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Energy-efficient Resource Allocation for UAV-enabled B5G

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Abstract

Due to geographical communication problem, aerial-to-ground wireless communication is widely adopted. Normal ground-to-ground channel can be replaced by aerial-to-ground channel using unmanned aerial vehicle (UAV) as relay. The high mobility and flexibility of UAV provide advantages for building a wireless communication system, especially as a mobile relay.

This report shows fundamental knowledge of wireless communication and the features of UAV, and then describes a the fifth generation (5G) or beyond the fifth generation (B5G) communication system model enabled by UAV and proposes a formulation to maximize the energy efficiency (EE) of the system, which is known as green 5G. After the calculation by using successive convex approximation (SCA) and the iterative Dinkelbach method, the optimal resource allocation and trajectory could be obtained and be shown by numerical results.

Acknowledgements

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Abbreviations

5G	The fifth-generation communication
B5G	Beyond the fifth-generation communication
D2D	Device-to-device
M-MIMO	Massive multiple-input multiple-output
GR	Green radio
UAV	Unmanned aerial vehicle
LoS	Line-of sight
UEs	User equipment
EE	Energy efficiency
SE	Spectral efficiency
UDNs	Ultra-dense networks
BSs	Base stations
EH	Energy harvesting
WPT	Wireless power transmission
DE	Deployment efficiency
AWGN	Additive white Gaussian noise
CNPC	Control and non-payload communications
GN	Ground node’s
SNR	Signal-to-noise ratio
SCA	Successive convex approximation

Chapter 1

Introduction

A concept of using UAV in the 5G wireless communication is increasingly focused due to its flexibility and potential coverage. The aim of this report is to study the characteristics of UAV-enabled wireless system and to analyze the methods and algorithm of resource allocation of UAV-enabled system to boost the energy efficiency of 5G or B5G wireless communication.

1.1 The green fifth generation communication

Thanks to the dramatic popularity of smartphones and other electronic devices, new demands, and the desire of having better user experience arise. As a result, the 5G wireless networks is coming now as people and society's expectation due to the high transmit rate and the large amount of capacity. 5G network is a kind of digital cellular networks, and the coverage range of the service can be divided into some small cells. Its capacity will increase up to 1000-fold compared to last generation wireless networks, and it can connect more and more devices increasing by the demand of users, which is at least 100 billion devices with about 7.6 billion mobile users[1]. The most important part of 5G is to increase the system throughput, which could be achieved by several technologies, such as, utilizing mm wave, D2D communication and massive multiple-input multiple-output (M-MIMO). Simultaneously, decreasing the energy consumption is also urgent no matter for the development of new generation wireless networks or for the environment. The escalation of energy consumption takes a major part of leading to greenhouse gas emission and the radio access of the cellular network takes the main part of energy consumer. Some energy saving devices were built to try to mitigate this phenomenon, such as ultra-efficient power amplifiers, which could reduce losses of feeder. However, those single devices were isolated, and their efforts were limited. Hence, an innovative solution Green radio (GR), which is dedicated to build a top-down architecture as well as joint design, which is covering all system levels and protocol stacks, was raised[2],[16]-[20].

1.2 UAV-enabled communication

There is a dramatic increase in use of unmanned aerial vehicle (UAV) in modern applications due to their high-mobility, cost-effective, on-demand deployment nature, and the advantages of its inherent line-of-sight, air-to-ground channels[5]. Nevertheless, it is an innovative technology to utilizing UAV in communication field, especially being an application in 5G communication[6]. UAV-enabled communication could provide a cost-effective and fast-respond wireless connection without infrastructure coverage, which means that it is more feasible to construct a communication network with UAV on some extreme situations[6]. For instance, after the earthquake in the city, the infrastructure of communication was destroyed, and the rescue team could build a temporary communication network for rescuing using UAV. Moreover, UAV-ground link can easily achieve Line-of sight (LoS) channels compared to ground-to-ground channels, which makes it have a higher link capacity[7]. The aim of UAV-enabled communication is to enable low latency, high speed rate, and reliable features in the two-way communication in UAVs and ground users[5]. To achieve it, Cellular-connected UAV integrates various applications into cellular networks as aerial user equipment (UEs), which has several advantages, such as ubiquitous accessibility, enhanced performance, monitoring and management approach, and robust navigation as well as cost-effectiveness[5]. Nevertheless, the UAV-enabled wireless communication system could be easily attacked by malicious eavesdropping because if it cannot distinguish eavesdropping from legitimate receivers, those benefit will also be utilizing by eavesdropping. Besides, there are few challenges associated with new technologies on UAV-enabled communication system, for instance, physical layer security need to be guaranteed against pilot contamination and malicious UAV attacks and an optimal joint trajectory design with appropriate resource allocation method should be found[8],etc. Hence, several technologies, aiming to design the optimal trajectory, to find the best performance of resource allocation and to make UAVs cooperative are raised to improve security and spectral efficiency simultaneously[8],[21]-[30].

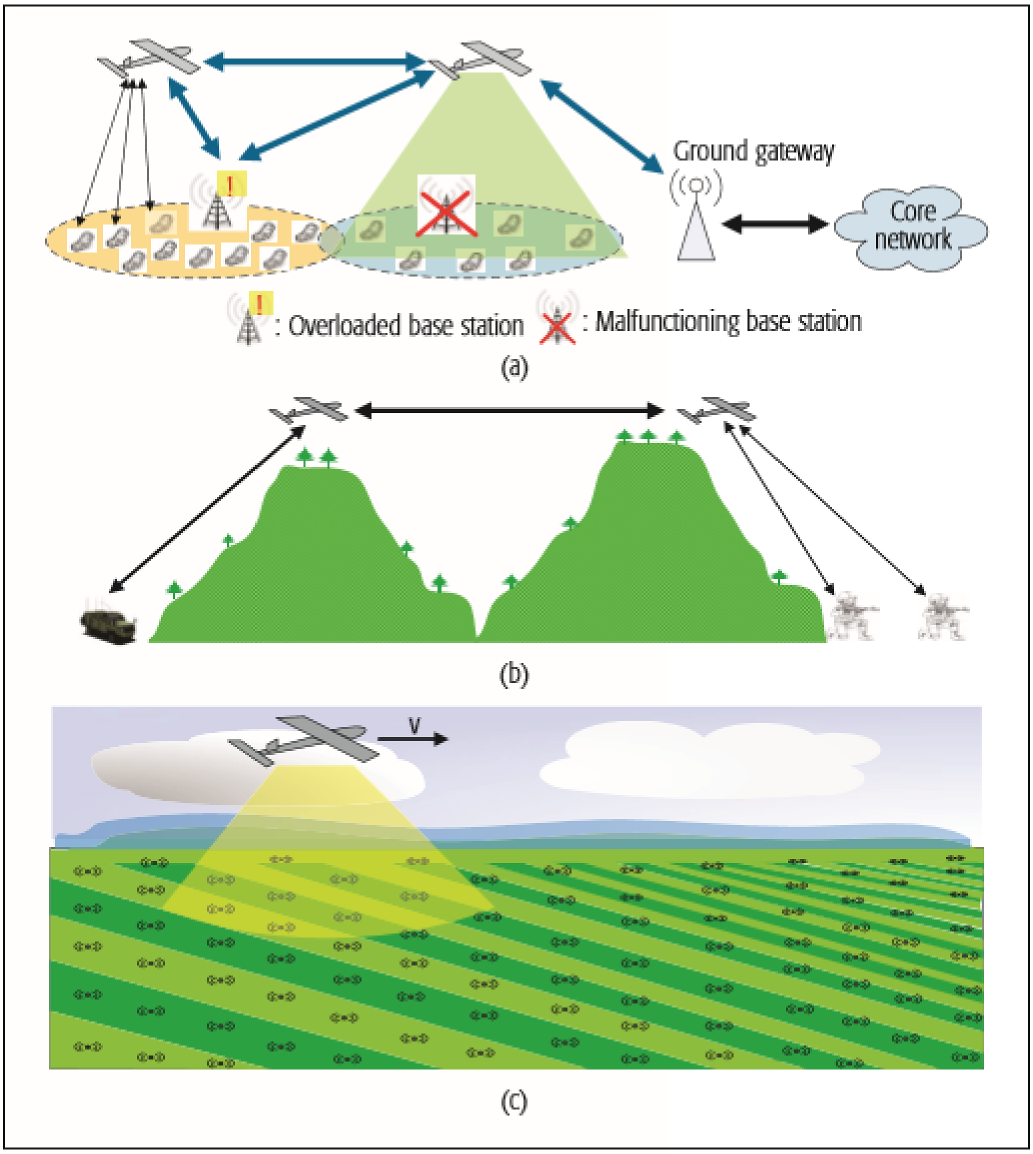

Figure 1. a) wide range of coverage in UAV-aided wireless communications; b) A communication method using relay in UAV-aided wireless communications; c) principle of information dissemination and data collection.

1.3 Resource allocation

When multiple UAV coordination as a dominant part in wireless communication system, the resource allocation of them is essential. There is a typical question. It is more likely to meet various tactical/technical constraints when trying to achieve the desired goals, and then, which UAV should execute which task is still an issue[33]. As UAVs, there are many operation that need to execute, such as classifying, searching, attacking or performing battle damage assessment on potential targets[9], and it must be answered by resource allocation. The importance of resource allocation will increase by the grows of numbers of UAV, the complexity, and capacities of the communication system. Moreover, there are various parameters in resource of the UAV system, such as cruising speed, transmit power, time allocation and frequency bandwidth, which need to be allocated[8],[31]. It is vital to find the optimized resource allocation option according to the tradeoff between trajectory and energy efficiency[32]. It has more possibility that UAV system will work under the Green communication circumstance. Furthermore, physical layer security of UAV wireless system could be boosted by the approach of the joint of trajectory and resource allocation. For example, the proper allocation of the distance to receivers and the strength of transmission power could make UAV avoid from leaking information when they are close to an eavesdropper[8]. In figure 2, it clearly demonstrates the trajectory when a UAV is close enough to the legitimate receiver and eavesdropper, and the speed as well as transmitting rate in the whole process[34]-[36].

