RESOURCE-EFFICIENT COVERAGE PATH PLANNING FOR UNMANNED AERIAL VEHICLE BASED AERIAL GATEWAY IN LoRaWAN

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ABSTRACT

Unmanned aerial vehicles (UAV) have enormous potential in enabling new applications in various areas, ranging from communication, military, security, to traffic-monitoring applications. In the context of the highly distributed and vast nature of Internet of Things (IoT) network, UAV could work as Aerial Gateway (AG) for communications among low-powered and distributed ground IoT devices (ID). This research focused on the path planning and deployment system that can improve decision making thus ensuring resource-efficient UAV mission assignment in utilizing energy during the process of serving ground ID. Due to finite resource, multiple issues need to be considered in designing such system, including AG flight time, coverage radius and the achievable data rate of the ground-to-air system, thus an Energy Efficient Coverage Path Planning (EECPP) algorithm has been proposed. EECPP consist of two algorithms which is Stop Point Prediction Algorithm using K-Means, which finding the stop point for the AG after grouping the IDs into clusters, and Path Planning Algorithm using Particle Swarm Optimization which connect all of the stop point in shortest route. The result shows that EECPP outperform Close Enough Traveling Salesman Problem (CETSP) by 19.99% in terms of total flight distance. In comparison to Energy-Efficient Path Planning (E2PP), EECPP lowered energy consumption by average of 56.15%. With efficient path planning along with mobile nature of AG, enabled it to hover at each stop points thus making it ideal to be used in remote areas where fixed base station is not accessible, crowded areas with high demand, and in emergency situations.

ABSTRAK

Kenderaan udara tanpa pemandu (UAV) memiliki potensi besar dalam memungkinkan aplikasi baru dalam pelbagai bidang, bermula dari bidang komunikasi, ketenteraan, keamanan, hingga ke aplikasi pemantauan lalu lintas. Dalam konteks rangkaian Internet of Things (IoT) yang sangat meluas, UAV dapat digunakan sebagai Aerial Gateway (AG) untuk komunikasi di antara peranti IoT (ID). Penyelidikan ini memfokuskan kepada perancangan laluan yang dapat membantu dalam memastikan penggunaan sumber yang cekap ketika AG mengakses data dari ID. Oleh kerana keadaan sumber yang terbatas, beberapa perkara perlu dipertimbangkan dalam merancang sistem penggunaan tenaga termasuk waktu penerbangan, radius liputan dan juga kadar penghantaran data yang dapat dicapai oleh ID. Justeru, algoritma Energy Efficient Coverage Path Planning (EECPP) telah dicadangkan. EECPP terdiri daripada dua algoritma iaitu *Stop Point Prediction Algorithm Using K-Means*, iaitu menentukan titik berhenti bagi AG selepas mengelompokkan ID ke dalam kluster, dan *Path Planning Algorithm Using Particle Swarm Optimization* digunakan untuk menghubungkan semua titik berhenti tersebut dalam satu laluan terpendek. Keputusan menunjukkan bahawa EECPP mampu mengatasi *Close Enough Traveling Salesman Problem (CETSP)* sebanyak 19.99 peratus dari segi jumlah jarak penerbangan. Untuk perbandingan dengan *Energy-Efficient Path Planning* (E2PP), EECPP mengurangkan penggunaan tenaga secara purata sebanyak 56.15 peratus. Dengan perancangan laluan yang cekap, serta sifat mudah alih AG, menjadikannya ideal untuk digunakan di kawasan terpencil, kawasan yang sesak dengan permintaan tinggi, serta ketika situasi kecemasan. EECPP dapat ditingkatkan pada masa akan datang untuk mengurangkan kerumitan proses komputasi. Skop kajian juga boleh diperluas untuk merangkumi lebih banyak bilangan AG supaya lebih banyak ID dapat diakses pada masa akan datang.

