy transfer with limited feedback,” *Ieee Transactions on Signal Processing*, vol. 64, no. 10, pp. 2475–2488, 2016.

[72] M. Gharibi, R. Boutaba, and S. Waslander, “Internet of drones,” *Ieee Access*, vol. 4, pp. 1148–1162, 2016.

[73] Z. Zhou, J. Irizarry, and Y. Lu, “A multidimensional framework for unmanned aerial system applications in construction project management,” *Journal of Management in Engineering*, vol. 34, no. 3, p. 04018004, 2018.

[74] Y. Li and C. Liu, “Applications of multirotor drone technologies in construction management,” *International Journal of Construction Management*, pp. 1–12, 2018.

[75] B. Hubbard, H. Wang, M. Leasure, T. Ropp, T. Lofton, S. Hubbard, and S. Lin, “Feasibility study of uav use for rfid material tracking on construction sites,” in *Proc., ASCE Annual International Conference*, 2015, pp. 669–676.

[76] H. Hamledari, “Inpro: Automated indoor construction progress monitoring using unmanned aerial vehicles,” *Master of Applied Science University of Toronto, Toronto, Canada*, 2016.

[77] H. I. Moud, A. Shojaei, and I. Flood, “Current and future applications of unmanned surface, underwater, and ground vehicles in construction,” in *Proceedings of the Construction Research Congress*, 2018, pp. 106–115.

[78] A. Abdallah, M. Z. Ali, J. Mišić, and V. B. Mišić, "Efficient security scheme for disaster surveillance uav communication networks," *Information*, vol. 10, no. 2, p. 43, 2019.

[79] H. Kim, L. Mokdad, and J. Ben-Othman, "Designing uav surveillance frameworks for smart city and extensive ocean with differential perspectives," *IEEE Communications Magazine*, vol. 56, no. 4, pp. 98–104, 2018.

[80] I. Maza, F. Caballero, J. Capitán, J. R. Martínez-de Dios, and A. Ollero, "Experimental results in multi-uav coordination for disaster management and civil security applications," *Journal of intelligent & robotic systems*, vol. 61, no. 1-4, pp. 563–585, 2011.

[81] N. Zhao, W. Lu, M. Sheng, Y. Chen, J. Tang, F. R. Yu, and K.-K. Wong, "Uav-assisted emergency networks in disasters," *IEEE Wireless Communications*, vol. 26, no. 1, pp. 45–51, 2019.

[82] G. Tuna, B. Nefzi, and G. Conte, "Unmanned aerial vehicle-aided communications system for disaster recovery," *Journal of Network and Computer Applications*, vol. 41, pp. 27–36, 2014.

[83] M. Deruyck, J. Wyckmans, W. Joseph, and L. Martens, "Designing uav-aided emergency networks for large-scale disaster scenarios," *EURASIP Journal on Wireless Communications and Networking*, vol. 2018, no. 1, p. 79, 2018.

[84] A. D. Ibrah, L. Chuang, L. Na, and Z. Meng-yuan, "Optimization method of relay network deployment using multi-uav for emergency communication," in *Journal of Physics: Conference Series*, vol. 1060, no. 1. IOP Publishing, 2018, p. 012042.

[85] P. Sujit, J. Manathara, D. Ghose, and J. de Sousa, "Decentralized multi-uav coalition formation with limited communication ranges," *Handbook of unmanned aerial vehicles*, pp. 2021–2048, 2015.

[86] A. Orsino, A. Ometov, G. Fodor, D. Moltchanov, L. Militano, S. Andreev, O. N. Yilmaz, T. Tirronen, J. Torsner, G. Araniti *et al.*, "Effects of heterogeneous mobility on d2d-and drone-assisted mission-critical mtc in 5g." *IEEE Communications Magazine*, vol. 55, no. 2, pp. 79–87, 2017.

[87] Z. Xiao, P. Xia, and X.-G. Xia, "Enabling uav cellular with millimeter-wave communication: Potentials and approaches," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 66–73, 2016.

[88] S. A. R. Naqvi, S. A. Hassan, H. Pervaiz, and Q. Ni, "Drone-aided communication as a key enabler for 5g and resilient public safety networks," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 36–42, 2018.

[89] G. Ding, Q. Wu, L. Zhang, Y. Lin, T. Tsiftsis, and Y. Yao, "An amateur drone surveillance system based on the cognitive internet of things," *Ieee Communications Magazine*, vol. 56, no. 1, pp. 29–35, 2018.

[90] Y. Wu, Y. Luo, G. Zhao, J. Hu, F. Gao, and S. Wang, "A novel line position recognition method in transmission line patrolling with uav using machine learning algorithms," in *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*. IEEE, 2018, pp. 491–495.

[91] H. Wang, B. Yan, X. Li, X. Luo, Q. Yang, and W. Yan, "On optimal path planning for uav based patrolling in complex 3d topographies," in *2016 IEEE International Conference on Information and Automation (ICIA)*. IEEE, 2016, pp. 986–990.

[92] J. Seok, M. Faied, and A. Girard, "Unpredictably dynamic environment patrolling," *Unmanned Systems*, vol. 5, no. 04, pp. 223–236, 2017.

[93] X. Zhou, W. Wang, T. Wang, X. Li, and T. Jing, "Continuous patrolling in uncertain environment with the uav swarm," *PloS one*, vol. 13, no. 8, p. e0202328, 2018.

[94] S. Chen, F. Wu, L. Shen, J. Chen, and S. D. Ramchurn, "Decentralized patrolling under constraints in dynamic environments," *IEEE transactions on cybernetics*, vol. 46, no. 12, pp. 3364–3376, 2015.

[95] H. Menouar, I. Guvenc, K. Akkaya, A. S. Uluagac, A. Kadri, and A. Tuncer, "Uav-enabled intelligent transportation systems for the smart city: Applications and challenges," *IEEE Communications Magazine*, vol. 55, no. 3, pp. 22–28, 2017.