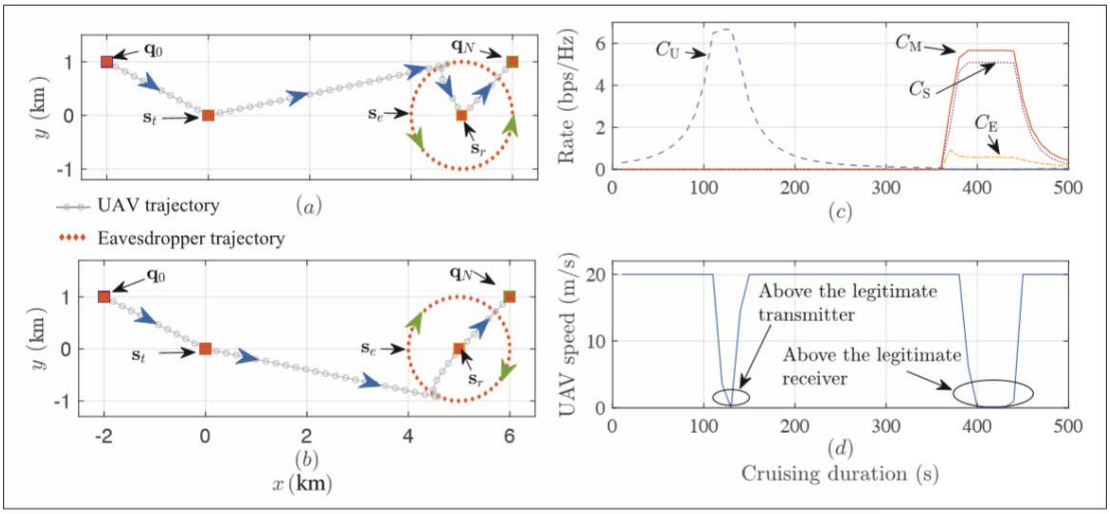

Figure 2. (a) and (b) show the optimized UAV trajectories when the eavesdropper moves counterclockwise and clockwise around the legitimate receiver, respectively. (c) the achieved system rate; (d) the corresponding cruising speed after an improvement of the physical layer security in UAV-aided wireless communication by joint trajectory and resource allocation design method.

The function of UAV will be achieved in the system is as a mobile relay, which will propose a new level of freedom for performance enhancement due to the high mobility. However, the system should be designed carefully for the resource allocation, transmit power and flight trajectory[37]-[40]. Besides, we should consider practical mobility and transmission constraints, which are vital to design and optimal the system. To achieve the maximum energy efficiency of the system, we should maximize the throughput of the system and optimize the trajectory of UAV and power allocation. The mobile relaying system could obtain a significant throughput gain compared to the conventional static relaying system[54]. To be noticed, the design of UAV's trajectory should be a constrained trajectory optimization. Any unconstrained trajectory optimizations are vanishing the energy efficiency and become energy-inefficient[52].

Chapter 2

Literature review

The article[1] provides an outline of sustainable green 5G and introduces three different paradigms, which is expanding spectrum availability, shortening Tx-Rx distances, and boosting the spatial degrees of freedom, to enhance energy efficiency (EE) through increasing spectral efficiency (SE). Firstly, a tradeoff between EE and SE is introduced as figure 4 and formula (1) shown below.

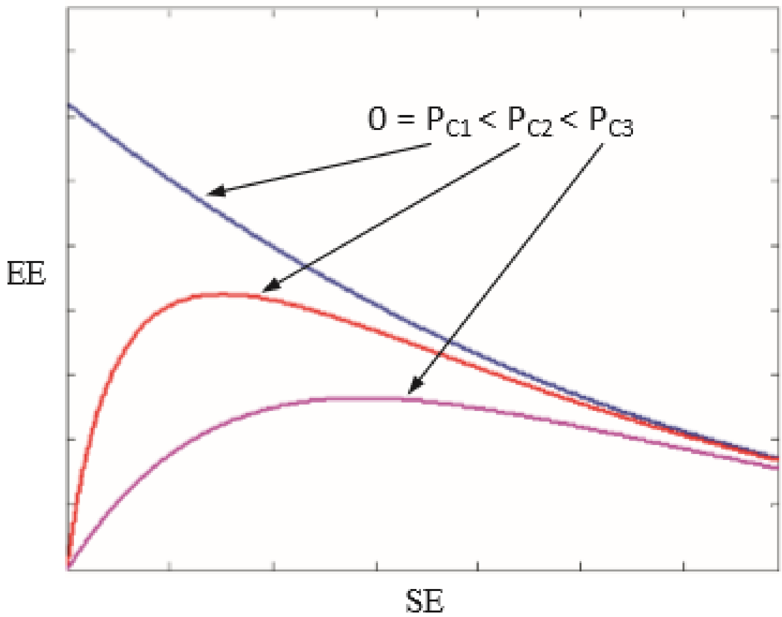

Figure 3. Fundamental tradeoff between EE and SE.

$$EE = \frac{K*B*N*log_2(1+SINR(d))}{P_t+P_c} \quad (1)$$

Where $SE = K * B * N * log_2(1 + SINR(d))$, K is the frequency reuse factor, B is the signal bandwidth, N is the number of spatial beams or the spatial multiplexing factor, P_t is the consumed transmit power, P_c is the circuit power, and d is the distance of single link. $SINR$ denotes the signal-to-interference-plus-noise ratio at the receiver and will increase with the decrease of the distance of single link.

Secondly, millimeter wave (mmWave 30 to 300 GHZ) and Long Term Evolution in unlicensed spectrum (LTE-U 5 GHZ) communications are two parts of spectrum that could be used to expand the available radio spectrum for enlarging spectrum availability by increasing the signal bandwidth. Besides, utilizing ultra-dense networks (UDNs) as well as D2D communications are the effective approaches to boost the SE by shortening the distances between Txs and Rxs. These methods could provide a high spatial reuse factor and high-quality links. Furthermore, placing a huge number of antennas at the base stations (BSs), by achieving multiplexing gain and array gain, could increasing the spatial beams or spatial multiplexing factor's number, so that it can achieve the goal. Lastly, there are two methods of energy harvesting (EH), such as EH from renewable resources and from RF signal via wireless power transmission (WPT).

For achieving a fundamental framework of green radio (GR), excepting for SE-EE trade-off, there are three other trade-offs, deployment efficiency (DE)-energy efficiency (EE) trade-off, bandwidth (BW)-power (PW) trade-off, and delay (DL)-PW trade-off[2]. The relationships of them with and without practical concerns are shown in figure 5.

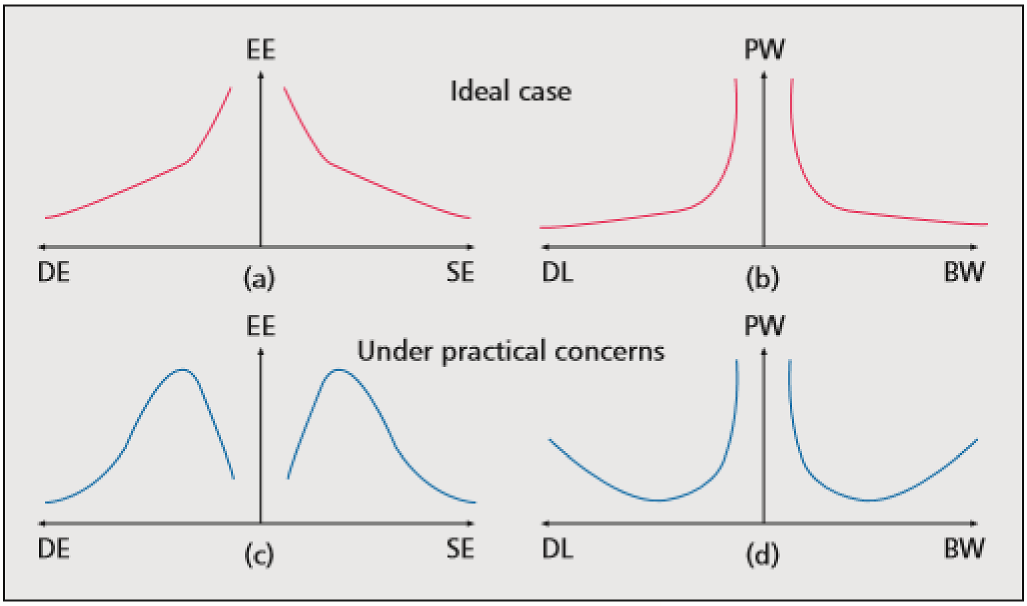

Figure 4. Four trade-off relations: (a) and (b) are ideal case; (c) and (d) are under practical concerns.

From shannon's formula, the SE-EE relation, BW-PW relation, DL-PW relation, can be expressed as formula (2), (3), (4), respectively.

$$\eta_{EE} = \frac{\eta_{SE}}{(2^{\eta_{SE}}-1)N_0} \tag{2}$$

$$P = WN_0(2^{\frac{R}{W}-1}) \tag{3}$$

$$P_b = WN_0t_b(2^{\frac{1}{t_bW}-1}) \tag{4}$$

Where $\eta_{SE} = log_2\left(1+\frac{P}{WN_0}\right)$, $\eta_{EE} = Wlog_2\left(1+\frac{P}{WN_0}\right)/(P)$, $\frac{1}{t_bW} = \frac{R}{W}$, R is the achievable transmission rate, P is the under a given transmit power, W is system's bandwidth and N_0 represents the power spectral density of additive white Gaussian noise (AWGN). Those trade-offs provide opportunities to find the optimal performance and lead to green evolution.

For upcoming 5G and beyond, the UAVs could achieve a better performance in reliability, latency, and power consumption aspects and this technology is testing in many big corporations. In paper [6] it provides an overview of the structure of UAV-enabled wireless communications and the channel characteristics of it. Besides, it shows some important advantages of UAV-enabled system, such as cost-effective, being swiftly deployed, useful short-range line-of-sight (LoS) communication, etc. Furthermore, there are three typical use cases of this system, for example, the coverage of UAV-enabled communication is wide, UAV can be used as relaying, and it is more convenient to disseminate information and collect data. As for the fundamental networking architecture of wireless communication with UAVs, it can be divided into two parts. One is control and non-payload communications (CNPC) link, it supports the low-latency and highly reliable two-way communications, sometimes with low data rate transmission requirements in all UAV systems. There are some typical CNPC messages: One is telemetry report from the UAV to the ground, which provide status of UAV, and real-time remote C&C and flight command update for non-autonomous UAVs and (semi-)autonomous UAVs, respectively. Besides, there are navigation aids as well as sense-and-avoid (S&A) related information, which is necessary for UAV to travel with safety, and air traffic control (ATC) information relaying[5]. Another is data link, which supports mission-related communications between UAV-to-UAV and UAV-to-ground terminals. These links are achieved via two channels, UAV-UAV channel, which is dominated by the LoS component, and UAV-ground channel, which is complicated to achieve due to the environment with complex unknow factors.

