

**EFFICIENT LOCATION AWARE PROTOCOL
FOR MULTI-UAV NETWORKS**

A Thesis submitted in fulfilment of the requirement for the award of
the degree of

DOCTOR OF PHILOSOPHY

IN

COMPUTER SCIENCE AND ENGINEERING

Submitted By

Sahil Vashist

(Registration No: 901503021)

Under the guidance of

Dr. Sushma Jain



THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

COMPUTER SCIENCE AND ENGINEERING DEPARTMENT
THAPAR INSTITUTE OF ENGINEERING AND TECHNOLOGY,
PATIALA – 147004

July 2020

CERTIFICATE

I, Sahil Vashist, Registration. No. 901503021, hereby declare that the thesis entitled “Efficient Location Aware Protocol for Multi-UAV Networks” submitted to the Computer Science and Engineering Department at Thapar Institute of Engineering and Technology, Patiala, Punjab, India is an authentic record of my own work for the award of the degree of “Doctor of Philosophy” under the supervision of Dr. Sushma Jain. This report has not been submitted to any other institution for award of any other degree.



Sahil Vashist

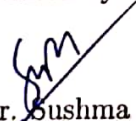
Regn. No. 901503021

Place: Patiala

Date: 10.07.2020

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Verified by:



Dr. Sushma Jain,

Associate Professor,

Computer Science and Engineering Department,

Thapar Institute of Engineering and Technology, Patiala.

ABSTRACT

Unmanned aerial vehicles (UAVs), generally known as drones, have gained considerable attention from the research community and business organizations over the past few years. Indeed, UAVs are being widely deployed to provide on-demand wireless coverage in extreme conditions such as disaster-prone areas and delivery of essential products such as medicines and food during rescue operations. For this purpose, multiple UAVs can form a web of drones, geo-distributed across a large coverage area to perform ad hoc and distributed operations quickly and cost-effectively. The UAVs can also collaborate and coordinate with other cutting edge technologies such as Software Defined Networking (SDN), Internet of Things (IoT) and Blockchain to realization various futuristic on-demand consumer applications and service across the smart city. The popular UAV-based applications can be categorized into domains like UAV-assisted data relaying, UAV-assisted monitoring and data collection and UAV-assisted product delivery.

Despite various advantages of using UAVs, there are associated challenges while utilizing them in on-demand applications. The key challenges are deployment, data offloading and bandwidth, power consumption, energy efficiency, accuracy, latency etc. Thus, it is consequential to formalize an efficient solution, which can provide sustainable connectivity in drone networks with efficient control as well as provisioning of the high Quality of Service (QoS). So, far the drone to drone and drone to ground communication, the work is presented on four major challenges: (i) collision (ii) network congestion (iii) energy consumption (iv) location-aware and Quality of Service (QoS) (v) energy optimization of UAVs at the time of charging, discharging,

and information transmission. To resolve the above mentioned challenges, the task has been accomplished in this research work with three different approaches.

The first approach presents a Medium Access Control (MAC) protocol is proposed that utilizes the firefly optimization algorithm for operating the timing cycle of the network. To support the proposed protocol, three algorithms are designed to accomplish the challenges related to collision, network congestion, and energy consumption. The first algorithm deals with collision avoidance and is designed on the basis of the light intensity property of the firefly optimization. The second algorithm handles the network congestion by controlling the size of the congestion window. The third algorithm computes the nearby optimal route with minimum energy consumption along with the QoS requirements. The performance analysis suggests that the proposed approach provides an efficient congestion-free, collision-free, and energy efficient MAC with signaling quality amended up to 59.04% along with 80.1% conservation of energy.

The second approach focused on QoS provisioning in a multi-UAV ecosystem. The parameters considered for the improvement of QoS provisioning are network throughput, end-to-end delay, and handover latency. Thus, the proposed approach works in two phases. In the first phase, an opportunistic offloading scheme based on SDN adaptive controller is proposed to handle congestion issues in the network. The SDN controller automatically reacts to the suspicious change of the network state and thereby maintains a high level of security. The second phase focused on the network selection to be coordinated by priority manager and network manager. Priority manager helps in deciding the data priority to be offloaded, whereas the network managers provide the information of the available uncongested heterogeneous network so that the SDN controller can perform data offloading. The proposed scheme minimizes the handover latency upto 47% in comparison to other schemes. In addition, the proposed scheme increases the network throughput upto 14% and minimizes the end-to-end delay upto 25%.

Finally, the third approach considered the challenge of energy optimization. In UAVs network, the charging of UAVs batteries while performing their operations without being grounded, referred as energy replenishment is one of the major issues when they are deployed in civilian applications. For the purpose, an opportunistic SDN-enabled wireless energy charging scheme is proposed. The proposed solution of the energy charging system works in two parts, (i) the first part is solar energy harvesting model using solar cells, and (ii) the second part is wireless charging of UAVs through geo-located charging points in a grid-based layout. The solar energy harvesting model helps the UAVs to replenish their batteries during the day time, while the wireless charging model perfectly works in the night time or in extreme conditions. The proposed wireless energy-charging scheme helps to elongate the flight time of UAVs and sustain the flight whenever the battery state of charge is low.

ACKNOWLEDGEMENTS

I deem it my duty to express a word of hearty gratitude to all those helping hands that of doctoral work and writing become part and parcel of this endeavour. First of all, I wish to acknowledge the benevolence of omnipotent almighty who gave me strength, courage and patience to overcome all obstacles.

With profound sense of gratitude and heartiest regard, I express my sincere feelings of indebtedness to my supervisor Dr. Sushma Jain, Associate Professor, Computer Science and Engineering Department, Thapar Institute of Engineering and Technology for her valuable guidance, motivation, encouragement, moral support and invaluable co-operation. The generous and positive attitude with which she solved my queries will always have a shadow on my character. I deeply admire the delightful ambiance for learning provided by her that made this thesis possible. It has been a great pleasure and experience to work under her sanctuary.