[96] R. Ke, Z. Li, J. Tang, Z. Pan, and Y. Wang, "Real-time traffic flow parameter estimation from uav video based on ensemble classifier and optical flow," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 1, pp. 54–64, Jan 2019.

[97] S. Bertrand, N. Raballand, and F. Viguier, "Evaluating ground risk for road networks induced by uav operations," in *2018 International Conference on Unmanned Aircraft Systems (ICUAS)*. IEEE, 2018, pp. 168–176.

[98] R. Reshma, T. Ramesh, and P. Sathishkumar, "Security situational aware intelligent road traffic monitoring using uavs," in *2016 international conference on VLSI systems, architectures, technology and applications (VLSI-SATA)*. IEEE, 2016, pp. 1–6.

[99] Y. Zhou, N. Cheng, N. Lu, and X. S. Shen, "Multi-UAV-aided networks: Aerial-ground cooperative vehicular networking architecture," *ieee vehicular technology magazine*, vol. 10, no. 4, pp. 36–44, 2015.

[100] S. A. Hadiwardoyo, E. Hernández-Orallo, C. T. Calafate, J.-C. Cano, and P. Manzoni, "Evaluating uav-to-car communications performance: Testbed experiments," in *2018 IEEE 32nd International Conference on Advanced Information Networking and Applications (AINA)*. IEEE, 2018, pp. 86–92.

[101] S. A. Hadiwardoyo, E. Hernández-Orallo, C. T. Calafate, J. C. Cano, and P. Manzoni, "Experimental characterization of uav-to-car communications," *Computer Networks*, vol. 136, pp. 105–118, 2018.

[102] T. Perera, A. Priyankara, and G. Jayasinghe, "Unmanned arial vehicles (uav) in smart agriculture: Trends, benefits and future perspectives," 2019.

[103] G. Milics, "Application of uavs in precision agriculture," in *International Climate Protection*. Springer, 2019, pp. 93–97.

[104] X. Wu, X. Wu, L. Qiu, and L. Zhou, "Agricultural unmanned aerial vehicle," Jan. 10 2019, uS Patent App. 16/120,590.

[105] C. de Souza, R. Lamparelli, J. Rocha, and P. Magalhaes, "Mapping skips in sugarcane fields using object-based analysis of unmanned aerial vehicle (uav) images," *Computers and Electronics in Agriculture*, vol. 143, pp. 49–56, 2017.

[106] J. Albetis, S. Duthoit, F. Guttler, A. Jacquin, M. Goulard, H. Poilve, J. Feret, and G. Dedieu, "Detection of flavescence doree grapevine disease using unmanned aerial vehicle (uav) multispectral imagery," *Remote Sensing*, vol. 9, no. 4, 2017.

[107] B. Duan, S. Fang, R. Zhu, X. Wu, S. Wang, Y. Gong, and Y. Peng, "Remote estimation of rice yield with unmanned aerial vehicle (uav) data and spectral mixture analysis," *Frontiers in Plant Science*, vol. 10, 2019.

[108] A. Laliberte, J. Herrick, A. Rango, and C. Winters, "Acquisition, orthorectification, and object-based classification of unmanned aerial vehicle (uav) imagery for rangeland monitoring," *Photogrammetric Engineering and Remote Sensing*, vol. 76, no. 6, pp. 661–672, 2010.

[109] M. Abdelkader, M. Shaqura, C. G. Claudel, and W. Gueaieb, "A uav based system for real time flash flood monitoring in desert environments using lagrangian microsensors," in *2013 International Conference on Unmanned Aircraft Systems (ICUAS)*. IEEE, 2013, pp. 25–34.

[110] I. Sparelli, L. Albertini, T. Izquierdo, M. Abad, P. Mozzi, and A. Fontana, "Geomorphological analysis of recent flash-flood events in the atacama desert using high-resolution uav images," in *EGU General Assembly Conference Abstracts*, vol. 20, 2018, p. 9225.

[111] D. Sun, J. Zheng, T. Ma, J. Chen, and X. Li, "The analysis of burrows recognition accuracy in xinjiang's pasture area based on uav visible images with different spatial resolution." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 42, p. 3, 2018.

[112] M. Phillips, J. Moersch, N. Cabrol, and A. Davila, "Thresholds of detection and identification of halite nodule habitats in the atacama desert using remote imaging," 2018.

[113] T. T. Sankey, J. McVay, T. L. Swetnam, M. P. McClaran, P. Heilman, and M. Nichols, "Uav hyperspectral and lidar data and their fusion for arid and semiarid land vegetation monitoring," *Remote Sensing in Ecology and Conservation*, vol. 4, no. 1, pp. 20–33, 2018.

[114] C.-W. Lin, J. Kim, S.-Y. Lin, and Y. Choi, "A new paradigm for aeolain process monitoring employing uav and satellite sensors: Application case in kubuqi desert, china," in *EGU General Assembly Conference Abstracts*, vol. 20, 2018, p. 12235.

[115] R. I. H. Abushahma, M. A. Ali, N. A. A. Rahman, and O. I. Al-Sanjary, "Comparative features of unmanned aerial vehicle (uav) for border protection of libya: A review," in *2019 IEEE 15th International Colloquium on Signal Processing & Its Applications (CSPA)*. IEEE, 2019, pp. 114–119.

[116] C. Alexander, A. Korstjens, E. Hankinson, G. Usher, N. Harrison, M. Nowak, A. Abdullah, S. Wich, and R. Hill, "Locating emergent trees in a tropical rainforest using data from an unmanned aerial vehicle (uav)," *International Journal of Applied Earth Observation and Geoinformation*, vol. 72, pp. 86–90, 2018.

[117] S. Klosterman, E. Melaas, J. Wang, A. Martinez, S. Frederick, J. O'Keefe, D. Orwig, Z. Wang, Q. Sun, C. Schaaf, M. Friedl, and A. Richardson, "Fine-scale perspectives on landscape phenology from unmanned aerial vehicle (uav) photography," *Agricultural and Forest Meteorology*, vol. 248, pp. 397–407, 2018.