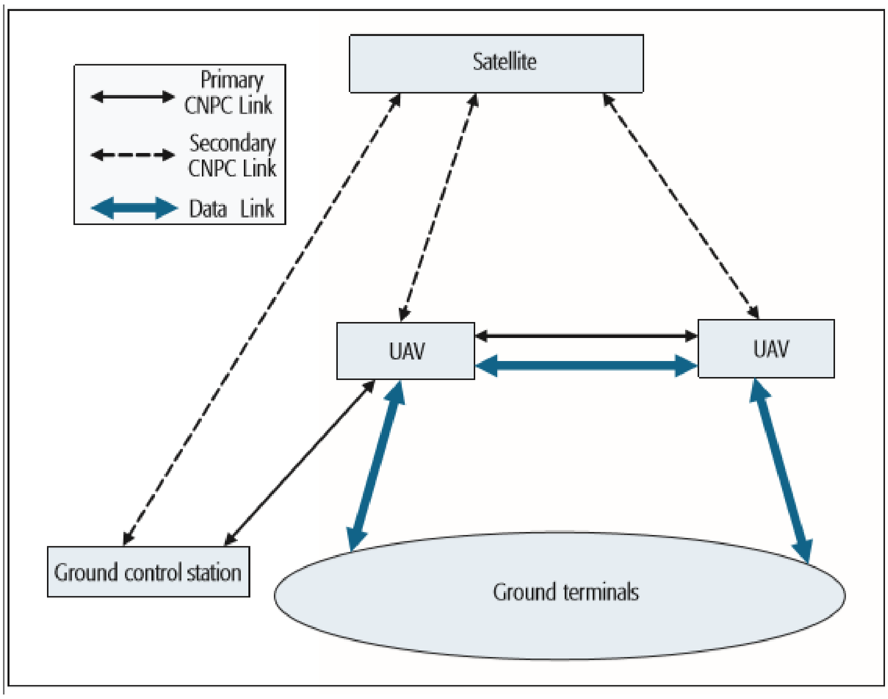

Figure 5. Fundamental structure of CNPC and data link.

It also presents several main design considerations. UAV deployment and path planning are vital to design trajectory, and energy-aware deployment and operation could make UAV become more energy saving. Besides, MIMO for UAV-enabled communications would achieve several benefits of energy efficiency and security. An optimal path planning may effectively shorten the communication distance and to achieve the high-capacity performance. Besides, the limited onboard energy would be the factor that affect the optimal plans, which can be fixed by two approaches. Effective energy-aware deployment mechanisms for replenishment and energy-efficient operation for minimum energy consumption are trying to address this issue in cutting-down consumption and recharging perspectives. When utilizing MIMO, one way is to acquire the spatial multiplexing gain and another way is to obtain the MIMO array gain[6].

For achieving the high-rate, low-latency and ultra-reliable performance, various applications of UAVs are integrated into the existing cellular network. The characteristics of cellular-connected UAV and its unique communication/spectrum requirement are shown in paper [5]. It provides some design considerations, which are different from conventional cellular communication system with ground UEs. For instance, UAV system has 3D coverage, which has more dimension than terrestrial system, so it also has its unique channel characteristics. However, these characteristics make it has more troubles. Such as, a new aerial-ground interference, and asymmetric uplink/downlink traffic requirement.

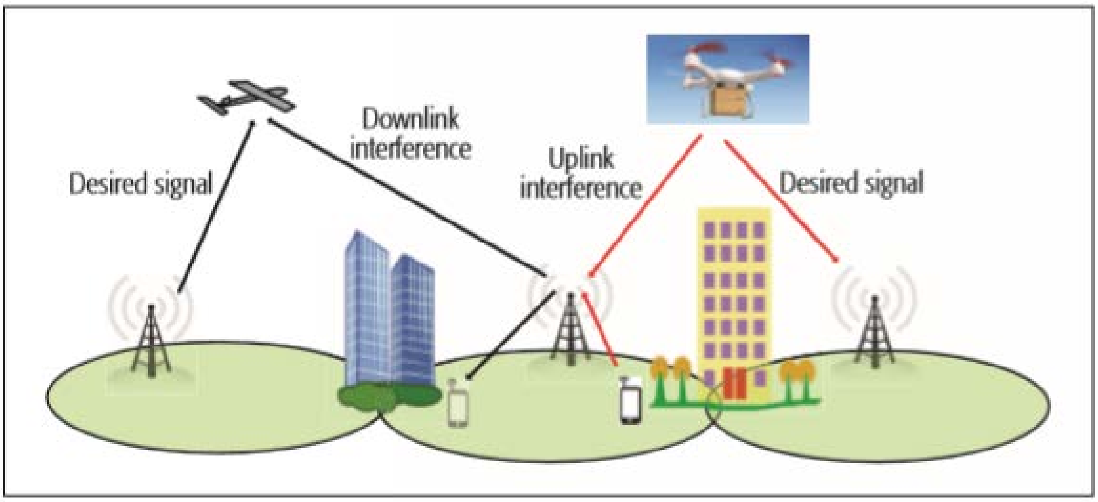

Figure 6. Interferences caused by characteristic of UAV-BS channels.

However, UAV system may be inevitably attacked by malicious eavesdropping. In paper [8], it demonstrates how passive and active eavesdropping works to eavesdrop the wireless communication. Resource allocation approach jointed with trajectory design arises to alleviate this issue by designing appropriate trajectories and allocating parameters in UAVs resources. Besides, other two approaches, robust joint design and artificial noise also work.

In paper [14], two algorithms are raised to maximize the energy-efficient resource allocation by using Lagrangian optimization and gradient decent methods. The issue of optimization of energy efficiency could be divided into two sub-problems. In UAV positioning part, it optimizes the position of UAV, such as, the optimal distances and elevation angles, to minimize the path loss of the air-to-ground channels, according to ground node's (GN) demand. In this part, $\lambda = [\lambda_1 + \lambda_2]$ as the vector of Lagrangian multipliers is introduced and the value of λ_i can be simplified by introducing the gradient decent method as follow:

$$\lambda_j(i+1) = [\lambda_j(i) - \Delta_{\lambda_j}(h_{u,min} - d_j cos(\theta_j))]^+ \quad (5)$$

where $\lambda_j(i), j \in \{1,2\}$, is the value of λ_j at the i^{th} iteration, Δ_{λ_j} is the iteration step, and $[x]^+ = max(0,x)$. Another is energy-efficient resource allocation, the optimal power and switching time could be determined by using the optimized positioning and a closed-form expression, and subsequently, to achieve the energy efficiency. In this part, the Lagrangian multipliers $\vartheta \geq 0, \varsigma \geq 0, \varepsilon \geq 0, \varphi_1 \geq 0, and\ \varphi_2 \geq 0$ are introduced to formulate the lagrangian function and these variables can be solved by using the gradient method as follow:

$$\vartheta(i+1) = \left[\vartheta(i) - \Delta_\vartheta\left(P_{u,max} - P\right)\right]^+ \quad (6)$$

$$\varsigma(i+1) = \left[\varsigma(i) - \Delta_\varsigma(\tau_{max} - \tau)\right]^+ \quad (7)$$

$$\varepsilon(i+1) = [\varepsilon(i) - \Delta_{\varepsilon}(1-\tau)]^{+} \quad (8)$$

$$\varphi_1(i+1) = \left[\varphi_1(i) - \Delta_{\varphi_1}\left(R_1(P_1, \tau, \theta_1^*, d_1^*) - r_{1,min}\right)\right]^{+} \quad (9)$$

$$\varphi_2(i+1) = \left[\varphi_2(i) - \Delta_{\varphi_2}(R_2(P_2, \tau, \theta_2^*, d_2^*) - r_{2,min})\right]^{+} \quad (10)$$

where i is the iteration index, and $\Delta_{\vartheta}, \Delta_{\varsigma}, \Delta_{\varepsilon}, \Delta_{\varphi_1}$ and Δ_{φ_2} are the iteration steps. After the simulation, the energy efficiency can be dramatically improved via these resource allocation methods.

It also proposes a iterative algorithm to acquire an sub-optimal solution of the nonconvex optimization issue of preventing UAVs from eavesdroppers in paper[15]. According to the result, this algorithm can effectively achieve the energy efficiency when UAVs can keep their adaptive velocity and flexible trajectory, and simultaneously, guarantee the secure communications.

In paper [54], it designs a UAV-enabled communication system, which has a UAV as relay. The UAV works as a relay to communicate between the source and the destination, and it aims to maximize the throughput of the system. In optimization part, it divides the problem into two sub-problem and optimize those two problems independently. The theory of Lagrangian optimization and successive convex optimization are used in solving the problems.

Paper[52] shows different designs of UAV's trajectory to achieve energy efficiency maximization, such as unconstrained trajectory, general constrained trajectory, circular trajectory. After simulations, unconstrained trajectory is energy-inefficient compared to other two trajectories.

Chapter 3

System model

3.1 motivation

To make sure the high quality of communication between two users and achieve a maximum throughput of transmission, the UAV could be designed as a relay. Utilizing the high mobility of UAV, it can travel between users. When the UAV gets close to a user, it will transmit information or receive information. With a certain trajectory, the UAV-enabled wireless communication system could be built.

However, what kind of trajectory is, when should the UAV transmit or receive information, how to allocate resource and what the velocity of UAV is during the flight, are still problems that need to be addressed[41]-[45].