I am grateful to the Head of Department, Prof. Maninder Singh and Prof. Inderveer Channa (Associate HOD), who made my study a knowledgeable experience during my stay in the department. I am much beholden to the Director, Dean (RSP) and the Management of Thapar Institute of Engineering and Technology, who provided me all the necessary resources and encouraged to produce results. I am thankful to my doctoral committee members Prof. Rajesh Kumar, Prof. Neeraj Kumar, and Dr. Mukesh Singh for their constructive suggestions and ensuring the correct pace of the progress of my research work. I sincerely thank the faculty and support staff of Computer Science and Engineering Department for their constant

motivation. I would also like to thank Dr. Sanjay Kumar Jain for providing his able guidance to me throughout this journey.

I would like to pay deep gratitude to my parents Mr. Ashwani Vashisht and Mrs. Neelam Vashisht for their unconditional love, affection, and encouragement through all the good and bad times. I would like to shower hearty gratitude, feeling of indebtedness and endless love to my wife Roopkamal Vashisht for her unconditional love, moral support and sacrifices which helped me achieve this target. I would also like to acknowledge my parent-in-laws Mr. Gurjit Singh and Mrs. Bupinder Kaur for the encouragement and support they provided to me during this journey. I want to pay humble gratitude to my brothers Mr. Shubham Vashisht, Mr. Abhishek Vashisht and brotherly friend Dr. Gagangeet Singh for being my strength at every moment.

Words can not truly express my feelings and appreciation to all friends and colleagues in lab, Dr. Anish Jindal, Mr. Rajat Chaudhary, Dr. Sahil Garg, and Mr. Ishan Budhiraja, who shared their knowledge and worked as a team to make my journey during this work memorable and pleasant. I would also like to thank Dr. Rajwinder Singh (Head, Computer Centre, NIPER) and Mr. Dharminder Kumar (IMTech, Chandigarh) for providing me the support during the tough time of this journey. These words of gratitude may have missed the names of lots of well wishers, critics, friends and beloved ones. I pay regard to one and everyone who knowingly or unknowingly supported me during this journey of knowledge.

Finally, I want to bestow all my love to my world, my daughter, Mehrose Vashisht who came into my life during this journey and showed me with the path of positiveness with her heavenly and divine smile. Love you.

(Sahil Vashist)

Contents

Certificate	i
Abstract	iii
Acknowledgment	vii
List of Figures	xi
List of Tables	xv
List of Abbreviations	xvii
1 Introduction	1
1.1 Expansion and Categories of UAVs	3
1.2 Communication in Multi-UAVs Network	6
1.3 UAV-assisted Applications	11
1.4 Role of Data Offloading and Energy Efficiency in UAV	14
1.5 Challenges in Multi-UAVs Networks	18
1.6 Research Gaps	20
1.7 Objectives of the Research Work	21
1.8 Research Methodology and Contributions	21
1.9 Organization of Thesis	23
1.10 Summary	26

2	Literature Review	27
2.1	MAC Layer for UAV Networks	31
2.2	Software Defined Networks with UAVs	40
2.3	Data Offloading in UAV Ecosystem	44
2.4	Energy-Efficiency in UAV Ecosystem	49
2.5	Summary	51
3	ELMAC for UAVs Networks	53
3.1	Overview	53
3.1.1	Firefly Optimization	54
3.1.2	MAC Layer for UAV Networks	55
3.2	System Model	60
3.3	Network Model and Problem Formulation	62
3.3.1	Current Position and Location Prediction	63
3.3.2	Transmission Window	65
3.3.3	Energy-Efficient Transmission	65
3.4	Proposed MAC Model	68
3.5	Simulation Results and Discussion	72
3.5.1	Result and Discussion	79
3.6	Summary	81
3.6.1	Future Work	81
4	SLAO Offloading Scheme in Multi-UAVs	83
4.1	Overview	83
4.2	Software Defined Network Architecture	83
4.3	System Model	86
4.3.1	Problem Formation	90
4.4	SDN-based Location Aware Opportunistic Offloading Scheme using Adaptive Controller	92

4.4.1	SDN-based Adaptive Controller for Location Aware Data Offloading	92
4.4.2	Location Aware Offloading and Network Selection Control Scheme	96
4.5	Simulation Results and Discussion	99
4.6	Summary	106
4.6.1	Future Work	106
5	SLAO Energy Charging Scheme	107
5.1	Overview	107
5.2	System Model	107
5.3	Energy Consumption Model	108
5.4	Solar Harvesting Model	109
5.5	Wireless Charging Model	109
5.6	Charging Characteristics	110
5.7	Proposed Location Aware Opportunistic Energy Charging Algorithm	112
5.8	Simulation Results and Discussion	114
5.9	Summary	118
5.9.1	Future Work	119
6	Conclusion and Future Scope	121
6.1	Future Scope	123
	References	125
	List of Publications	142

List of Figures

1.1	Design considerations and networking players in UAVs networks	2
1.2	UAV statistical report [1]	3
1.3	Comparison graph between civilian and commercial application	3
1.4	Expected market trend of UAVs [1]	4
1.5	Layered architecture of multi-UAV ecosystem	8
1.6	Classification of antennas	9
1.7	UAV assisted data relaying	11
1.8	UAV-assisted monitoring and data collection	12
1.9	UAV-assisted product delivery	13
1.10	Various data offloading techniques	15
3.1	System model for the ELMAC	60
3.2	Illustration of the time slot diagram based on location and arrival rate.	63
3.3	Effect of height variation on SINR.	74
3.4	The variation in PDR with varying number of UAVs for varying users	76
3.5	Effects on average network throughput with varying number of UAVs and users	77
3.6	Effect on average end to end delay with varying number of UAVs and users	78
3.7	End to End Delay comparison of proposed model with existing tech- niques	80