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LIST OF SYMBOLS AND ABBREVIATIONS

λ	-	Wavelength
ACO	-	Ant Colony Optimization
AG	-	Aerial Gateway
AWGN	-	Additive White Gaussian Noise
c_1	-	Acceleration constant 1
c_2	-	Acceleration constant 2
CAAM	-	Civil Aviation Authority Malaysia
CPP	-	Coverage Path Planning
d	-	Distance in meter
D_{EECPP}	-	Distance obtained by EECPP Algorithm
D_{CETSP}	-	Distance obtained by CETSP Algorithm
EECPP	-	Energy Efficient Coverage Path Planning
FSPL	-	Free Space Path Loss
GA	-	Genetic Algorithm
h_{AG}	-	Height of AG
HAP	-	High Altitude Platform
ID	-	Internet of Things Devices
IoT	-	Internet of Things
LAP	-	Low Altitude Platform
LoS	-	Line of Sight
LPWAN	-	Low-Power Wide Area Network
$pbest_{id}^{y}$	-	Previous best position
PRM	-	Probabilistic Roadmap Method
PSO	-	Particle Swarm Optimization
r_1^y	-	Random number in range of [0,1]
r_2^y	-	Rnadom number in range of [0,1]
RRT	-	Rapidly-exploring Random Tree

SA	-	Simulated Annealing
SNR	-	Signal-to-Noise Ratio
TSP	-	Traveling Salesman Problem
UAVs	-	Unmanned Air Vehicles
V_{id}^{y}	-	Velocity of particle
VTOL	-	Vertical Take-off and Landing
W	-	Weight of particles
X_{id}^{y}	-	Position of particles
X_{AG}	-	Latitude of AG
Y_{AG}	-	Longitude of AG

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Unmanned aerial vehicles (UAVs) have become increasingly popular in public applications, such as aerial surveillance, traffic management, photography, package delivery and communication platforms, in recent years [1]. Due to high agility and usability, UAV communications and networking have received a lot of attention recently. Both businesses and academics are interested in UAV-assisted wireless network architectures, particularly in internet of things (IoT) network. There are four representative scenarios using UAVs in communication system, including UAVs as aerial gateways (AG), UAVs as mobile relays, UAVs as motorial energy sources and UAVs as aerial caches [2].

UAVs are expected to be widely used to replace fixed base station as they come up with low-cost production of accurate, low-power and high-quality data that can be obtained and generated in a shorter time compared to fixed terrestrial base station. AG provides mobile connectivity from the sky, allowing the rapid expansion of outdoor wireless communication. By using programmed path planning, AG may travel dynamically toward IoT devices, collect data, and transmit it to other devices. Due to its mobile characteristic which enables the UAV to alter its altitude easily, it is capable of changing the area of coverage according on demand while satisfying the Line-of-Sight (LoS) [3]. UAVs can also be deployed rapidly to serve IoT devices without being obstructed by geographical constraints due to their high altitude, thus mitigating signal blockage and shadowing, which cannot be accomplished by fixed terrestrial base station [4]. UAV mobile base station is currently able to provide many opportunities for mitigating communication issues with a cost-effective approach. This was studied in [5], which showed a reduction of 56% in the total transmit power of IoT devices for reliable uplink communications compared to static base station. The development of a complete cellular infrastructure can be very expensive in certain regions or countries. In solving this issue, UAV deployment becomes highly beneficial as it eliminates the need for expensive towers and infrastructure deployment [6].

In general, this contributes in improving network coverage and reducing operating cost and overall process time. However, wastage of resources such as energy, power and time consumption still occurs in path planning and data transmission due to inefficient management system. To deal with this problem, this research was conducted to ensure improvement in decision-making, including UAV path planning and IoT data collection. For energy-efficiency improvement, the flight time of UAV needs to be minimized [7], [8] with sophisticated path planning and management system. Path planning is a path-finding operation that covers all points in a target area. The best path and deployment with efficient resource management can be determined using this system. The whole system is expected able to help users utilize resources more efficiently in ensuring competitiveness and quality of service of IoT communication system.