3.2 model of system

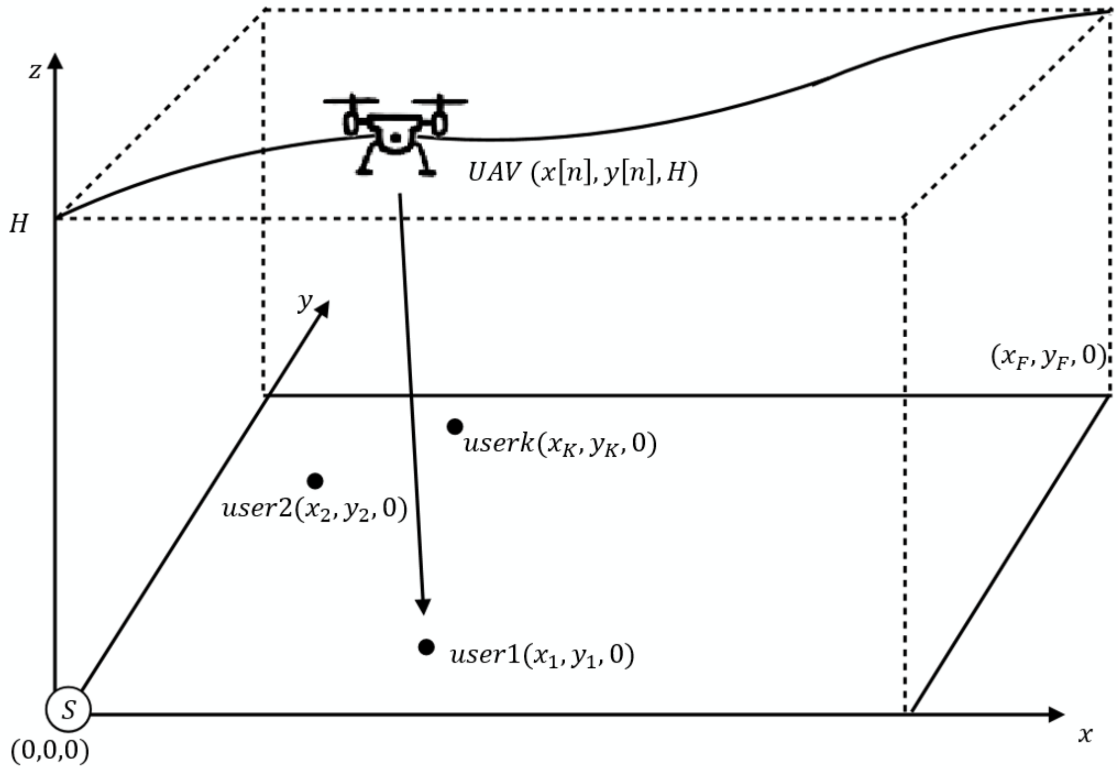

Figure 7. A UAV relaying system between the source and several users.

As shown in figure 11, this wireless communication system includes a ground node as source, a UAV as relay and some users. The ground node (GN) located at $(0, 0, 0)$ and it transmits data to the relay UAV, flying at a constant altitude H. Assuming that there is a data buffer inside the UAV, then UAV carries those data flying toward users. When UAV gets close to or gets away from a user in a distance range, the user at $(x_k, y_k, 0)$ will receive information from UAV. If the time is not enough to completely transmit data to user, UAV will hover above the user. The initial location of UAV is $(0, 0, H)$ and the final location is (x_F, y_F, H). Hence, there is a complex trajectory from initial location to final location when there are huge number of users. Besides, the total duration T is divided into several time slot N. Then, the UAV's location at every time slot could be represented by $(x[n], y[n], 0)$. Thus, the time-varying distances from the ground node to UAV and from UAV to users $k \in \{1, \dots, K\}$ at time slot $n \in \{1, \dots, N\}$ can be expressed as[15],[46]-[48]:

$$d_{SR}[n] = \sqrt{\|\boldsymbol{q}[n]\|^2 + H^2} \tag{11}$$

$$d_{RD}[n] = \sqrt{\|\boldsymbol{q}[n] - \boldsymbol{q}_k\|^2 + H^2} \tag{12}$$

where $\boldsymbol{q}[n] = \left[x[n], y[n]\right]^T \in \mathbb{R}^{2\times 1}$ represents the horizontal location of UAV and $\boldsymbol{q}_k = [x_k, y_k]^T \in \mathbb{R}^{2\times 1}$ represents the location of users. Assuming that both air-to-ground channels are dominated by LoS links. Hence, the channel power gain at time slot $\boldsymbol{n}$ from the source to UAV and from UAV to users can be expressed utilizing a free-space path loss model [31]:

$$h_{SR}[n] = \frac{\beta_0}{{d_{SR}}^2[n]} = \frac{\beta_0}{\|\boldsymbol{q}[n]\|^2 + H^2} \tag{13}$$

$$h_{RD}[n] = \frac{\beta_0}{{d_{RD}}^2[n]} = \frac{\beta_0}{\|\boldsymbol{q}[n] - \boldsymbol{q}_k\|^2 + H^2} \tag{14}$$

where β_0 is the channel power gain per meter at reference distance. Thus, the data transmission rate of these two channels are:

$$\begin{aligned} R_{SR}[n] &= \lambda(n)\, log_2\left(1 + \frac{P_s[n] h_{SR}[n]}{\sigma^2}\right) \\ &= \lambda(n)\, log_2\left(1 + \frac{P_s[n]\gamma_0}{\|\boldsymbol{q}[n]\|^2 + H^2}\right) \end{aligned} \tag{15}$$

$$\begin{aligned} R_{RD}[n] &= \left(1 - \lambda(n)\right) log_2\left(1 + \frac{P_r[n] h_{RD}[n]}{\sigma^2}\right) \\ &= \left(1 - \lambda(n)\right) log_2\left(1 + \frac{P_s[n]\gamma_0}{\|\boldsymbol{q}[n] - \boldsymbol{q}_k\|^2 + H^2}\right) \end{aligned} \tag{16}$$

where $P_s[n]$ and $P_r[n]$ represents the transmission power of the source and UAV, respectively. σ^2 is the white Gaussian noise power. $\gamma_0 = \frac{\beta_0}{\sigma^2}$ denotes the reference signal-to-noise ratio (SNR). $\lambda(n)$ is a binary variable. The source transmits data to UAV when $\lambda(n) = 1$, and UAV transmits data to users when $\lambda(n) = 0$.

The power consumption of the whole system should be considered as follows. It can be divided into two parts, communication power and flight power consumptions. The flight power consumption for could be expressed with velocity $\boldsymbol{v}[n] = \left[v_x[n], v_y[n]\right]^T \in \mathbb{R}^{2\times1}$[57]:

$$P_{flight}[n] = c_1\|\boldsymbol{v}[n]\|^3 + \frac{c_2}{\|\boldsymbol{v}[n]\|} \tag{17}$$

where c_1 and c_2 are two parameters related to UAV's weight, air density, etc. Thus, the total power consumption of the system is:

$$\begin{aligned} P_{total} &= P_{flight} + \lambda(n)P_s + \big(1 - \lambda(n)\big)P_r \\ &= \sum_{n=1}^{N}\left(c_1\|v[n]\|^3 + \frac{c_2}{\|v[n]\|}\right) + \lambda(n)\sum_{n=1}^{N} P_s[n] + \big(1 - \lambda(n)\big)\sum_{n=1}^{N} P_r[n] \end{aligned} \tag{18}$$

Thus, the energy efficiency of this system in bits-per-Joule (bits/J) could be expressed as:

$$\eta E = \frac{BR_{SD}}{P_{total}} \tag{19}$$

where B denotes the channel bandwidth. In this system, UAV can only transmit data after receiving data from the source. Hence, the information-causality constraint could be achieved as[53]-[54]:

$$\sum_{n=1}^{N} R_{RD}[n] \leq \sum_{n=1}^{N} R_{SR}[n], \forall n \in \{1, \ldots, N\} \tag{20}$$

Then, the system energy efficiency formula could be rewritten as:

$$\eta E = \frac{B\frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{K}\big(1-\lambda(n)\big)\, log_2\left(1+\frac{P_S[n]\gamma_0}{\|q[n]-q_k\|^2+H^2}\right)}{\frac{1}{N}\sum_{n=1}^{N} P_{total}} \tag{21}$$

Chapter 4

Problem formulation

To maximize the energy efficiency of this model system, it is necessary to optimize the user scheduling, power allocation, flight velocity and UAV's trajectory[50]-[52]. Then, it can be formulated as the following optimization problem:

$$(P1) \quad \underset{\{\lambda[n], p_s[n], p_r[n], \boldsymbol{q}[n], v[n]\}}{maximize} \quad \boldsymbol{\eta E}$$

$$s.t. C1: \sum_{n=1}^{N} R_{RD}[n] \leq \sum_{n=1}^{N} R_{SR}[n], \forall n \in \{2, \dots, N\},$$

$$C2: \frac{1}{N}\sum_{n=1}^{N-1} \lambda[n]P_s[n] \leq \overline{P_s}; \ \frac{1}{N}\sum_{n=1}^{N-1}(1-\lambda[n])P_r[n] \leq \overline{P_r}, \forall n,$$

$$C3: \lambda[n] \in \{0, 1\}$$

$$C4: (x[n+1]-x[n])^2 + (y[n+1]-y[n])^2 \leq V^2,$$

$$\forall n \in \{0,1,\dots, N-1\}$$

$$C5: \ \|v[n]\| \leq V_{max}, \forall n$$

$$C6: \ \boldsymbol{q}[0] = \boldsymbol{q}_0,$$

$$C7: \ \boldsymbol{q}[N] = \boldsymbol{q}_F,$$

where $C1$ and $C2$ define the UAV's initial and final locations, respectively. $C3$ shows that UAV can only transmit data after receiving data from the source. In $C4$, $\overline{P_s}$ and $\overline{P_r}$ represent average power limits at the source and UAV. $C5$ makes a velocity constraint that velocity at each time slot will not exceed a constant V and $C6$ also limits the velocity change[wenxian6]. $\lambda[n]$ is a binary variable which is 0 or 1 in $C7$. However, (P1) is a non-convex problem, which cannot be solved by conventional convex optimization methods. To address this problem, the problem can be divided into two sub-problems[55]. We aim to optimize the power allocation $p_s[n]$, $p_r[n]$ and user scheduling $\lambda[n]$ with fixed trajectory $\boldsymbol{q}[n]$ and velocity $v[n]$ in sub-problem 1. And then in sub-problem 2, we aim to optimize the trajectory $\boldsymbol{q}[n]$ and velocity $v[n]$ with feasible power allocation $p_s[n]$, $p_r[n]$ and user scheduling $\lambda[n]$ [15], [54].