3.8	Channel Utilization comparison of proposed model with existing techniques	80
4.1	Architecture of SDN	85
4.2	SDN based system model and architecture	88
4.3	SDN-based adaptive controller for data offloading	94
4.4	Variation of messages exchanged with change in number of UAVs	100
4.5	Impact on Handover latency w.r.t the numbers of UAVs	101
4.6	Impact on Throughput vs number of UAVs	102
4.7	Average delay w.r.t the number of UAVs	104
4.8	Impact on End-to-End delay w.r.t the number of UAVs	104
5.1	Representation of charging points for wireless charging	111
5.2	Deployment of charging points	115
5.3	Impact on Solar radiations w.r.t time	116
5.4	Energy required by single UAV	116
5.5	Energy map with respect to solar harvester	117
5.6	Energy drawn from charging points	118
5.7	Comparison of energy consumption for proposed technique with data dissemination and RIDSR (energy efficient routing algorithm)	118

List of Tables

1.1	Categorization of UAVs on the basis of type, range, flight altitude and weight	5
1.2	Comparison of traditional ad hoc network with UAV network	7
1.3	Different types of communication links	15
2.1	Comparison analysis of existing application for UAVs network	30
2.2	A comparison of various MAC protocols on the basis of different problems with high applicability to UAV scenarios.	32
2.3	Comparison of existing proposals for UAVs based on SDN	46
2.4	Comparison of existing proposals for data offloading in UAVs	48
2.5	Comparison of existing proposals for energy replenishment in UAVs	50
3.1	List of symbols	64
3.2	Input parameters	73
3.3	Parameter configurations	74
3.4	Simulation evaluation of the proposed model for ground users.	78
3.5	Comparison of the proposed model with the state-of-the-art MAC approaches (*Data gathering phase, **Network throughput).	79
4.1	List of symbols	87
4.2	Hypothesis t-Test: Soocs vs Without SDN for Handover Latency	101
4.3	Hypothesis t-Test: Soocs vs Conventional Scheme for Handover Latency	102
4.4	Hypothesis t-Test: Soocs vs Without SDN Scheme for Throughput	103

4.5	Hypothesis t-Test: Soocs vs Conventional Scheme for Throughput . .	103
4.6	Hypothesis t-Test: Soocs vs Without SDN Scheme for Delay	105
4.7	Hypothesis t-Test: Soocs vs Conventional Scheme for Delay	105
5.1	Battery specifications of EVs	116

LIST OF ABBREVIATIONS

Acronym	Meaning
AAA	Adaptive Array Antenna
ABS	Aerial Base Station
ACK	Acknowledge
AED	Automated External Defibrillator
APIs	Application Program Interfaces
BEB	Binary Exponential Backoff
BS	Base Station
BTS	Busy to Send
CL	Code List
CNPC	Control and Non Payload Communication
CSI	Channel State Information
CSMA/CA	Carrier Sensing Multiple Access with Collision Avoidance
CTS	Clear to Send
CW	Contention Window
DC	Data Center
DCF	Distributed Coordinated Function
DIFS	DCF Interframe Spacing
DoA	Direction of Arrival
DSCs	Drone Small Cells
D2D	Device-to-device
E2E	End-to-End
FANETs	Flying Ad hoc Network

FDs	Forwarding Devices
GBS	Ground Base Station
GPS	Global Positioning System
HoL	Head of Line
IMU	Inertial Measurement Unit
LoS	Line of Sight
MAC	Medium Access Control
MANETs	Mobile Ad hoc Network
MIMO	Multiple Input Multiple Output
MPR	Multiple Packet Reception
NAV	Network Allocation Vector
NBI	North Bound Interface
NFV	Network Function Virtualisation
NL	Neighbor List
NLoS	Non Line of Sight
NoD	Network of Drone
NS2	Network Simulator version 2
ODO	Opportunistic Data Offloading
OF	OpenFlow
OFDM	Orthogonal Frequency Division Multiplexing
PCS	Physical Carrier Sensing
PDR	Packet Delivery Ratio
PTS	Prepare to Send
PTR	Prepare to Receive
QoE	Quality of Experience
RF	Radio Frequency
RTS	Request to Send

Acronym	Meaning
SAR	Search and Rescue
SBI	South Bound Interface
SCN	Small Cell Network
SDN	Software Defined Networks
SIFS	Short Interframe Spacing
SINR	Signal to Noise Ratio
SoI	Signal of Interest
VCS	Virtual Carrier Sensing
UAV	Unmanned Aerial Vehicles
UE	User Equipment
U2U	UAV-to-UAV
U2I	UAV-to-Infrastructure
VANETs	Vehicular Ad hoc Network
WET	Wireless Energy Transfer
WPT	Wireless Power Transfer
5G	Fifth generation

Chapter 1

Introduction

The advent of unmanned aerial vehicles (UAVs) provide an eye in the sky facility to keep a watch and track on various activities remotely. Generally, UAVs work in collaboration while leveraging the existing technologies for successful communications. UAV systems are not only confined to small flying aircraft, but these also include a ground mission controller, communication infrastructure, and other instruments like Global Positioning System (GPS), and Inertial Measurement Unit (IMU). These pre-programmed vehicles can fly autonomously or can be controlled remotely by a mission controller from the ground. There are numerous characteristics of a UAV such as it is lightweight, has the capability to hover, and there is no runway requirements for takeoff and for the landing which make them favourite among various UAV assisted military and consumer applications.