[118] V. Otero, R. Van De Kerchove, B. Satyanarayana, C. Martínez-Espinosa, M. A. B. Fisol, M. R. B. Ibrahim, I. Sulong, H. Mohd-Lokman, R. Lucas, and F. Dahdouh-Guebas, "Managing mangrove forests from the sky: Forest inventory using field data and unmanned aerial vehicle (uav) imagery in the matang mangrove forest reserve, peninsular malaysia," *Forest ecology and management*, vol. 411, pp. 35–45, 2018.

[119] S. Puliti, S. Saarela, T. Gobakken, G. Ståhl, and E. Næsset, "Combining uav and sentinel-2 auxiliary data for forest growing stock volume estimation through hierarchical model-based inference," *Remote Sensing of Environment*, vol. 204, pp. 485–497, 2018.

[120] F. Giannetti, G. Chirici, T. Gobakken, E. Næsset, D. Travaglini, and S. Puliti, "A new approach with dtm-independent metrics for forest growing stock prediction using uav photogrammetric data," *Remote Sensing of Environment*, vol. 213, pp. 195–205, 2018.

[121] K. Jun, B. Jun, H. Lee, S. Kim, and W. Tak, "The study of utilization and precision based on the comparison and analysis of drone-based coastal hazard data and its application in the ocean environment," *Journal of Coastal Research*, pp. 811–815, 2018.

[122] M. A. e. a. Trasviña-Moreno C, Blasco R, "Unmanned aerial vehicle based wireless sensor network for marine-coastal environment monitoring," *Sensors*, vol. 17(3): 460.

[123] Y. Matsuba and S. Sato, "Nearshore bathymetry estimation using uav," *Coastal Engineering Journal*, vol. 60, no. 1, pp. 51–59, 2018.

[124] O. J. Gooday, N. Key, S. Goldstien, and P. Zawar-Reza, "An assessment of thermal-image acquisition with an unmanned aerial vehicle (uav) for direct counts of coastal marine mammals ashore," *Journal of Unmanned Vehicle Systems*, vol. 6, no. 2, pp. 100–108, 2018.

[125] S. Wang, L. Liu, L. Qu, C. Yu, Y. Sun, F. Gao, and J. Dong, "Accurate ulva prolifera regions extraction of uav images with superpixel and cnns for ocean environment monitoring," *Neurocomputing*, vol. 348, pp. 158–168, 2019.

[126] G. D. Bousquet, M. S. Triantafyllou, and J.-J. E. Slotine, "The unav, a wind-powered uav for ocean monitoring: Performance, control and validation," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2018, pp. 1259–1266.

[127] G. Fontanesi, H. Ahmadi, and A. Zhu, "Over the sea uav based communication," *arXiv preprint arXiv:1905.04954*, 2019.

[128] S. Wu, Q. Wang, B. Liu, J. Liu, K. Zhang, and X. Song, "Uav-borne coherent doppler lidar for marine atmospheric boundary layer observations," in *EPJ Web of Conferences*, vol. 176. EDP Sciences, 2018, p. 02012.

[129] D. W. Johnston, "Unoccupied aircraft systems in marine science and conservation," *Annual review of marine science*, vol. 11, pp. 439–463, 2019.

[130] A. S. Aniceto, M. Biuw, U. Lindstrøm, S. A. Solbø, F. Broms, and J. Carroll, "Monitoring marine mammals using unmanned aerial vehicles: quantifying detection certainty," *Ecosphere*, vol. 9, no. 3, 2018.

[131] G. Rieucau, J. J. Kiszka, J. C. Castillo, J. Mourier, K. M. Boswell, and M. R. Heithaus, "Using unmanned aerial vehicle (uav) surveys and image analysis in the study of large surface-associated marine species: a case study on reef sharks carcharhinus melanopterus shoaling behaviour," *Journal of fish biology*, vol. 93, no. 1, pp. 119–127, 2018.

[132] B. Barritt, T. Kichkaylo, K. Mandke, A. Zalcman, and V. Lin, "Operating a uav mesh & internet backhaul network using temporospatial sdn," in *2017 IEEE Aerospace Conference*. IEEE, 2017, pp. 1–7.

[133] E. P. De Freitas, T. Heimfarth, I. F. Netto, C. E. Lino, C. E. Pereira, A. M. Ferreira, F. R. Wagner, and T. Larsson, "Uav relay network to support wsn connectivity," in *International Congress on Ultra Modern Telecommunications and Control Systems*. IEEE, 2010, pp. 309–314.

[134] M. Hua, Y. Wang, M. Lin, C. Li, Y. Huang, and L. Yang, "Joint comp transmission for uav-aided cognitive satellite terrestrial networks," *Ieee Access*, vol. 7, pp. 14 959–14 968, 2019.

[135] F. Cheng, S. Zhang, Z. Li, Y. Chen, N. Zhao, F. Yu, and V. Leung, "UAV Trajectory Optimization for Data Offloading at the Edge of Multiple Cells," *Ieee Transactions on Vehicular Technology*, vol. 67, no. 7, pp. 6732–6736, 2018.

[136] X. Cao, J. Xu, and R. Zhangt, "Mobile edge computing for cellular-connected uav: Computation offloading and trajectory optimization," in *2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*. IEEE, 2018, pp. 1–5.

[137] Y. Dong, Z. Hassan, J. Cheng, J. Hossain, and V. Leung, "An edge computing empowered radio access network with uav-mounted fso fronthaul and backhaul: Key challenges and approaches," *Ieee Wireless Communications*, vol. 25, no. 3, pp. 154–160, 2018.

[138] R. Duan, J. Wang, C. Jiang, Y. Ren, and L. Hanzo, "The transmit-energy vs computation-delay trade-off in gateway-selection for heterogenous cloud aided multi-uav systems," *Ieee Transactions on Communications*, vol. 67, no. 4, pp. 3026–3039, 2019.

[139] S. Jeong, O. Simeone, and J. Kang, "Mobile edge computing via a uav-mounted cloudlet: Optimization of bit allocation and path planning," *Ieee Transactions on Vehicular Technology*, vol. 67, no. 3, pp. 2049–2063, 2018.