4.1 Sub-problem 1 with fixed trajectory and velocity

In this part, we aim to optimize user scheduling and transmit power allocation. And we introduce two variables $\widetilde{P_s}[n] = \lambda(n)P_s[n]$ and $\widetilde{P_r}[n] = \big(1-\lambda(n)\big)P_r[n]$ to solve this problem easily. Then, the sub-problem formulation could be expressed as follows[54],[55]:

$$(P1.1) \qquad \underset{\{\lambda[n], p_s[n], p_r[n]\}}{maximize} \quad \frac{B\frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{K}\tilde{R}_{RD}[n]}{\frac{1}{N}\sum_{n=1}^{N}\tilde{P}_{total}[n]}$$

$$s.t.\ \widetilde{C1}:\ \sum_{n=1}^{N}\tilde{R}_{RD}[n] \le \sum_{n=1}^{N}\tilde{R}_{SR}[n], \forall n \in \{2,\dots,N\},$$

$$\widetilde{C2}:\ \frac{1}{N}\sum_{n=1}^{N-1}\tilde{P}_s[n] \le \bar{P}_s;\quad \frac{1}{N}\sum_{n=1}^{N-1}\tilde{P}_r[n] \le \bar{P}_r, \forall n,$$

$$\widetilde{C3}:\ 0 \le \lambda[n] \le 1, \forall n,$$

where $$h[n] = \frac{\gamma_0}{\|\boldsymbol{q}[n]-\boldsymbol{q}_k\|^2+H^2},$$

$$\tilde{R}_{RD}[n] = \big(1-\lambda(n)\big)\,log_2\left(1+\frac{\widetilde{P_s}[n]h[n]}{\big(1-\lambda(n)\big)}\right), \forall n,$$

$$\tilde{P}_{total}[n] = \left(c_1\|V[n]\|^3 + \frac{c_2}{\|V[n]\|}\right) + \tilde{P}_s[n] + \tilde{P}_r[n], \forall n,$$

Then we can start to tackle this fractional-form objective function by applying the iterative Dinkelbach method[15]. First, let q_1^* be the maximum energy efficiency result of the objective function (P1.1), then the formulation can be expressed as follows:

$$q_1^* = \frac{R_{RD}(\tilde{P}_r^*[n], \lambda^*(n))}{P_{total}(\tilde{P}_s^*[n], \tilde{P}_r^*[n])} = \underset{\{\lambda[n], \tilde{p}_s[n], \tilde{p}_r[n]\}}{maximize} \frac{R_{RD}(\tilde{p}_r[n], \lambda[n])}{P_{total}(\tilde{p}_s[n], \tilde{p}_r[n])} \tag{22}$$

where $\lambda^*(n)$, $\tilde{P}_s^*[n]$, $\tilde{P}_r^*[n]$ are the optimal user schedule, power allocation of the source and UAV, respectively. The optimal value of q_1^* could be achieved if and only if the function equals to zero[54]. Then, the fractional form objective function could transform to a subtractive form:

$$\underset{\{\lambda[n], \tilde{p}_s[n], \tilde{p}_r[n]\}}{maximize} \frac{R_{RD}(\tilde{p}_r[n], \lambda[n])}{P_{total}(\tilde{p}_s[n], \tilde{p}_r[n])} = 0 \tag{23}$$

$$= R_{RD}(\tilde{p}_r[n], \lambda[n]) - q_1^* P_{total}(\tilde{p}_s[n], \tilde{p}_r[n]) = 0 \tag{24}$$

for $R_{RD}(\tilde{p}_r[n], \lambda[n]) \geq 0, \quad P_{total}(\tilde{p}_s[n], \tilde{p}_r[n]) \geq 0$. Hence, the sub-problem 1 (P1.1) could be solved using this method by g^{Algo1}-th iteration and $q_1^{(g^{Algo1})}$ could be used to acquire the optimal $\lambda[n]$, $\tilde{p}_s[n]$, $\tilde{p}_r[n]$:

$$\left\{\underline{\lambda[n]}, \underline{\tilde{p}_s[n]}, \underline{\tilde{p}_r[n]}\right\} = \arg \underset{\{\lambda[n], \tilde{p}_s[n], \tilde{p}_r[n]\}}{maximize} \frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{K} \tilde{R}_{RD}[n] - q_1^{(g^{Algo1})} \frac{1}{N}\sum_{n=1}^{N} \tilde{P}_{total}[n]$$

$$s.t.\ \widetilde{C1} \sim \widetilde{C3}$$

For each iteration of Dinkelbach method, updating $q_1^{(g^{Algo1})} = \frac{\underline{R_{RD}}(\tilde{p}_r[n], \lambda[n])}{\underline{P_{total}}(\tilde{p}_s[n], \tilde{p}_r[n])}$ until convergence or $g^{Algo1} = G_{max}^{Algo1}$. This can be solved by using numerical convex program solvers. In this case, CVX is our first choice[15],[52].

4.2 Sub-problem 2 with fixed user scheduling and power allocation

In this part, the user scheduling and transmission power allocation are given. Hence, the problem (P1) can be transformed by introducing a slack variable $u_k[n]$ as follows:

$$(P1.2) \quad \underset{\{\boldsymbol{q}[n], v[n]\}}{maximize} \ \frac{B\frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{K}\bar{R}_{RD}[n]}{\frac{1}{N}\sum_{n=1}^{N}P_{total}[n]}$$

$$s.t.\ C4 \sim C7$$

$$\overline{C1}: \sum_{n=1}^{N}\bar{R}_{RD}[n] \leq \sum_{n=1}^{N}\bar{R}_{SR}[n], \forall n \in \{2, \dots, N\},$$

$$C8: \ \|\boldsymbol{q}[n]-\boldsymbol{q}_k\|^2 + H^2 \leq \ u_k[n], \forall k,$$

where $$\bar{R}_{RD}[n] = \left(1-\lambda(n)\right) log_2\left(1+\frac{\delta_0}{u_k[n]}\right),$$

$$\delta_0 = P_r[n]\gamma_{0,}$$

We should solve the objective function because both the denominator and the numerator are non-convex function[15]. For both numerator and denominator functions, we could find the lower bound of data rate $\bar{R}_{RD}[n]$ and total power consumption $P_{total}[n]$ utilizing successive convex approximation (SCA). Firstly, we handle the data rate as follow:

$$\bar{R}_{RD}[n] \geq \bar{R}_{RD_{lb}}[n] = \left(1-\lambda(n)\right) log_2\left(1+\frac{\delta_0}{u_k^{\left(j^{Algo2}\right)}[n]}\right) - \frac{\left(1-\lambda(n)\right)\delta_0\left(u_k[n]-u_k^{\left(j^{Algo2}\right)}[n]\right)}{u_k^{\left(j^{Algo2}\right)}[n]\left(u_k^{\left(j^{Algo2}\right)}[n]+\delta_0\right)\ln 2}, \forall n, k \quad (25)$$

where $u_k^{\left(j^{Algo2}\right)}[n]$ denotes the feasible solution of $u_k[n]$ in the j^{Algo2}-th iteration. Then, the problem could be solved by convex program solver. For the total power consumption[52], we could use the same method. However, we should find an equivalent function as follow:

$$\bar{\bar{P}}_{total}[n] = \sum_{n=1}^{N}\left(c_1\|v[n]\|^3 + \frac{c_2}{V[n]}\right) + \lambda(n)\sum_{n=1}^{N}P_s[n] + \left(1 - \lambda(n)\right)\sum_{n=1}^{N}P_r[n] \quad (26)$$

$$s.t.\, C9: \|v[n]\|^2 \geq V^2[n], \forall n,$$

$$C10: V[n] \geq 0, \forall n,$$

where $V[n]$ is a slack variable. Then, as $\|v[n]\|^2$ is differentiable, we should tackle the non-convex constraint $C9$ with acquiring the lower bound of it in the $j^{(Algo2)}$-th iteration:

$$\|v[n]\|^2 \geq \left\|v^{j^{(Algo2)}}[n]\right\|^2 - 2\left[v^{j^{(Algo2)}}[n]\right]\left(v[n] - v^{j^{(Algo2)}}[n]\right) \quad (27)$$

Now, the lower bound of sub-problem 2 (P1.2) could be obtained by acquiring the lower bound of data rate and the equivalent form of total power consumption. Then, we could solve (P1.2) with its lower bound by solving the following problem[56],[57]:

$$(P1.2^{eq}) \quad \underset{\{\boldsymbol{q}[n], u_k[n], v[n], V[n]\}}{maximize} \frac{B\frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{K}\bar{R}_{RD\_lb}[n]}{\frac{1}{N}\sum_{n=1}^{N}\bar{\bar{P}}_{total}[n]}$$

$$s.t.\, C4 \sim C7, C10$$

$$\overline{C1}: \sum_{n=1}^{N}\bar{R}_{RD\_lb}[n] \leq \sum_{n=1}^{N}\bar{R}_{SR}[n], \forall n \in \{2, \dots, N\},$$

$$C8: \|\boldsymbol{q}[n] - \boldsymbol{q}_k\|^2 + H^2 \leq u_k[n], \forall k,$$

$$C9: \left\|v^{j^{(Algo2)}}[n]\right\|^2 - 2\left[v^{j^{(Algo2)}}[n]\right]\left(v[n] - v^{j^{(Algo2)}}[n]\right) \geq V^2[n], \forall n,$$

After transformation, $(P1.2^{eq})$ satisfies the requirement of convex optimization, then we still utilize the iterative Dinkelbach method[15]. The optimal value q_2^* could be obtained if and only if:

$$\underset{\{\boldsymbol{q}[n], u_k[n], v[n], V[n]\}}{maximize} \bar{R}_{RD\_lb}(u_k[n]) - q_2^*\bar{\bar{P}}_{total}(v[n], V[n])$$

$$= \bar{R}_{RD_{lb}}(u_k^*[n]) - q_2^*\bar{\bar{P}}_{total}(v^*[n], V^*[n]) = 0$$

Hence, the sub-problem 2 (P1.2) could be solved using this method by j^{Algo2}-th iteration in inner loop and $q_2^{\left(j_{inner}^{Alog2}\right)}$ could be used to acquire the optimal $\boldsymbol{q}[n], u_k[n], v[n], V[n]$:

$$\left\{\underline{\boldsymbol{q}[n]}, \underline{u_k[n]}, \underline{v[n]}, \underline{V[n]}\right\} = \arg \underset{\{\boldsymbol{q}[n], u_k[n], v[n], V[n]\}}{maximize} \frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{K} \bar{R}_{RD\_lb}[n] - q_2^{\left(j_{inner}^{Alog2}\right)} \frac{1}{N}\sum_{n=1}^{N} \bar{\bar{P}}_{total}[n]$$

$$s.t. \overline{C1}, C4{\sim}C10$$

After the inner loop convergence, to acquire the tighten bound, we could still update $\left\{\underline{\boldsymbol{q}[n]}^{j^{Algo2}}, \underline{u_k[n]}^{j^{Algo2}}, \underline{v[n]}^{j^{Algo2}}, \underline{V[n]}^{j^{Algo2}}\right\}$ in the main loop and obtain results when the main loop convergence is true or $j^{Algo2} = J_{max}^{Algo2}$ [56].