A group of UAVs, often referred to a network of drones (NoD), are deployed to cater to the dynamic requirements of the military and consumer applications. In comparison to a single UAV ecosystem, the multi-UAV system provides higher scalability, faster multitasking ability, and longer network wingspan. For example, in disaster-affected areas, the deployment of multiple drones can perform search and rescue operations rapidly which are beyond the capabilities of an individual UAV. Such advantages prompt the service providers to design applications using UAVs to provide enhanced quality of experience (QoE) to the consumers [2, 3]. For ex-

ample, the Aquila [4] and Loon [5] are aspiring projects of Facebook and Google respectively to provide WiFi services in remote areas using a network of multi-UAVs. Similarly, consumer vendors such as Amazon, DHL and Dominos have successfully tested UAVs for cargo and product deliveries in smart city testbeds [6–9]. These recent ambitious UAV projects have a strong and vast potential to facilitate various consumer application in futuristic smart cities [10]. An overview of UAV supported applications and technologies are shown in Figure 1.1.

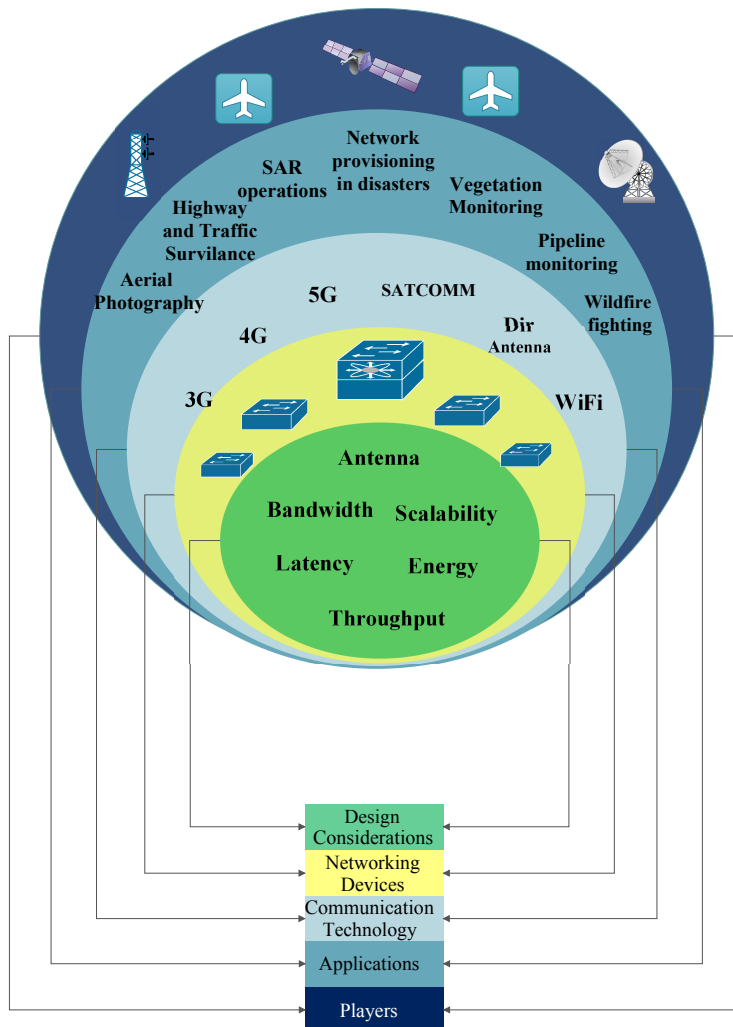


Figure 1.1: Design considerations and networking players in UAVs networks

1.1 Expansion and Categories of UAVs

According to Aerospace forecast report of Federal Aviation Administration (FAA) (2016-2036) [1], Figure 1.2, an exponential increase is observed in the deployment of small UAVs(a rotary wing). According to this report, a fleet of 5,42,500 UAVs is projected to hover the skies of the USA by 2020.

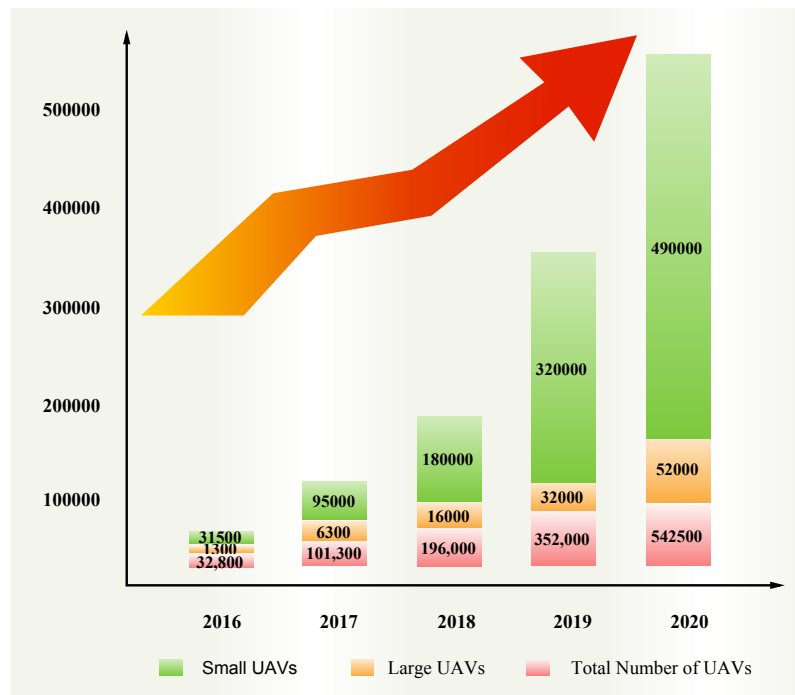


Figure 1.2: UAV statistical report [1]