1.2 Problem Statement

The application of UAV as AG, replacing existing ground base station can enhance network coverage especially in IoT communication system. Limited LoS of ground base station due to its fixed location, has led to the issue of signal blockage and shadowing. By considering the height, AG can successfully establish LoS communication linkages with ground users [9]. The development of a complete cellular infrastructure can be very expensive in certain regions or countries. Therefore, AG deployment becomes extremely advantageous in solving this problem as it eliminates the requirement for costly towers and infrastructure deployment [6]. Unexpected demand in certain coverage areas lead to insufficient network resources which then deteriorates the service quality in that particular area. With the implementation of AG in the system, the service demand not only depends on the ground base station, but can be distributed to the aerial base station, hence improving quality of service (QoS). AG can be deployed to complement existing cellular systems by providing additional capacity to hotspot locations as well as to provide network coverage in emergency and public safety situations [6].

In terms of IoT communication system, IoT devices (ID) encounter energy constraint due to their small transmit power and battery life, making them unable to transmit data remotely to ground base stations. This entails the utilization of AG technology to maximize link quality and data transmission by programming AG to move closer to IoT devices and establish reliable connections with low transmit power [5] from IoT devices.

If the distance between the take-off point and the target point is not taken into account in the UAV as an AG, it may result in loss of energy as traveling to the points will be time consuming and long distance for the vehicle [10]. With a proper resource-efficient path planning method, the flight time of the AG can be minimized thus enabling the AG and IoT device to maximize their performance.

1.3 Objectives

The main objectives of the study are:

(i) To investigate the deployment and resource efficient clustering of the ground ID in LoRaWAN technology.

(ii) To propose efficient resources management method for path planning between AG to ID.

(iii) To assess the efficiency of flight time, distance traveled, and energy consumption for UAV as aerial gateway AG to serve ground ID.

1.4 Scope of the Research

The research focuses on the investigation and proposal of an efficient fleet management in terms of path planning and deployment system for UAVs as aerial gateway (AG) to serve ground IoT devices known as the Energy Efficient Coverage Path Planning (EECPP) algorithm. The research revolves on simulation using software to prove the efficiency of proposed solution compared to other solutions. It focuses on

Low Altitude Platform (LAP) UAV, a quad-rotor UAV type with flying altitude set to 100 meters [11], [12]. The ID specifications in this research are based on the long range (LoRa) 32 specifications, while the gateway is based on the HT-M02 Edge LoRa Gateway. Both ID and gateway are based on long range wide area network (LoRaWAN) technology. The AG is to be used for off-grid or remote IoT devices that are difficult to reach by conventional ground base station in suburban and rural areas and is piloted. The study considers fixed take-off and landing point, fixed location of ID, and uplink data transmission with fixed data packet size. The data rate considered is in range of 300bps to 50kbps [13] with frequency of 919 Mhz [14], [15]. The development of mathematical system model for path planning and deployment is performed in Python language and simulated in Visual Studio Code to obtain the graphical result. Simulation needs to achieve optimal path planning and deployment that can minimize the energy usage of ID and AG. It is the integration of K-means algorithm to group all of the IDs into multiple clusters with maximum radius of 283 meters for each cluster, and Particle Swarm Optimization to solve Traveling Salesman Problem to find shortest path. Validation of the research outcome is conducted based on comparison with other simulation models.

Table 1.1 : Parameter Assumption

Parameter	Value
AG Height	100 Meter [11], [12]
Data Rate	300bps to 50kbps [13]
Frequency	919 Mhz [14], [15]

1.5 Significance of Research

The significance of the study is to produce a resource-efficient coverage path planning of UAV to be used as AG to serve ground IDs. Remote IDs limits the communication of data from the IDs to existing base station. Thus, by using UAV as AG, the data can be successfully collected as the AG can fly towards the locations of the IDs without having the need of building fix network infrastructure in that remote area.