4.3 Overall solution of sub-problem 1 and 2.

In this overall solution, we name it as algorithm 3. To start it, we should set the maximum number of iterations L_{max}^{Algo3} and the maximum tolerance ε. Firstly, we use the algorithm 1 for sub-problem 1 to obtain result q_1 and $\lambda[n], p_s[n], p_r[n]$. Secondly, we use the given result and the algorithm 2 for sub-problem 2 to obtain the sub-optimal result q_2 and $\boldsymbol{q}[n], v[n]$. If $q_2{}^{(l^{Algo3})} - q_2{}^{(l^{Algo3}-1)} < \varepsilon$, then convergence is true and those results we got are the optimal results[54]. If there is not a convergence, then continue the iteration until convergence is true or meets the maximum number of iterations[15].

Chapter 5

Numerical results

After simulation by using CVX, we obtained performances of optimizing the resource allocation and UAV's trajectory in this part. The simulation value settings are summarized in table 1. Figure 8. shows the convergence of the algorithm after iteration. Besides, we increase the induced power in hovering status as comparison. When the induced power in hovering status increases, the energy efficiency will dramatically reduce and will use more iterations to converge. We can notice that the proposed algorithm converges within 8 iterations. Hence, using more power in hovering status will have adverse impacts on the performance of energy efficiency.

Notations	Simulation value	Notations	Simulation value
K	3	N	50
V_{max}	50 m/s	P_i	790.67/2370 W
t_1	[250;150] m	t_2	[50;400] m
t_3	[100;450] m	t_0	[0;0] m
t_F	[500;500]	B	1 MHZ
$\overline{P_s}$	1 W	$\overline{P_r}$	1 W
H	100 m	G_{max}^{Algo1}	10
J_{max}^{Algo2}	10	L_{max}^{Algo3}	8

Table 1. Simulation value settings

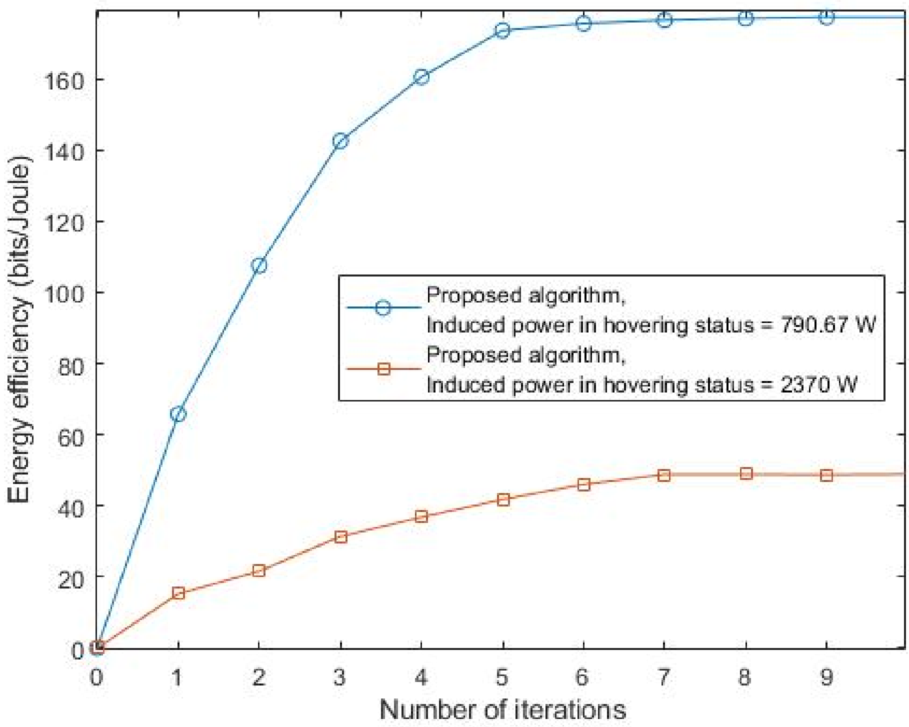

Figure 8. Energy efficiency under proposed algorithm in different induced power in hovering status versus number of iterations.

In figure 9. it shows the trajectory of UAV under proposed algorithm to transmit data to multi-users between $\boldsymbol{q}_0 = [0; 0]$ and $\boldsymbol{q}_F = [500; 500]$. The location of user1, user2 and user3 is $[250; 150]$, $[50; 400]$, $[100; 450]$, respectively. When the UAV gets close to users, the velocity of it will become low and even in hovering status. When it far away from users, the velocity becomes high[15].

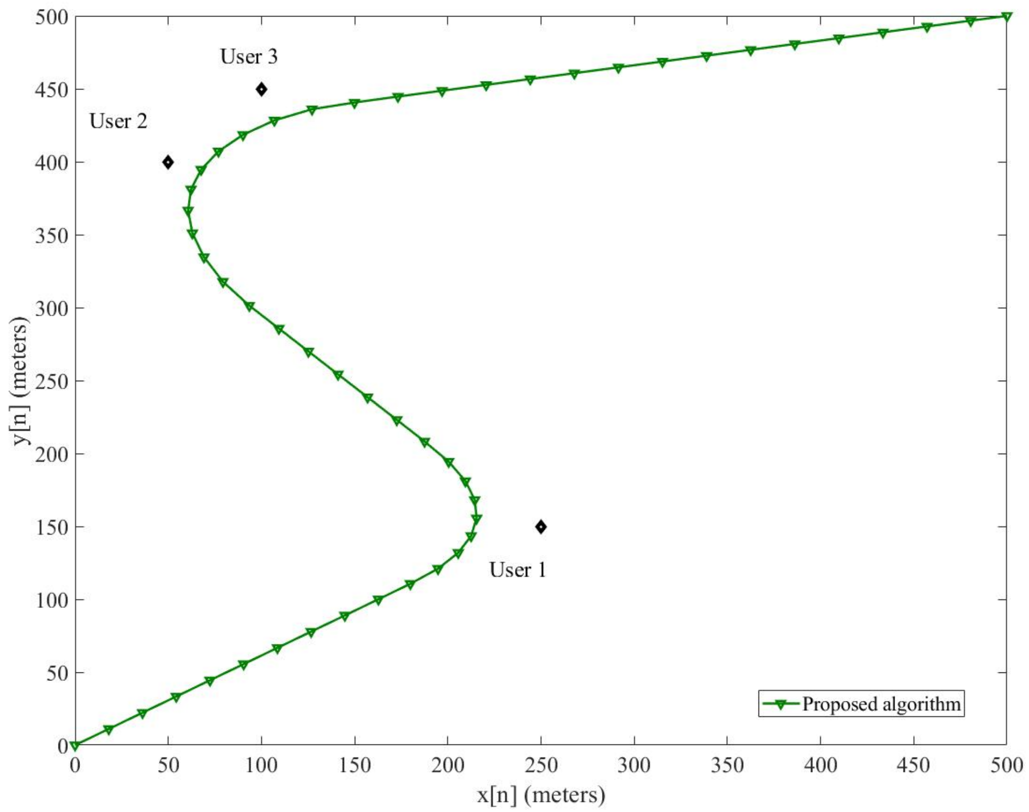

Figure 9. The trajectory of UAV under the proposed algorithm.

Thus, the algorithm1-3 are both convergence and the optimal solution of UAV's trajectory and the maximum of energy efficiency is obtained.

Chapter 6

Conclusion

In this report, we proposed an algorithm to solve a non-convex problem, which is trying to boost the energy efficiency in UAV-enabled wireless communication system. Specifically, we optimized resource allocation strategy and trajectory of UAV. After optimization, the UAV, as a relay, could work energy-efficient to transmit data towards users at different locations. This also can be proved by numerical results, which show the fast convergence of energy efficiency and optimal trajectory of UAV. Thus, the system under this optimal solution can achieve a superior performance[55]-[57].