[140] S. ur Rahman, G.-H. Kim, Y.-Z. Cho, and A. Khan, "Deployment of an sdn-based uav network: Controller placement and tradeoff between control overhead and delay," in *2017 International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE, 2017, pp. 1290–1292.

[141] Z. Yuan, X. Huang, L. Sun, and J. Jin, "Software defined mobile sensor network for micro uav swarm," in *2016 IEEE International Conference on Control and Robotics Engineering (ICCRE)*. IEEE, 2016, pp. 1–4.

[142] R. Kumar, M. A. Sayeed, V. Sharma, and I. You, "An sdn-based secure mobility model for uav-ground communications," in *International Symposium on Mobile Internet Security*. Springer, 2017, pp. 169–179.

[143] X. Zhang, H. Wang, and H. Zhao, "An sdn framework for uav backbone network towards knowledge centric networking," in *IEEE INFOCOM 2018-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE, 2018, pp. 456–461.

[144] T. Bai, J. Wang, Y. Ren, and L. Hanzo, "Energy-efficient computation offloading for secure uav-edge-computing systems," *IEEE Transactions on Vehicular Technology*, 2019.

[145] S. Garg, A. Singh, S. Batra, N. Kumar, and L. Yang, "Uav-empowered edge computing environment for cyber-threat detection in smart vehicles," *Ieee Network*, vol. 32, no. 3, pp. 42–51, 2018.

[146] Y. Khosiawan and I. Nielsen, "A system of uav application in indoor environment," *Production & Manufacturing Research*, vol. 4, no. 1, pp. 2–22, 2016.

[147] A. M. Madni, M. W. Sievers, J. Humann, E. Ordoukhanian, B. Boehm, and S. Lucero, "Formal methods in resilient systems design: application to multi-uav system-of-systems control," in *Disciplinary Convergence in Systems Engineering Research*. Springer, 2018, pp. 407–418.

[148] C. Luo, J. Nightingale, E. Asemota, and C. Grecos, "A uav-cloud system for disaster sensing applications," in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*. IEEE, 2015, pp. 1–5.

[149] M. Saigh and X. Zhang, "Uav policing, enforcement and deployment system," Sep. 7 2017, uS Patent App. 15/061,256.

[150] M. Khan, K. Heurtefeux, A. Mohamed, K. Harras, and M. Hassan, "Mobile target coverage and tracking on drone-be-gone uav cyber-physical testbed," *Ieee Systems Journal*, vol. 12, no. 4, pp. 3485–3496, 2018.

[151] H. Aasen, A. Burkart, A. Bolten, and G. Bareth, "Generating 3d hyperspectral information with lightweight uav snapshot cameras for vegetation monitoring: From camera calibration to quality assurance," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 108, pp. 245–259, 2015.

[152] K. Van Beeck, T. Tuytelaars, D. Scarramuza, and T. Goedemé, "Real-time embedded computer vision on uavs," in *European Conference on Computer Vision*. Springer, 2018, pp. 3–10.

[153] C. Eling, L. Klingbeil, and H. Kuhlmann, "Real-time single-frequency gps/mems-imu attitude determination of lightweight uavs," *Sensors*, vol. 15, no. 10, pp. 26 212–26 235, 2015.

[154] L. Wang, P. Huang, K. Wang, G. Zhang, L. Zhang, N. Aslam, and K. Yang, "Rl-based user association and resource allocation for multi-uav enabled mec," *arXiv preprint arXiv:1904.07961*, 2019.

[155] L. Hu, Y. Tian, J. Yang, T. Taleb, L. Xiang, and Y. Hao, "Ready player one: Uav-clustering-based multi-task offloading for vehicular vr/ar gaming," *IEEE Network*, vol. 33, no. 3, pp. 42–48, 2019.

[156] F. Zhou, Y. Wu, R. Q. Hu, and Y. Qian, "Computation rate maximization in uav-enabled wireless-powered mobile-edge computing systems," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 9, pp. 1927–1941, 2018.

[157] Y. Qian, F. Wang, J. Li, L. Shi, K. Cai, and F. Shu, "User association and path planning for uav-aided mobile edge computing with energy restriction," *IEEE Wireless Communications Letters*, 2019.

[158] L. Zhang, Z. Zhao, Q. Wu, H. Zhao, H. Xu, and X. Wu, "Energy-aware dynamic resource allocation in uav assisted mobile edge computing over social internet of vehicles," *Ieee Access*, vol. 6, pp. 56 700–56 715, 2018.

[159] W. Chen, B. Liu, H. Huang, S. Guo, and Z. Meng, "When uav swarm meets edge-cloud computing: The qos perspective," *Ieee Network*, vol. 33, no. 2, pp. 36–43, 2019.

[160] H. Cao, Y. Liu, X. Yue, and W. Zhu, "Cloud-assisted uav data collection for multiple emerging events in distributed wsns," *Sensors*, vol. 17, no. 8, 2017.

[161] M. Itkin, M. Kim, and Y. Park, "Development of cloud-based uav monitoring and management system," *Sensors*, vol. 16, no. 11, 2016.

[162] A. Koubaa, B. Qureshi, M. Sriti, A. Allouch, Y. Javed, M. Alajlan, O. Cheikhrouhou, M. Khalgui, and E. Tovar, "Dronemap planner: A service-oriented cloud-based management system for the internet-of-drones," *Ad Hoc Networks*, vol. 86, pp. 46–62, 2019.

[163] B. Liu, Y. Chen, A. Hadiks, E. Blasch, A. Aved, D. Shen, and G. Chen, "Information fusion in a cloud computing era: A systems-level perspective," *Ieee Aerospace and Electronic Systems Magazine*, vol. 29, no. 10, pp. 16–24, 2014.

[164] D. Turner, A. Lucieer, and L. Wallace, "Direct georeferencing of ultrahigh-resolution uav imagery," *Ieee Transactions on Geoscience and Remote Sensing*, vol. 52, no. 5, pp. 2738–2745, 2014.