With the numerous numbers of IDs on the map, in order for the AG to cover all of those IDs, it requires clustering or grouping of the IDs instead of visiting all of the IDs individually for better resource management. In previous studies, they require number of clusters to be set by the user by predicting the exact value manually. In this proposed Energy Efficient Coverage Path Planning (EECPP), the number of clusters can be determined automatically once the algorithm satisfies the maximum radius of the cluster which based on the achievable data rate of the communication between ground ID to the AG.

The clustered IDs are then will be visited by the AG using the shortest path generated by the algorithm, which can reduce the travel time and total distance, hence reducing the energy consumption of AG. This method also reduces the total energy needed for the IDs to transmit data to the AG as the distance is near. Hence, using EECPP, it is now possible to obtain remote data efficiently.

1.6 Thesis Outline

The layout of the thesis is outlined in this section. The thesis is generally organized into five chapters. Chapter 1 describes the background of the study, problem statements, objectives, scope, significance of the study, and the overall flow of the thesis structure.

Chapter 2 generally aims to identify methods or approaches for energy efficient path planning. Initially, UAV classification is discussed to better understand which type of UAV is most suitable for use in communication system. This chapter also discusses the basic architecture of IoT devices, Low Power Wide Area Network technologies and configuration modes of IoT gateway. Clustering methods for the IoT devices are also discussed in this chapter. The Traveling Salesman Problem along with a few solution algorithms are also presented in chapter 2. The link budget analysis is discussed thoroughly and lastly energy performance evaluation method from related study has presented.

The steps for formulating the energy efficient path planning problem for AG is explained in chapter 3. The research flow is first presented, which is organized into five phases. System specification and consideration including system model and algorithm are also discussed. This chapter also explains the problem formulation of the research, the development of selected environment simulation and also and the method for validating the proposed algorithm.

Chapter 4 presents the results and discussion for the proposed Energy Efficient Coverage Path Planning (EECPP) algorithm in terms of distance and energy consumed. This chapter also highlights the validation of the EECPP algorithm by comparing it to other algorithms and analysation using the regression method.

Lastly, in Chapter 5, the research's outcomes are summarized and possible recommendations for future studies are proposed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter generally aims to identify methods or approaches for energy efficient path planning. Initially, UAV classification is discussed to better understand which type of UAV is most suitable for use in communication system. The UAVs compared based on their wing architecture, which is fixed wings and rotary wings. This chapter also discusses the basic architecture of IoT devices, Low Power Wide Area Network technologies and configuration modes of IoT gateway. The IoT devices are compared between Sigfox, LoRa and BN-IoT in various crucial IoT parameters such as the operating range, coverage, cost efficiency, battery life and others. Clustering methods for the IoT devices are also discussed in this chapter which includes Partition-Based Technique, Hierarchical Technique, Density-Based Technique. The Traveling Salesman Problem along with a few solutions for path planning algorithms are also presented which divided into three categories; Graph search, Sampling-based, and Biological-based. The link budget analysis is discussed thoroughly in this chapter. Lastly, energy performance evaluation method from related study has presented.

2.2 UAV Classification

Unmanned aerial vehicles (UAVs) is a small aircraft, balloon or drone that can be controlled or pre-programmed remotely. The UAVs can be applied in military, surveillance, search and rescue, and telecommunications. It can be classified based on altitude and type [6]. For altitude, UAVs can be classified into High Altitude Platform (HAP) and Low Altitude Platform (LAP), and the UAV-based types are fixed wings, and rotary wings.

The HAP can fly more than 17 km in the air [16], [17]. It has the longest flight time among all types of UAVs and requires the highest operating cost. In contrast, the LAP can fly from tens of meters up to a few kilometers above the ground [16]. The advantages of this LAP are that it is fast to deploy and having good maneuverability which makes it suitable for temporary event and scenarios.