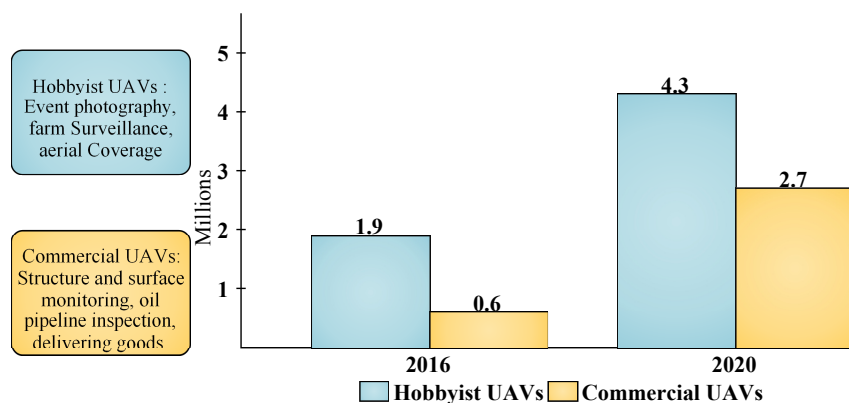


Figure 1.3: Comparison graph between civilian and commercial application [1]

The Figure 1.3 suggests the interest of Rotary wing or quadcopter UAVs among

the consumers. The graph clearly suggests that the demand of this class remains ahead in 2020 with almost double in number than that of 2016. To sum up, the afore-said, Figure 1.4 shows that the expected market of UAVs in 2022 will be USD 28.27 billion, approximately, with the 13.51% of CAGR taking 2016 as a base year [1].

Such facts and figures motivate the researcher to find out more capabilities and

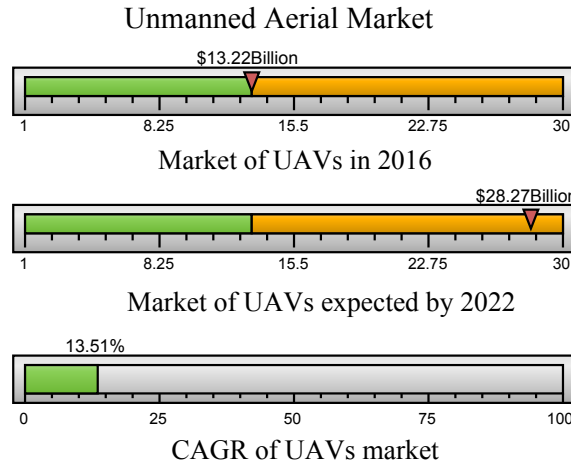


Figure 1.4: Expected market trend of UAVs [1]

forms of UAVs. It is also observed in various research operations that the increasing capabilities and shrinking sizes of microelectronic devices in recent years are the main reason behind the development of such autopilot and real-time UAV applications.

In general, the UAVs are categorized based on their range, weight and flying altitude capacity as presented in Table 1.1. This extensive categorization of UAVs helps a user to find an appropriate UAV according to requirement. The development and deployment of small UAVs instead of a single high-cost UAV reduce the operation cost as well as the failure rate. Moreover, it provides additional fault-tolerant infrastructure and facilities to various user groups. Due to its light-weight, ease of deployment, and moderate coverage capabilities, rotary wing UAVs is known as "Quadcopter" are found most favourable among various hobbyist and commercial applications. Whereas the fixed wing UAVs are generally used by military and

Table 1.1: Categorization of UAVs on the basis of type, range, flight altitude and weight

UAV Categories	UAV Types	Range (in km)	Flight Altitude (in meters)	Weight (in kg)	UAV applications	Characteristics
Rotary Wings	Nano	<1	100	<0.025	Logistic	Ease of use
	Micro	<10	250	<5	Monitoring & Data collection	Can hover in confined area
	Mini	<10	150 to 300	<30	Aerial Photography	e.g., Quadcopter
Fixed Wings	Close Range	10 to 30	3000	150	Search & Target decoy	Fast flight speed
	Short Range	30 to 70	3000	200	Aerial Mapping	Good camera control
	Medium Range	70 to 200	5000	1250	Oil pipeline Inspection	Large area coverage
Low Altitude Platform	Low Altitude Deep Penetration	>250	50 to 9000	350	Coverage & Capacity Enhancement	Quick & flexible deployment
	Low Altitude Long Endurance	>500	3000	<30	Surveillance & Intelligence	Can hover upto several hours
High Altitude Platform	Medium & High Altitude long Endurance	>500	17000	1500	Weather & Environment Monitoring	Very long endurance

commonly used in reconnaissance, target and decoy applications, the other relevant categories of these aerial networks are Low and High altitude platforms. These platforms are used in long endurance applications such as- wide coverage and capacity enhancement, weather and environment monitoring, and most prestigious research and development.

In order to achieve tenacious tasks, data communication or information sharing among inter-UAVs, and UAV-to-base station is particularly important to make mission controller aware of the real-time situations. Whereas, the broad applicability of these aerial vehicles requires meeting individual QoS demands.

1.2 Communication in Multi-UAVs Network

To provide high-performance data links and govern autonomous movements between multiple UAVs, an exclusive ad hoc network can be established to administrate UAV-to-UAV communication. This exclusive network is classified as Flying Ad hoc Networks (FANETs), which is derived from its two parental networks, i.e. Mobile Ad hoc Networks (MANETs) and Vehicular Ad hoc Networks (VANETs). The characteristics which distinguish it from other ad hoc networks are described in Table 1.2. Further, the key aspect to boost the applicability of UAVs is the communication and data sharing among UAVs and with the infrastructure. For providing efficient communication, the UAVs network is classified into centralized and decentralized architecture [11–14]. In the centralized architecture, all UAVs are connected through a central node, i.e., all network is centred at base station wherein UAVs are restricted to communicate directly to each other. On the contrary, the decentralized network allows the UAVs to communicate directly to each other, thereby removing the barriers of the central control system. Further, this communication architecture utilizes UAV-to-UAV (U2U) and UAV-to-Infrastructure (U2I) architecture to provide communication at a different layer in the multi-UAV ecosystem. The layered communication architecture of UAVs is shown in Figure 1.5. In U2U architecture,