[165] L. J. Myslinski, "Drone device security system for protecting a package," Feb. 21 2019, uS Patent App. 16/169,328.

[166] M. S. Evans, "Drone transport system," Feb. 19 2019, uS Patent App. 10/207,805.

[167] I. H. B. Pizetta, A. S. Brandão, and M. Sarcinelli-Filho, "Avoiding obstacles in cooperative load transportation," *ISA transactions*, 2019.

[168] B. Shirani, M. Najafi, and I. Izadi, "Cooperative load transportation using multiple uavs," *Aerospace Science and Technology*, vol. 84, pp. 158–169, 2019.

[169] A. Rahmadhani, Richard, R. Isswandhana, A. Giovani, and R. A. Syah, "Lorawan as secondary telemetry communication system for drone delivery," in *2018 IEEE International Conference on Internet of Things and Intelligence System (IOTAIS)*, Nov 2018, pp. 116–122.

[170] K. Dorling, J. Heinrichs, G. G. Messier, and S. Magierowski, "Vehicle routing problems for drone delivery," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 1, pp. 70–85, Jan 2017.

[171] V. Gatteschi, F. Lamberti, G. Paravati, A. Sanna, C. Demartini, A. Lisanti, and G. Venezia, "New frontiers of delivery services using drones: A prototype system exploiting a quadcopter for autonomous drug shipments," in *2015 IEEE 39th Annual Computer Software and Applications Conference*, vol. 2, July 2015, pp. 920–927.

[172] S. Sawadsitang, D. Niyato, P. S. Tan, and P. Wang, "Supplier cooperation in drone delivery," in *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*, Aug 2018, pp. 1–5.

[173] C. Yuan, Z. Liu, and Y. Zhang, "Fire detection using infrared images for uav-based forest fire surveillance," in *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*. IEEE, 2017, pp. 567–572.

[174] N. Nigam, S. Bieniawski, I. Kroo, and J. Vian, "Control of multiple uavs for persistent surveillance: Algorithm description and hardware demonstration," in *AIAA Infotech@ Aerospace Conference and AIAA Unmanned... Unlimited Conference*, 2009, p. 1852.

[175] J. Nygårds, P. Skoglar, M. Ulvklo, and T. Högström, "Navigation aided image processing in uav surveillance: Preliminary results and design of an airborne experimental system," *Journal of Robotic Systems*, vol. 21, no. 2, pp. 63–72, 2004.

[176] J. Faigl, P. Váňa, R. Pěnička, and M. Saska, "Unsupervised learning-based flexible framework for surveillance planning with aerial vehicles," *Journal of Field Robotics*, vol. 36, no. 1, pp. 270–301, 2019.

[177] S. d'Oleire Oltmanns, I. Marzolff, K. Peter, and J. Ries, "Unmanned aerial vehicle (uav) for monitoring soil erosion in morocco," *Remote Sensing*, vol. 4, no. 11, pp. 3390–3416, 2012.

[178] C. Handford, F. Reeves, and P. Parker, "Prospective use of unmanned aerial vehicles for military medical evacuation in future conflicts." *Journal of the Royal Army Medical Corps*, vol. 164, no. 4, pp. jramc–2017–000 890, 2018.

[179] M. A. Ma'sum, M. K. Arrofi, G. Jati, F. Arifin, M. N. Kurniawan, P. Mursanto, and W. Jatmiko, "Simulation of intelligent unmanned aerial vehicle (uav) for military surveillance," in *2013 International Conference on Advanced Computer Science and Information Systems (ICACSIS)*, Sep. 2013, pp. 161–166.

[180] D. Orfanus, E. P. D. Freitas, and F. Eliassen, "Self-organization as a supporting paradigm for military uav relay networks," *IEEE Communications Letters*, vol. 20, no. 4, pp. 804–807, 2016.

[181] S. J. Kim, G. J. Lim, and J. Cho, "Drone relay stations for supporting wireless communication in military operations," in *International Conference on Applied Human Factors and Ergonomics*. Springer, 2017, pp. 123–130.

[182] J. Xu, J. Yao, L. Wang, Z. Ming, K. Wu, and L. Chen, "Narrowband Internet of Things: Evolutions, Technologies and Open Issues," *IEEE Internet of Things Journal*, vol. PP, no. 99, pp. 1–1, 2017.

[183] Y. Mehmood, F. Ahmad, I. Yaqoob, A. Adnane, M. Imran, and S. Guizani, "Internet-of-things-based smart cities: Recent advances and challenges," *IEEE Communications Magazine*, vol. 55, no. 9, pp. 16–24, 2017.

[184] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 757–789, 2015.

[185] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of LPWAN technologies for large-scale IoT deployment," *ICT Express*, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2405959517302953

[186] L. R. Varshney, "Transporting information and energy simultaneously," in *IEEE International Symposium on Information Theory*, 2013, pp. 1612–1616.

[187] S. Sudevalayam and P. Kulkarni, "Energy Harvesting Sensor Nodes: Survey and Implications," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 3, pp. 443–461, 2011.

[188] R. Zhang and C. K. Ho, "MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989–2001, 2013.

[189] J. Xu and R. Zhang, "Energy beamforming with one-bit feedback," *IEEE Transactions on Signal Processing*, vol. 62, no. 20, pp. 5370–5381, 2014.

[190] J. Guo, X. Zhou, and S. Durrani, "Wireless power transfer via mmwave power beacons with directional beamforming," *IEEE Wireless Communications Letters*, vol. PP, no. 99, pp. 1–1.

[191] S. Buzzi and C. D'Andrea, "Energy Efficiency and Asymptotic Performance Evaluation of Beamforming Structures in Doubly Massive MIMO mmWave Systems," *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 2, pp. 385–396, 2018.

[192] Y. Zeng, R. Zhang, and T. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *Ieee Communications Magazine*, vol. 54, no. 5, pp. 36–42, 2016.