For fixed wings UAVs, as shown in Figure 2.1 (a) it must move to stay aloft which means it cannot stay stationary at one place. Fixed-wing planes have benefits in speed and altitude, making them ideal for wide area surveillance and carrying more payload. However, due to high flying speeds, the fixed-wing planes require high-speed sensors for surveys. Furthermore, the fixed-wing plane is difficult to hold in position, take-off, or landing in small locations; therefore, it cannot be utilized as a remote flying camera controller [18].

Unlike fixed wings, rotary wing is type of UAVs that can remain stationary in the air [19]. The rotary wing has the ability to hover and decouple between orientation and position motions. This type of UAV can be classified into single-rotor and multi-rotor [20]. The single-rotor UAV is also commonly known as helicopter as shown in Figure 2.1 (b). Having two rotors, the main one for navigation and the tail one for controlling the heading. Depending on the number of rotor blades, this class of UAV can be separated into subclasses, where quadrotor and hexa-rotor UAVs are the most common. They can usually take-off and land vertically, and do not require airflow across the blades to advance as the blades themselves produce essential airflow [21]. On the other hand, quadrotors are made up of four rotors mounted on a cross-shaped frame that also houses the main board, sensors and other supporting modules as shown in Figure 2.1 (c). Controlling the speeds of the four motors allows the adjustments of attitude and elevation. Quadrotors are affordable and maneuverable, but their limited payload capacity restricts the weight of the onboard sensors and flight time. As a result, they are ideally suited for small-scale survey missions. Quadrotors are extensively used in surveillance missions nowadays due to their excellent mobility combined with the readily available autopilot program.

(a)

(b)

(c)

Figure 2.1 : (a) Fixed wing UAV. (b) Single Rotor UAV. (c) Quadrotor UAV

Table 2.1 below shows the comparison of advantages and disadvantages of three types of UAVs and its typical uses in real life application [22].

Table 2.1: Types of UAVs Comparison

UAV Type	Advantages	Disadvantages	Typical Uses
Multi-rotor	1. Accessibility 2. Ease of use 3. Vertical take-off and landing (VTOL) and hover flight 4. Can operate in a confined area 5. Inexpensive 6. Readily available autopilot program	1. Short flight time 2. Small payload capacity 3. Low speed	1. Aerial photography 2. Video aerial inspection 3. communication
Fixed-wing	1. Long endurance-can fly for several hours. 2. Carry large payload 3. Fast flight speed	1. Launch and landing needs a lot of space 2. No VTOL and hover flight 3. Harder to fly, more training is needed 4. Expensive	1. Aerial mapping, pipeline 2. Power line inspection
Single-rotor	1. VTOL and hover flight 2. Long endurance (with gas power) 3. Heavier payload capability	1. Harder to fly, more training is needed 2. Expensive	1. Aerial Light Imaging, Detection, 2. And Ranging laser scanner

2.3 Internet of Things Devices.

In this modern age, electrical and digital devices of different sizes and capabilities connected to the internet are represented by the term Internet of Things (IoT) or Internet of Objects. Various objects linked to the internet through many types of short-range wireless technologies such as ZigBee, RFID, sensor networks and location-based technologies, allowing IoT technology to evolve. The IoT enables things to be sensed and controlled remotely through existing Network infrastructure, thus allowing for more direct integration of the physical world into computer-based systems and improved efficiency and accuracy [23]. The range of IoT devices connection is not only limited to machine-to-machine (M2M) communication but employs a broad array of networking protocols, applications and domains [24]. The IoT architecture consists of four layers with distinctive functionalities which provide interoperability among the devices in multiple ways as follows:

(i) Sensing layer is integrated with all available objects (things) to sense their status.

(ii) Network layer is the infrastructure to support the wireless or wired connections among things.