Appendix

The algorithm1-3 I used in this paper are referenced to algorithms in paper[15], which are as follows:

Algorithm 1 Proposed Algorithm for Solving Sub-problem 1

Initialize the maximum number of iterations $G_{\max}^{\mathrm{Algo1}}$

Set the energy efficiency $q_1^{(0)} = 0$ and the iteration index $g^{\mathrm{Algo1}} = 0$

repeat {Main Loop}

  Solve (18) for a given $q_1^{(g^{\mathrm{Algo1}})}$ and obtain resource allocation $\{\underline{\mathcal{A}}^{(g^{\mathrm{Algo1}})}, \underline{\tilde{\mathcal{P}}}^{(g^{\mathrm{Algo1}})}\}$

  if $R(\underline{\mathcal{A}}^{(g^{\mathrm{Algo1}})}, \underline{\tilde{\mathcal{P}}}^{(g^{\mathrm{Algo1}})}) - q_1^{(g^{\mathrm{Algo1}})} P(\underline{\tilde{\mathcal{P}}}^{(g^{\mathrm{Algo1}})}) < \epsilon$ **then**

    Convergence $=$ **true**

    return $\{\alpha_k^i[n], p_k^i[n]\} = \{\underline{\mathcal{A}}^{(g^{\mathrm{Algo1}})}, \underline{\tilde{\mathcal{P}}}^{(g^{\mathrm{Algo1}})}\}$ and

    $q_1 = \frac{R(\underline{\mathcal{A}}^{(g^{\mathrm{Algo1}})}, \underline{\tilde{\mathcal{P}}}^{(g^{\mathrm{Algo1}})})}{P(\underline{\tilde{\mathcal{P}}}^{(g^{\mathrm{Algo1}})})}$

  else

    Set $g^{\mathrm{Algo1}} = g^{\mathrm{Algo1}} + 1$

    $q_1^{(g^{\mathrm{Algo1}})} = \frac{R(\underline{\mathcal{A}}^{(g^{\mathrm{Algo1}})}, \underline{\tilde{\mathcal{P}}}^{(g^{\mathrm{Algo1}})})}{P(\underline{\tilde{\mathcal{P}}}^{(g^{\mathrm{Algo1}})})}$

    Convergence $=$ **false**

  end if

until Convergence $=$ **true** or $g^{\mathrm{Algo1}} = G_{\max}^{\mathrm{Algo1}}$

Algorithm 2 Proposed Algorithm for Solving Sub-problem 2

Initialize the maximum number of iterations $J_{\max}^{\text{Algo2}}$, $J_{\text{inner},\max}^{\text{Algo2}}$
Set the energy efficiency $q_2^{(0)} = 0$ and the iteration index $j^{\text{Algo2}} = 0$
repeat {Main Loop}
  Set the inner loop iteration index $j_{\text{inner}}^{\text{Algo2}} = 0$
  repeat {Inner Loop}
    Solve the problem in (47) for a given $q_2^{j_{\text{inner}}^{\text{Algo2}}}$ and obtain trajectory and velocity $\{\underline{\mathcal{T}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\mathcal{U}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\mathcal{V}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\Upsilon}^{(j_{\text{inner}}^{\text{Algo2}})}\}$
    if $\bar{R}(\underline{\mathcal{U}}^{(j_{\text{inner}}^{\text{Algo2}})}) - q_2^{(j_{\text{inner}}^{\text{Algo2}})} P^{\text{UB}}(\underline{\mathcal{V}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\Upsilon}^{(j_{\text{inner}}^{\text{Algo2}})}) < \epsilon$ **then**
      Inner Loop Convergence $=$ **true**
      return $\{\underline{\mathcal{T}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\mathcal{U}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\mathcal{V}}^{(j_{\text{inner}}^{\text{Algo2}})}\}$ and $q_2^{(j_{\text{inner}}^{\text{Algo2}})}$
    else
      Set $j_{\text{inner}}^{\text{Algo2}} = j_{\text{inner}}^{\text{Algo2}} + 1$ and
      $q_2^{(j_{\text{inner}}^{\text{Algo2}})} = \frac{\bar{R}(\underline{\mathcal{U}}^{(j_{\text{inner}}^{\text{Algo2}})})}{P^{\text{UB}}(\underline{\mathcal{V}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\Upsilon}^{(j_{\text{inner}}^{\text{Algo2}})})}$
      Inner Loop Convergence $=$ **false**
    end if
  until Inner Loop Convergence $=$ **true** or $j_{\text{inner}}^{\text{Algo2}} = J_{\text{inner},\max}^{\text{Algo2}}$
  if $q_2^{(j^{\text{Algo2}})} - q_2^{(j^{\text{Algo2}}-1)} < \epsilon$ **then**
    Main Loop Convergence $=$ **true**
    return $\{\mathbf{t}[n], \mathbf{v}[n]\} = \{\underline{\mathcal{T}}^{(j^{\text{Algo2}})}, \underline{\mathcal{U}}^{(j^{\text{Algo2}})}, \underline{\mathcal{V}}^{(j^{\text{Algo2}})}\}$ and $q_2 = q_2^{(j^{\text{Algo2}})}$
  else
    Set $j^{\text{Algo2}} = j^{\text{Algo2}} + 1$, $\{\underline{\mathcal{T}}^{(j^{\text{Algo2}})}, \underline{\mathcal{U}}^{(j^{\text{Algo2}})}, \underline{\mathcal{V}}^{(j^{\text{Algo2}})}\} = \{\underline{\mathcal{T}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\mathcal{U}}^{(j_{\text{inner}}^{\text{Algo2}})}, \underline{\mathcal{V}}^{(j_{\text{inner}}^{\text{Algo2}})}\}$ and $q_2^{(j^{\text{Algo2}})} = q_2^{(j_{\text{inner}}^{\text{Algo2}})}$
    Main Loop Convergence $=$ **false**
  end if
until Main Loop Convergence $=$ **true** or $j^{\text{Algo2}} = J_{\max}^{\text{Algo2}}$

Algorithm 3 Overall Algorithm for Solving Problem (10)

Initialize the maximum number of iterations $L_{\max}^{\text{Algo3}}$ and the maximum tolerance $\epsilon \to 0$
Set the iteration index $l^{\text{Algo3}} = 0$ and the initial trajectory $\{\mathbf{t}[n], \mathbf{v}[n]\}$
repeat
  Using **Algorithm 1** obtain the optimal result q_1, $\{\alpha_k^i[n], p_k^i[n]\}$
  Using **Algorithm 2** obtain the sub-optimal result q_2, $\{\mathbf{t}[n], \mathbf{v}[n]\}$
  if $q_2^{(l^{\text{Algo3}})} - q_2^{(l^{\text{Algo3}}-1)} < \epsilon$ **then**
    Convergence $=$ **true**
    return $\alpha_k^{i*}[n] = \alpha_k^i[n], p_k^{i*}[n] = p_k^i[n], \mathbf{t}^*[n] = \mathbf{t}[n], \mathbf{v}^*[n] = \mathbf{v}[n]$, and $q^* = q_2^{(l^{\text{Algo3}})}$
  else
    Set $l^{\text{Algo3}} = l^{\text{Algo3}} + 1$
    Convergence $=$ **false**
  end if
until Convergence $=$ **true** or $l^{\text{Algo3}} = L_{\max}^{\text{Algo3}}$

References

[1] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, and R. J. I. W. C. Schober, "An overview of sustainable green 5G networks," vol. 24, no. 4, pp. 72-80, 2017.

[2] Y. Chen, S. Zhang, S. Xu, and G. Y. J. I. C. M. Li, "Fundamental trade-offs on green wireless networks," vol. 49, no. 6, pp. 30-37, 2011.

[3] S. Bi, C. K. Ho, and R. J. I. C. M. Zhang, "Wireless powered communication: Opportunities and challenges," vol. 53, no. 4, pp. 117-125, 2015.

[4] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. J. I. C. M. Schober, "Simultaneous wireless information and power transfer in modern communication systems," vol. 52, no. 11, pp. 104-110, 2014.

[5] Y. Zeng, J. Lyu, and R. J. I. W. C. Zhang, "Cellular-connected UAV: Potential, challenges, and promising technologies," vol. 26, no. 1, pp. 120-127, 2018.

[6] Y. Zeng, R. Zhang, and T. J. J. I. C. M. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," vol. 54, no. 5, pp. 36-42, 2016.

[7] J. Zhang, Y. Zeng, and R. Zhang, "Spectrum and energy efficiency maximization in UAV-enabled mobile relaying," in *2017 IEEE International Conference on Communications (ICC)*, 2017, pp. 1-6: IEEE.

[8] X. Sun, D. W. K. Ng, Z. Ding, Y. Xu, and Z. J. I. W. C. Zhong, "Physical layer security in UAV systems: Challenges and opportunities," vol. 26, no. 5, pp. 40-47, 2019.

[9] J. Cruz, G. Chen, D. Li, and X. Wang, "Particle swarm optimization for resource allocation in UAV cooperative control," in *AIAA Guidance, Navigation, and Control Conference and Exhibit*,

2004, p. 5250.

[10] Z. Ding *et al.*, "Application of smart antenna technologies in simultaneous wireless information and power transfer," vol. 53, no. 4, pp. 86-93, 2015.

[11] I. Krikidis, S. Sasaki, S. Timotheou, and Z. J. I. T. o. C. Ding, "A low complexity antenna switching for joint wireless information and energy transfer in MIMO relay channels," vol. 62, no. 5, pp. 1577-1587, 2014.

[12] V. W. Wong, *Key technologies for 5G wireless systems*. Cambridge university press, 2017.

[13] Y.-H. Nam *et al.*, "Full-dimension MIMO (FD-MIMO) for next generation cellular technology," vol. 51, no. 6, pp. 172-179, 2013.

[14] S. Najmeddint, A. Bayat, S. Aïssa, and S. Tahar, "Energy-Efficient Resource Allocation for DAV-Enabled Wireless Powered Communications," in *2019 IEEE Wireless Communications and Networking Conference (WCNC)*, 2019, pp. 1-6: IEEE.

[15] Y. Cai, Z. Wei, R. Li, D. W. K. Ng, and J. Yuan, "Energy-efficient resource allocation for secure UAV communication systems," in *2019 IEEE Wireless Communications and Networking Conference (WCNC)*, 2019, pp. 1-8: IEEE.

[16] J. Zhang, E. Björnson, M. Matthaiou, D. W. K. Ng, H. Yang and D. J. Love, "Prospective Multiple Antenna Technologies for Beyond 5G," in *IEEE Journal on Selected Areas in Communications*.

[17] J. Zhang, E. Björnson, M. Matthaiou, D. W. K. Ng, H. Yang and D. J. Love, "Guest Editorial Special Issue on Multiple Antenna Technologies for Beyond 5G-Part II," in *IEEE Journal on Selected Areas in Communications*.

[18] D. W. K. Ng, M. Breiling, C. Rohde, F. Burkhardt and R. Schober, "Energy-Efficient 5G

Outdoor-to-Indoor Communication: SUDAS Over Licensed and Unlicensed Spectrum," in *IEEE Transactions on Wireless Communications*, vol. 15, no. 5, pp. 3170-3186, May 2016.

[19] W. Yuan, S. Li, L. Xiang and D. W. K. Ng, "Distributed Estimation Framework for Beyond 5G Intelligent Vehicular Networks," in *IEEE Open Journal of Vehicular Technology*, vol. 1, pp. 190-214, 2020.