[193] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Mobile Unmanned Aerial Vehicles (UAVs) for Energy-Efficient Internet of Things Communications," *IEEE Transactions on Wireless Communications*, vol. 16, no. 11, pp. 7574–7589, 2017.

[194] S. Ullah, K.-I. Kim, K. H. Kim, M. Imran, P. Khan, E. Tovar, and F. Ali, "Uav-enabled healthcare architecture: Issues and challenges," *Future Generation Computer Systems*, vol. 97, pp. 425–432, 2019.

[195] R. Austin, *Unmanned aircraft systems: UAVS design, development and deployment*. John Wiley & Sons, 2011, vol. 54.

[196] N. Kouzayha, H. Elsawy, Z. Dawy, and J. G. Andrews, "Analysis of an ID-Based RF Wake-Up Solution for IoT over Cellular Networks," in *IEEE GLOBECOM Workshops*, 2017, pp. 1–6.

[197] F. Jiang and A. L. Swindlehurst, "Dynamic UAV relay positioning for the ground-to-air uplink," in *IEEE GLOBECOM Workshops*, 2010, pp. 1766–1770.

[198] J. P. C. L. D. Costa, S. Schwarz, and L. F. D. A. Gadêlha, "Attitude determination for unmanned aerial vehicles via an antenna array," in *International Itg Workshop on Smart Antennas*, 2012, pp. 264–268.

[199] J. Zhao, F. Gao, L. Kuang, Q. Wu, and W. Jia, "Channel Tracking with Flight Control System for UAV mmWave MIMO Communications," *IEEE Communications Letters*, vol. PP, no. 99, pp. 1–1, 2018.

[200] F. Wang, J. Xu, X. Wang, and S. Cui, "Joint offloading and computing optimization in wireless powered mobile-edge computing systems," *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 1784–1797, 2018.

[201] C. E. Shannon, "A mathematical theory of communication," *Bell system technical journal*, vol. 27, no. 3, pp. 379–423, 1948.

[202] R. Corless, G. Gonnet, D. Hare, D. Jeffrey, and D. Knuth, "On the Lambert W function," *Advances in Computational Mathematics*, vol. 5, no. 4, pp. 329–359, 1996.

[203] T. Long, M. Ozger, O. Cetinkaya, and O. Akan, "Energy neutral internet of drones," *Ieee Communications Magazine*, vol. 56, no. 1, pp. 22–28, 2018.

[204] C. Lin, D. He, N. Kumar, K. Choo, A. Vinel, and X. Huang, "Security and privacy for the internet of drones: Challenges and solutions," *Ieee Communications Magazine*, vol. 56, no. 1, pp. 64–69, 2018.

[205] A. Y. Javaid, W. Sun, V. K. Devabhaktuni, and M. Alam, "Cyber security threat analysis and modeling of an unmanned aerial vehicle system," in *2012 IEEE Conference on Technologies for Homeland Security (HST)*. IEEE, 2012, pp. 585–590.

[206] M. F. Al-Sa'd, A. Al-Ali, A. Mohamed, T. Khattab, and A. Erbad, "Rf-based drone detection and identification using deep learning approaches: An initiative towards a large open source drone database," *Future Generation Computer Systems*, 2019.

[207] E. Unlu, E. Zenou, and N. Riviere, "Using shape descriptors for uav detection," *Electronic Imaging*, vol. 2018, no. 9, pp. 1–5, 2018.

[208] T. Yang, Z. Li, F. Zhang, B. Xie, J. Li, and L. Liu, "Panoramic uav surveillance and recycling system based on structure-free camera array," *IEEE Access*, 2019.

[209] N. Ammour, H. Alhichri, Y. Bazi, B. Benjdira, N. Alajlan, and M. Zuair, "Deep learning approach for car detection in uav imagery," *Remote Sensing*, vol. 9, no. 4, p. 312, 2017.

[210] Y. Xu, G. Yu, Y. Wang, X. Wu, and Y. Ma, "Car detection from low-altitude uav imagery with the faster r-cnn," *Journal of Advanced Transportation*, vol. 2017, 2017.

[211] T. Liu, H. Y. Fu, Q. Wen, D. K. Zhang, and L. F. Li, "Extended faster r-cnn for long distance human detection: Finding pedestrians in uav images," in *2018 IEEE International Conference on Consumer Electronics (ICCE)*. IEEE, 2018, pp. 1–2.

[212] H. Huang, J. Deng, Y. Lan, A. Yang, X. Deng, and L. Zhang, "A fully convolutional network for weed mapping of unmanned aerial vehicle (uav) imagery," *PloS one*, vol. 13, no. 4, p. e0196302, 2018.

[213] V. Moskalenko, A. Moskalenko, A. Korobov, and V. Semashko, "The model and training algorithm of compact drone autonomous visual navigation system," *Data*, vol. 4, no. 1, p. 4, 2019.

[214] K. Peng, J. Du, F. Lu, Q. Sun, Y. Dong, P. Zhou, and M. Hu, "A hybrid genetic algorithm on routing and scheduling for vehicle-assisted multi-drone parcel delivery," *IEEE Access*, vol. 7, pp. 49 191–49 200, 2019.

[215] S. K. Datta, J. Dugelay, and C. Bonnet, “Iot based uav platform for emergency services,” in *2018 International Conference on Information and Communication Technology Convergence (ICTC)*, Oct 2018, pp. 144–147.

[216] Boyd, Vandenberghe, and Faybusovich, “Convex optimization,” *IEEE Transactions on Automatic Control*, vol. 51, no. 11, pp. 1859–1859, 2006.

Appendix A

Derivation for $\mathbf{w}^*$.