(iii) Service layer is to create and manage services required by users or applications.

(iv) Interface's layer consists of the interaction methods with users or applications.

2.4 Low-Power Wide Area Network (LPWAN)

IoT systems have specific requirements such as long range, low data speed, low power consumption and cost efficiency. Commonly implemented short-range communication systems, such as ZigBee and Bluetooth, are not suitable for long-range communication scenarios. Therefore, cellular communications-based solutions, such as 2G, 3G, or 4G, can provide greater coverage, but excessive device energy is consumed, which makes them not a practical solution. To meet the requirements of IoT application, this has driven the development of new wireless communication infrastructure that is a low-power wide area network (LPWAN). Currently, Sigfox, LoRa and NarrowBand-Internet of Things (NB-IoT) are the three leading LPWAN technologies that compete for large-scale IoT deployment. A comparative study of LPWAN technologies has been conducted in [13] and summarized in Table 2.2.

Table 2.2: Comparison of LPWAN Technologies: Sigfox, LoRa, and NB-IoT.

	SigFox	LoRa	NB-IoT
Frequency	Unlicensed ISM bands (868 MHz 915 MHz,433 MHz)	Unlicensed ISM bands (868 MHz, 915 MHz ,433 MHz)	Licensed LTE frequency
Bandwidth	100 Hz	250 kHz and 125 kHz	200 kHz
Maximum data rate	100 bps	50 kbps	200 kbps
Range	10 km (urban), 40 km (rural)	5 km (urban), 20 km (rural)	1 km (urban), 10 km (rural)

From Figure 2.2 below, it shows that Sigfox and LoRa are low-cost devices with very long-range, large coverage, low communication rates, and very long battery life.

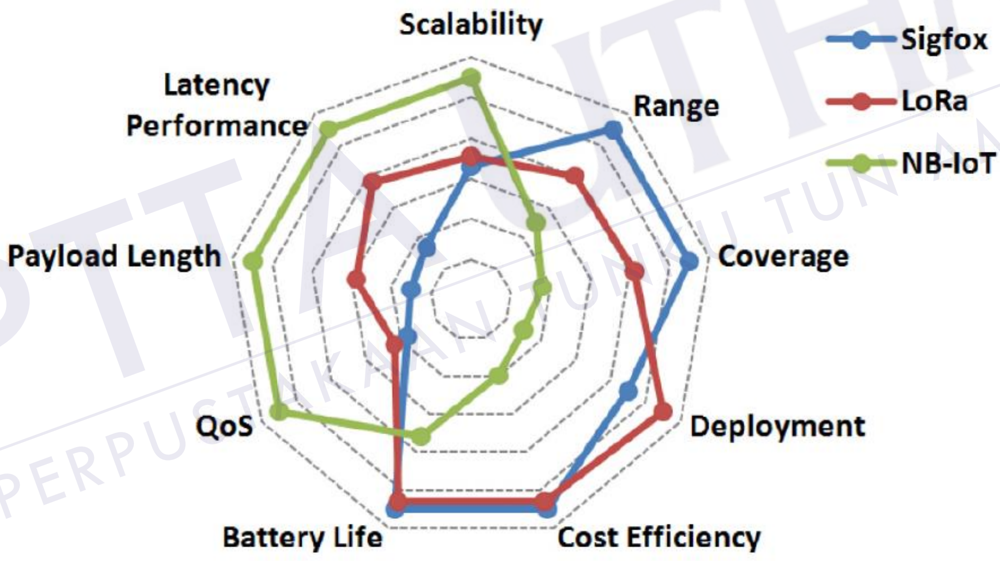

Figure 2.2 : Respective Advantages of Sigfox, LoRa, and NB-IoT in terms of IoT Factors [13]

2.4.1 LoRaWAN

In this study, the specification of the ID was based on the LoRa devices. Due to its long-range and low-power communication specifications, LoRa has become the

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