[20] X. Chen, Z. Zhang, C. Zhong, D. W. K. Ng and R. Jia, "Exploiting Inter-User Interference for Secure Massive Non-Orthogonal Multiple Access," in *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 4, pp. 788-801, April 2018.

[21] M. Sinaie, D. Wing Kwan Ng and E. A. Jorswieck, "Resource Allocation in NOMA Virtualized Wireless Networks Under Statistical Delay Constraints," in *IEEE Wireless Communications Letters*, vol. 7, no. 6, pp. 954-957, Dec. 2018.

[22] L. Xiang, D. W. K. Ng, T. Islam, R. Schober, V. W. S. Wong and J. Wang, "Cross-Layer Optimization of Fast Video Delivery in Cache- and Buffer-Enabled Relaying Networks," in *IEEE Transactions on Vehicular Technology*, vol. 66, no. 12, pp. 11366-11382, Dec. 2017.

[23] X. Liang, Y. Wu, D. W. K. Ng, Y. Zuo, S. Jin and H. Zhu, "Outage Performance for Cooperative NOMA Transmission with an AF Relay," in *IEEE Communications Letters*, vol. 21, no. 11, pp. 2428-2431, Nov. 2017.

[24] Y. Sun, D. Wing Kwan Ng, D. Xu, L. Dai and R. Schober, "Resource Allocation for Solar Powered UAV Communication Systems," *2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Kalamata, 2018, pp. 1-5.

[25] Z. Wei, S. Sun, X. Zhu, D. In Kim and D. W. K. Ng, "Resource Allocation for Wireless-Powered Full-Duplex Relaying Systems With Nonlinear Energy Harvesting Efficiency," in *IEEE*

Transactions on Vehicular Technology, vol. 68, no. 12, pp. 12079-12093, Dec. 2019.

[26] Derrick Wing Kwan Ng; Trung Q. Duong; Caijun Zhong; Robert Schober, "Wireless Power Transfer in Millimeter Wave," in *Wireless Information and Power Transfer: Theory and Practice* , , Wiley, 2019, pp.139-156

[27] W. Yuan, C. Liu, F. Liu, S. Li and D. W. K. Ng, "Learning-based Predictive Beamforming for UAV Communications with Jittering," in *IEEE Wireless Communications Letters*.

[28] D. Xu, Y. Sun, D. W. K. Ng and R. Schober, "Multiuser MISO UAV Communications in Uncertain Environments With No-Fly Zones: Robust Trajectory and Resource Allocation Design," in *IEEE Transactions on Communications*, vol. 68, no. 5, pp. 3153-3172, May 2020.

[29] D. Xu, Y. Sun, D. W. K. Ng and R. Schober, "Robust Resource Allocation for UAV Systems with UAV Jittering and User Location Uncertainty," *2018 IEEE Globecom Workshops (GC Wkshps)*, Abu Dhabi, United Arab Emirates, 2018, pp. 1-6.

[30] M. Cui, G. Zhang, Q. Wu and D. W. K. Ng, "Robust Trajectory and Transmit Power Design for Secure UAV Communications," in *IEEE Transactions on Vehicular Technology*, vol. 67, no. 9, pp. 9042-9046, Sept. 2018.

[31] Y. Sun, D. Xu, D. W. K. Ng, L. Dai and R. Schober, "Optimal 3D-Trajectory Design and Resource Allocation for Solar-Powered UAV Communication Systems," in *IEEE Transactions on Communications*, vol. 67, no. 6, pp. 4281-4298, June 2019.

[32] Y. Cai, Z. Wei, R. Li, D. W. K. Ng and J. Yuan, "Joint Trajectory and Resource Allocation Design for Energy-Efficient Secure UAV Communication Systems," in *IEEE Transactions on Communications*, vol. 68, no. 7, pp. 4536-4553, July 2020.

[33] R. Li, Z. Wei, L. Yang, D. W. K. Ng, J. Yuan and J. An, "Resource Allocation for Secure

Multi-UAV Communication Systems With Multi-Eavesdropper," in *IEEE Transactions on Communications*, vol. 68, no. 7, pp. 4490-4506, July 2020.

[34] Y. Zhou, F. Zhou, H. Zhou, D. W. K. Ng and R. Q. Hu, "Robust Trajectory and Transmit Power Optimization for Secure UAV-Enabled Cognitive Radio Networks," in *IEEE Transactions on Communications*, vol. 68, no. 7, pp. 4022-4034, July 2020.

[35] R. Li *et al.*, "Joint Trajectory and Resource Allocation Design for UAV Communication Systems," *2018 IEEE Globecom Workshops (GC Wkshps)*, Abu Dhabi, United Arab Emirates, 2018, pp. 1-6.

[36] Y. Zhou, H. Zhou, F. Zhou, D. W. K. Ng and R. Q. Hu, "Robust Chance-Constrained Trajectory and Transmit Power Optimization for UAV-Enabled CR Networks," *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, Dublin, Ireland, 2020, pp. 1-7.

[37] X. Sun, C. Shen, D. W. K. Ng and Z. Zhong, "Robust Trajectory and Resource Allocation Design for Secure UAV-Aided Communications," *2019 IEEE International Conference on Communications Workshops (ICC Workshops)*, Shanghai, China, 2019, pp. 1-6.

[38] Y. Cai, Z. Wei, S. Hu, D. W. K. Ng and J. Yuan, "Resource Allocation for Power-Efficient IRS-Assisted UAV Communications," *2020 IEEE International Conference on Communications Workshops (ICC Workshops)*, Dublin, Ireland, 2020, pp. 1-7.

[39] M. Robat Mili, A. Khalili, n. mokari, S. Wittevrongel, D. W. K. Ng and H. Steendam, "Tradeoff Between Ergodic Energy Efficiency and Spectral Efficiency in D2D Communications Under Rician Fading Channel," in *IEEE Transactions on Vehicular Technology*.

[40] J. Liu, K. Xiong, D. W. K. Ng, P. Fan, Z. Zhong and K. B. Letaief, "Max-Min Energy Balance in Wireless-Powered Hierarchical Fog-Cloud Computing Networks," in *IEEE Transactions on*

Wireless Communications.

[41] I. Ahmed, A. Ikhlef, D. W. K. Ng and R. Schober, "Power Allocation for an Energy Harvesting Transmitter with Hybrid Energy Sources," in *IEEE Transactions on Wireless Communications*, vol. 12, no. 12, pp. 6255-6267, December 2013.

[42] T. A. Le, Q. Vien, H. X. Nguyen, D. W. K. Ng and R. Schober, "Robust Chance-Constrained Optimization for Power-Efficient and Secure SWIPT Systems," in *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 3, pp. 333-346, Sept. 2017.

[43] Derrick Wing Kwan Ng; Trung Q. Duong; Caijun Zhong; Robert Schober, "The Era of Wireless Information and Power Transfer," in *Wireless Information and Power Transfer: Theory and Practice* , , Wiley, 2019, pp.1-16

[44] D. W. K. Ng, E. S. Lo and R. Schober, "Energy-efficient resource allocation in SDMA systems with large numbers of base station antennas," *2012 IEEE International Conference on Communications (ICC)*, Ottawa, ON, 2012, pp. 4027-4032.

[45] N. Zlatanov, D. W. K. Ng and R. Schober, "Capacity of the Two-Hop Relay Channel With Wireless Energy Transfer From Relay to Source and Energy Transmission Cost," in *IEEE Transactions on Wireless Communications*, vol. 16, no. 1, pp. 647-662, Jan. 2017.

[46] A. Khalili and D. W. K. Ng, "Energy and Spectral Efficiency Tradeoff in OFDMA Networks via Antenna Selection Strategy," *2020 IEEE Wireless Communications and Networking Conference (WCNC)*, Seoul, Korea (South), 2020, pp. 1-6.

[47] E. Boshkovska, D. W. K. Ng and R. Schober, "Power-Efficient and Secure WPCNs with Residual Hardware Impairments and a Non-Linear EH Model," *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, Singapore, 2017, pp. 1-7.

[48] S. Leng, D. W. K. Ng, N. Zlatanov and R. Schober, "Multi-objective beamforming for energy-efficient SWIPT systems," *2016 International Conference on Computing, Networking and Communications (ICNC)*, Kauai, HI, 2016, pp. 1-7.

[49] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," in *IEEE Communications Magazine*, vol. 52, no. 11, pp. 104-110, Nov. 2014.

[50] D. W. K. Ng and R. Schober, "Max-min fair wireless energy transfer for secure multiuser communication systems," *2014 IEEE Information Theory Workshop (ITW 2014)*, Hobart, TAS, 2014, pp. 326-330.

[51] Q. Wu and R. Zhang, "Common Throughput Maximization in UAV-Enabled OFDMA Systems With Delay Consideration," in *IEEE Transactions on Communications*, vol. 66, no. 12, pp. 6614-6627, Dec. 2018.

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

[53] C. Cheng, P. Hsiao, H. T. Kung and D. Vlah, "Maximizing Throughput of UAV-Relaying Networks with the Load-Carry-and-Deliver Paradigm," *2007 IEEE Wireless Communications and Networking Conference*, Kowloon, 2007, pp. 4417-4424.

[54] Y. Zeng, R. Zhang and T. J. Lim, "Throughput Maximization for UAV-Enabled Mobile Relaying Systems," in *IEEE Transactions on Communications*, vol. 64, no. 12, pp. 4983-4996, Dec. 2016.

[55] L. Xie, J. Xu and Y. Zeng, "Common Throughput Maximization for UAV-Enabled Interference Channel With Wireless Powered Communications," in *IEEE Transactions on Communications*,

vol. 68, no. 5, pp. 3197-3212, May 2020.

[56] Y. Yang, M. Pesavento, S. Chatzinotas and B. Ottersten, "Successive Convex Approximation Algorithms for Sparse Signal Estimation With Nonconvex Regularizations," in *IEEE Journal of Selected Topics in Signal Processing*, vol. 12, no. 6, pp. 1286-1302, Dec. 2018.

[57] Y. Zeng, J. Xu and R. Zhang, "Energy Minimization for Wireless Communication With Rotary-Wing UAV," in *IEEE Transactions on Wireless Communications*, vol. 18, no. 4, pp. 2329-2345, April 2019.