Table 1.2: Comparison of traditional ad hoc network with UAV network

Parameters	Traditional ad hoc networks	UAV network
Node Mobility	Slow, varies between 5-120km/hr	Fast, varies between 30-420km/hr
Node density	Moderate to high	Low
Topology change	Moderate	Very frequent
Trans-mission range	Low to moderate	Moderate to high
Antennas	Omni-directional	Directional
Power consumption	Low	High
Location awareness	High	Low
Bandwidth requirement	Low	High

the physical layer and data link layer depend on the IEEE 802.11 protocol for data communication as it can cover hundreds of meters in the line-of-sight (LoS). Moreover, at data link layer IEEE 802.11 protocol supports the carrier sensing multiple access with collision avoidance (CSMA/CA), which is appropriate for U2U communication.

In U2I architecture, the infrastructure can either be in the form of a base station, a mobile tower or a satellite. However, to share and receive inputs from infrastructure, the group of collaborative UAVs appoints a UAV as a gateway or backbone UAV. The responsibility of this backbone UAV is to exchange data between UAVs and connected infrastructure. Generally, IEEE 802.11 a/b/g/n (Wi-Fi) protocol and WiMAX are used for connection and exchange of data in U2I depending upon the requirement of the application. However, omni-directional and directional antennas are utilized to transmit and receive data in the form of signals.

The principal function of an antenna is to convert electronic signals to electromagnetic waves and vice versa. Thus, two major modes in which these signals are radiated and received by an antenna are Omni-directional mode and Directional

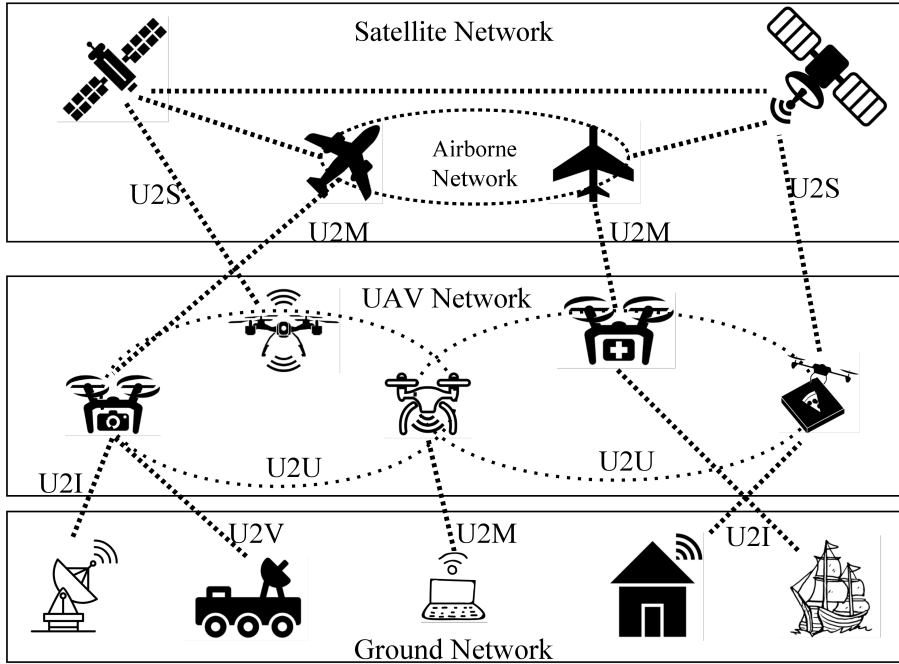


Figure 1.5: Layered architecture of multi-UAV ecosystem

mode. Generally, the omni-directional antennas follow an isotropic pattern, as it radiates a uniform amount of signals in all directions. On the contrary directional antennas are capable of radiating in an angular direction by focusing more energy in a particular direction and less in others. The key attribute of an antenna is its gain, as it measures the antenna efficiency and directivity. The Directivity of an antenna is “the ratio of the radiation intensity from an antenna in a certain direction to radiation intensity of an isotropic antenna”, whereas Antenna efficiency is the ratio of power delivered to the power radiated from an antenna”. Moreover, the gain of an antenna specifies the relative power in given a direction in contrast to the omni-directional antenna.

The basic **classification of antennas** is based on the mode of operation, their design peculiarities and radiation pattern followed by the antennas [15–19]. The Fig. 1.6 illustrates the classification of antennas system used in ad hoc networks.

- *Omni-Directional Antennas:* An omni-directional antenna follows an isotropic pattern to radiate and intercept Radio Frequency (RF) equally in horizontal direction and 2D geometric plane [19]. Such type of antennas is adequate