The harvested power of the energy signal at the IoT node is denoted by P_{EH}. Combining WET link h with the BF energy signal s, we can compute P_{EH} that is equal to $\mathrm{tr}(s^H H s) = P\mathrm{tr}(\mathbf{w}^H H \mathbf{w})$, where $H = hh^H$ is the covariance matrix of h. We can compute an optimal value of $\mathbf{w}$ by minimizing the energy harvested power. This minimization problem can be modelled as a simple semi-definite programming problem as follows

$$\max_{\mathbf{w}} \quad P_{EH} = P\mathrm{tr}(\mathbf{w}^H H \mathbf{w}) \qquad \text{s.t.} \quad \mathbf{w} \succ 0.$$

The optimal solution of the above problem is $\mathbf{w}^* = \mathbf{v}_1$, where $\mathbf{v}_1$ is an eigenvector that matches with the maximum eigenvalue λ_1 of matrix H. To get a normalized BF vector for fixing the power of BF energy signal $\sqrt{P}\mathbf{w}x$, we update the optimal $\mathbf{w}^*$ as $\frac{\mathbf{v}_1}{\|\mathbf{v}_1\|}$. The updated optimal BF vector leads to the maximum harvested power $\lambda_1 P / \|\mathbf{v}_1\|$ at the IoT node.

■

Appendix B

Proof of Theorem 1

The derivation steps are as follows. The objective function in $\mathscr{P}1$ (i.e., the overall energy consumption $e_{overall} = P\alpha T$) can be reduced to WET time αT; since P is assumed to be a fixed value as shown in the communication design of Subsection 3.2.1. Substituting the expression of T to $\mathscr{P}1$, we can reduce the three variables to two variables: α and p. Accordingly, we update $\mathscr{P}1$ to an simplified problem $\mathscr{P}2$ as follows:

$$
\begin{aligned}
(\mathscr{P}2): \quad & \min_{p,\alpha} \quad \frac{\alpha l}{(1-\alpha)B\log_2\left(1+\frac{p\mathrm{tr}(H)}{N_{noise}}\right)} \\
\text{s.t.} \quad & \frac{\frac{\alpha l \zeta \lambda_1 P}{\|\mathbf{v}_1\|}}{(1-\alpha)B\log_2\left(1+\frac{p\mathrm{tr}(H)}{N_{noise}}\right)} = \frac{lp}{B\log_2\left(1+\frac{p\mathrm{tr}(H)}{N_{noise}}\right)}, \\
& \frac{l}{(1-\alpha)B\log_2\left(1+\frac{p\mathrm{tr}(H)}{N_{noise}}\right)} \leq T^{\max}.
\end{aligned}
$$

However, the objective function in above problem is non-convex to α. Therefore, we set a new variable $\beta \triangleq 1/\alpha$ to replace α. We construct a new equivalent problem $\mathscr{P}3$ as follows.

$$
\begin{aligned}
(\mathscr{P}3): \quad & \max_{p,\beta} \quad (\beta-1)\log_2\left(1+\frac{p\mathrm{tr}(H)}{N_{noise}}\right), \\
\text{s.t.} \quad & l\beta - (\beta-1)B\log_2\left(1+\frac{p\mathrm{tr}(H)}{N_{noise}}\right)T^{\max} \leq 0, \\
& p(\beta-1) - \frac{\zeta\lambda_1 P}{\|\mathbf{v}_1\|} = 0,
\end{aligned}
$$

In $\mathscr{P}3$, both objective functions and constraints are either convex or affine for all variables. Therefore, we can derive the global optimal solution of three variables (i.e., $\alpha^{opt} = 1/\beta^{opt}$, T^{opt} and p^{opt}) by Karush-Kuhn-Tucker(KKT) conditions [216].

1. Construct the Lagrange function of Problem $\mathscr{P}3$ as follows:

$$\begin{aligned}\mathscr{L}(p,\beta,\lambda,\mu) = &-(\beta-1)\log_2\left(1+\frac{p\mathrm{tr}(H)}{N_{noise}}\right)\\ &+\lambda\left(l\beta-(\beta-1)B\log_2\left(1+\frac{p\mathrm{tr}(H)}{N_{noise}}\right)T^{\max}\right)\\ &+\mu\left(p(\beta-1)-\frac{\zeta\lambda_1 P}{\|\mathbf{v}_1\|}\right),\end{aligned}$$

   where λ and μ are Lagrange multipliers integrating all inequality-constraints into a Lagrange function as the new objective function.

2. Compute KKT equation groups: the first-order necessary condition for two variables (*(KKT 1)* and *(KKT 2)*), inequality-constraints (*(KKT 3)*) and Lagrange condition (*(KKT 4)*), as follows

$$\partial\mathscr{L}/\partial p|_{opt} = 0, \tag{KKT 1}$$

$$\partial\mathscr{L}/\partial\beta|_{opt} = 0, \tag{KKT 2}$$

$$\begin{aligned}&\mu^{opt}\left(p^{opt}(\beta^{opt}-1)-\zeta\frac{\lambda_1 P}{\|\mathbf{v}_1\|}\right)=0,\\ &\mu^{opt}>0,\\ &p(\beta^{opt}-1)-\zeta\frac{\lambda_1 P}{\|\mathbf{v}_1\|}=0.\end{aligned} \tag{KKT 3}$$

$$\begin{aligned}&\lambda^{opt}(l\beta^{opt}-(\beta^{opt}-1)B\log_2\left(1+\frac{p^{opt}\mathrm{tr}(H)}{N_{noise}}\right)T^{\max})=0,\\ &\lambda^{opt}\geq 0,\\ &l\beta^{opt}-(\beta^{opt}-1)B\log_2\left(1+\frac{p^{opt}\mathrm{tr}(H)}{N_{noise}}\right)T^{\max}\leq 0,\end{aligned} \tag{KKT 4}$$

   According to *(KKT 1)*, we have expression of μ^{opt} in $\mathscr{P}3$

$$\mu^{opt} = \frac{\lambda^{opt}T^{\max}B+1}{p+\frac{N_{noise}}{\mathrm{tr}(H)}}. \tag{4.18}$$

   Substituting (4.18) to *(KKT 2)*, we obtain p^{opt} and λ^{opt} in $\mathscr{P}3$

$$\log_2\left(1+\frac{p^{opt}\mathrm{tr}(H)}{N_{noise}}\right) = \frac{\lambda^{opt}l+\frac{p^{opt}(\lambda^{opt}T^{\max}B+1)}{p^{opt}+\frac{N_{noise}}{\mathrm{tr}(H)}}}{\lambda^{opt}T^{\max}B+1}. \tag{4.19}$$