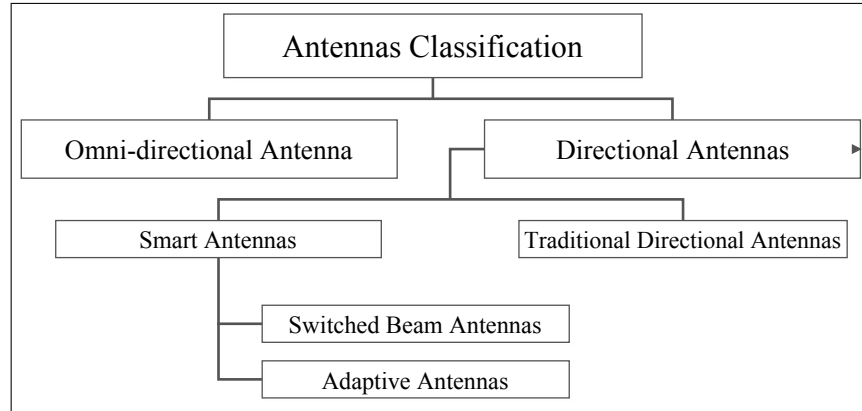


Figure 1.6: Classification of antennas

for elementary RF habitat where no prior information about user directions is either obtainable or required. Nevertheless, in this unfocused approach, the desired user gets only a small proportion of the overall power. Thus, there is a huge wastage of radio energy using such antenna where a major proportion of transmitting signal energy scatter in all directions besides the desired user direction. Moreover, to overcome the environmental hindrance, omni-directional antennas increased their broadcasting power [18]. As a result, the signals which miss the intended user act as interference for other adjoining cells or user. However, the single-element data transfer approach cannot be judicious on declining signals interfering with the communicating users. It also limits the spatial re-use, limiting frequency re-use and packet transmission.

- *Directional Antennas*: With an increase in the number of users and wireless services at an aggressive rate, the urgency of spatial re-use, higher transmission rate and more extensive coverage arise. Keeping such requirements at priority, the signal transmissions in ad hoc networks focus on the use of Directional antennas. The directional antennas radiate the signals in a specific direction with narrow beam width [17, 19, 20]. The narrow beam width that it allows targeting of the radio signal in a more focused way. Moreover, it robustly increases transmission rate, coverage area and spatial re-use [21]. The direction with the maximum gain in these antennas is known as boresight di-

rection. The boresight direction characterizes much greater gain than that of omnidirectional direction. The directional antennas are codified into *switched beam antennas* and *adaptive antenna array*.

The **Switched beam antennas**: are less complex and easy to fit with traditional wireless technology. This system forms numerous fixed beams at the antenna site with more intensity the direction in which the radiation pattern is beamformed. Each beam can be considered as a separate individual sector serving a user. Moreover, this system use switching technique which helps the continuously moving mobile units to select a pattern from predefined patterns based on the most robust signal strength [20]. The principal objective of switched beam antennas is to amplify the gain in the user defined direction. However, due to scalloping, they do not guarantee maximum gain. The beam can be steered in multiple directions throughout the space concerning the variations in the phase differences of the signals. The lack of command on multi path interference makes it inadequate to be used in highly sensitive networks [17].

The pattern of adaptive array directional antenna habitually consists of the main lobe, which contains the maximum gain and several small gain side and back lobes. Another important characteristic in the radiation pattern of a directional antenna is the beamwidth. The beamwidth of an antenna is the angle between the direction on either side of boresight, which is half of its maximum gain. The main beam of the radiation pattern is the main lobe of the antenna, from where continuous and maximum power is emitted by the antenna. Stated more simply, the area that is 3dB of the spike of the main lobe is known as the main beam. It contributes to the higher degree of freedom, as they can steer the main lobe towards the Signal of Interest (SoI). The signal processing algorithms robustly enhance the reception power of these antennas by suppressing the interferer. Moreover, such antennas are capable of providing a customized radiation pattern to the respective users. Although in

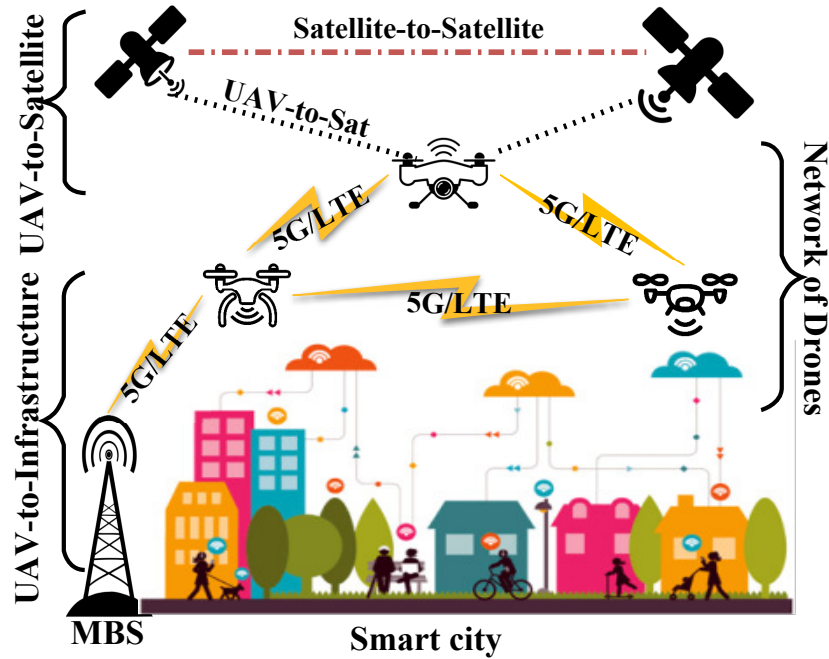


Figure 1.7: UAV assisted data relaying

low interference, both smart antennae provides notable gain over traditional antennas. However, when there is high level interference present, then adaptive antennas outperform both the traditional or switched beam antennas. As the number of UAVs based applications is increasing at an exponential rate, the necessity arises of spatial re-use, more comprehensive coverage areas and higher rate trade off between nodes arises [20, 22, 23].

1.3 UAV-assisted Applications

The UAV-assisted consumer applications are broadly classified into three domains, namely 1) UAV-assisted data relaying, 2) UAV-assisted monitoring & data collection, and 3) UAV-assisted product delivery.