According to Eq. (4.18), we determine $\mu^{opt} > 0$. Then substituting $\mu^{opt} > 0$ to *(KKT 3)*, we get the following equation

$$p^{opt}(\beta^{opt} - 1) - \zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|} = 0.$$

Solving the above equation, we got the optimal value of β as follows

$$\beta^{opt} = \zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|} / p^{opt} + 1.$$

Since $\beta^{opt} = 1/\alpha^{opt}$ as in Subsection 3.3.1, we derive the optimal WET time factor of $\mathscr{P}3$ as follows

$$\alpha^{opt} = p^{opt} / (\zeta \frac{\lambda_1 P}{\|\mathbf{v}_1\|} + p^{opt}). \tag{4.20}$$

3. For the final solution, we have two branches because of the indeterminate sign of λ^{opt}.

   When $\lambda^{opt} = 0$, $T^{opt} < T^{\max}$ always holds. Substituting $\lambda^{opt} = 0$ to Eq. (4.19), we get

   $$\log_2 \left(1 + \frac{p^{opt} \mathrm{tr}(H)}{N_{noise}}\right) = \frac{p^{opt}}{p^{opt} + \frac{N_{noise}}{\mathrm{tr}(H)}}.$$

   Solving the above equation, we get the optimal data transmission power in *Case 1* of Theorem 1, i.e., $p_1^{opt} = 2N_{noise}/\mathrm{tr}(H)$. Accordingly, we derive the optimal value α^{opt} by substituting p^{opt} to Eq. (4.20). Meanwhile, we can derive T^{opt} by substituting p^{opt} to Eq. (3.2) and Eq. (3.7a). In addition, substituting all above optimal expressions to the inequality $l\beta^{opt} - (\beta^{opt} - 1)B\log_2\left(1 + \frac{p^{opt}\mathrm{tr}(H)}{N_{noise}}\right) T^{\max} \leq 0$ in *(KKT 4)*, we get the feasible channel-fading range for *Case 1* of Theorem 1 in Eq. (3.6).

   When $\lambda^{opt} > 0$, $T^{opt} = T^{\max}$ always holds. Substituting $\lambda^{opt} > 0$ to *(KKT4)*, we get the equation

   $$l\beta - (\beta - 1)B\log_2(1 + p\mathrm{tr}(H)/N_{noise})\, T^{\max} = 0.$$

   Solving the above equation, we get the optimal data transmission power as Eq. (3.9b) in *Case 2* of Theorem 1.

   Following the similar steps of the derivation of *Case 1*, we derive the optimal value α^{opt} by substituting p^{opt} to Eq. (4.20). The value of T^{opt} is fixed as $T^{\max}$.

Substituting all optimal expressions to Eq. (4.18), we get expression of λ^{opt} as

$$\lambda^{opt} = \frac{1}{\frac{l}{\log_2\left(1+\frac{p^{opt}\mathrm{tr}(H)}{N_{noise}}\right)-\frac{p^{opt}}{p^{opt}+\frac{N_{noise}}{\mathrm{tr}(H)}}} - T^{\max}B}.$$

Substituting the above equation to $\lambda^{opt} > 0$, we get the feasible channel-fading range for *Case 2* of Theorem 1 in Eq. (3.8).

■

Lists of Publications

Journal

- **Yalin Liu**, Hong-Ning Dai, Hao Wang, Muhammad Imran, Xiaofen Wang. "UAV-enabled Data Acquisition Scheme with Directional Wireless Energy Transfer for Internet of Things" (Submitted to appear in Elsevier Computer Communications (**CC**))

Conference

- **Yalin Liu**, Hong-Ning Dai, Yuyang Peng, Hao Wang. "UAV-enabled Data Acquisition Scheme with Directional Wireless Energy Transfer" (Accepted to appear in The 2019 IEEE International Conference on Embedded Wireless Systems and Networks (**EWSN-2019**))

Acknowlegements

Firstly, I would like to express my heartfelt gratitude to my supervisor, Professor Hong-Ning Dai, for his much constant encouragement and guidance.

Secondly, my thanks would go to my beloved family for their loving considerations and great confidence in me all through these years.

Lastly, I also owe my sincere gratitude to my friends and my fellow classmates who are always by my side.

個人簡歷

<table>
<tr><td>姓　　名</td><td>劉亞林</td><td>入　學　時　間</td><td colspan="2">2017 年 9 月</td></tr>
<tr><td rowspan="2">教育背景</td><td>起 止 年 月</td><td colspan="2">就　讀　學 校</td><td>取 得 學 位 名 稱</td></tr>
<tr><td>2013.9 - 2017.6</td><td colspan="2">重慶郵電大學</td><td>本科學位</td></tr>
<tr><td>在讀期間學術成果</td><td colspan="4">發表的學術論文、著作（論文/著作名稱、報刊/出版社名稱、發表時間、刊物/出版社級別）

期刊論文:

1. Yalin Liu, Hong-Ning Dai, Hao Wang, Muhammad Imran, Xiaofen Wang. "UAV-enabled Data Acquisition Scheme with Directional Wireless Energy Transfer for Internet of Things", Elsevier Computer Communications (CC), 2019 (Under Review)

會議論文:

1. Yalin Liu, Hong-Ning Dai, Yuyang Peng, Hao Wang. "UAV-enabled Data Acquisition Scheme with Directional Wireless Energy Transfer" (Accepted to appear in The 2019 IEEE International Conference on Embedded Wireless Systems and Networks (EWSN-2019))</td></tr>
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	參加的學術項目(項目名稱、項目時間、立項單位、承擔的工作) 參加項目： 項目名稱：“超密集網絡的關鍵技術研究”（0026/2018/A1）； 項目時間：2018.10 - 2021.10；立項單位：澳門科技發展基金會； 承擔工作：建立網絡模型。