In *UAV-assisted data relaying*, depicted in Figure 1.7, the deployment of UAVs is in the form of balloons, small aircraft, and drones can provide reliable and cost effective wireless communication to User Equipments (UEs) in a smart city. On the other hand, the utilization of Drone Small Cells (DSCs) is a promising solution for temporal and on demand communication service to desired areas. It is specially,

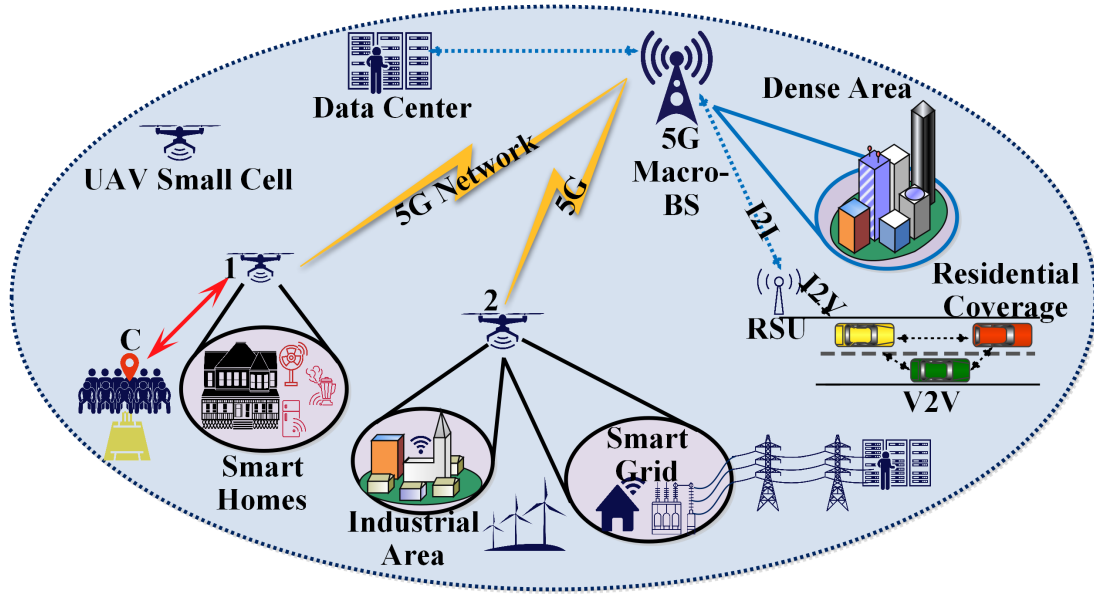


Figure 1.8: UAV-assisted monitoring and data collection

suited where fabrication of cellular infrastructure is expensive or challenging due to geographical challenges or where the need is totally temporary such as sport events, off-site media conferences, and political rallies. In such cases, the host cellular network has to witness a high traffic load, which may lead to channel congestion and delay in data relaying. The UAVs can handle a part of the data traffic load. Moreover, in comparison to the traditional terrestrial BSs, the UAVs gain advantages to calibrate their altitude, overcome the Non Line of Sight (NLoS) barriers and to have additional capacity to cover unreachable areas. Significantly, UAVs play a critical role in connecting the Internet of Things devices (IoT), such as wearable sensors, smart-phones, smart electricity meters and smart grids to Internet [24]. Generally, these devices have smaller transmission power and less capacity to communicate over a long distance. In this scenario, UAVs act as wireless data relays to upgrade the coverage and connectivity of these small devices. This aspect is key to enhanced QoS even for next-generation 5G networks [25, 26]. The capital and operational expenditure related to the deployment of UAVs can be handled by the flexible deployment of DSCs.

The *UAV-assisted monitoring and data collection* supports numerous applications such as traffic monitoring, public safety, homeland security, farm and oil

pipeline inspection, collection of sensor data and live coverage of sports events as shown in Figure 1.8. The UAVs act as data centres to collect data, information from the ground applications either by moving or staying quasi-stationary above the serving area. For example, the moving UAVs deployed for border patrolling covers a large geographical area and provide sensitive data to the remote controller without putting risk on human life. On the other side, UAVs are used for periodic data collection from the ground user, Internet of Things (IoT) sensors, smart grids and reading of energy consumption units from smart electricity meters. The UAVs can play a vital role of inter-mediator in providing Internet or 5G services to IoT devices and consumer applications [27].

The *UAV-assisted product delivery* is one of the latest entries into this domain

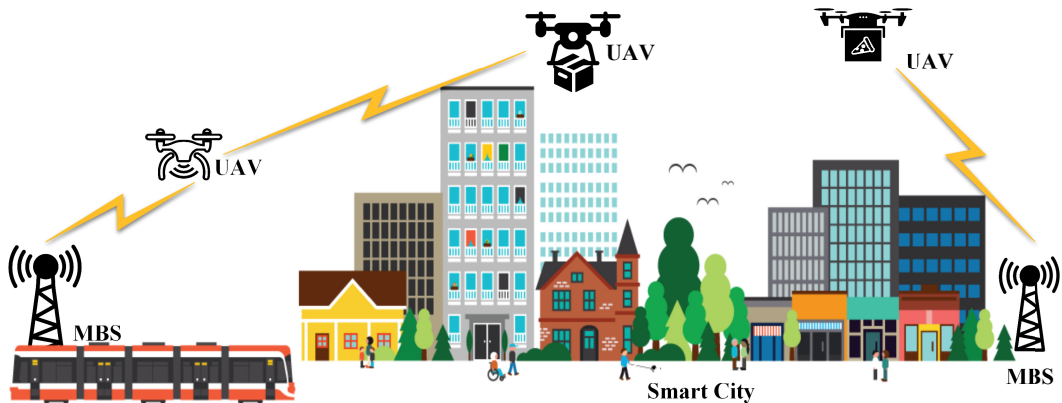


Figure 1.9: UAV-assisted product delivery

depicted in Figure 1.9. The capability of UAVs to hover and cover the distance with good speed, make them a favourite among various logistic applications. In recent years, the logistic applications have witnessed an increase in the trend of utilizing UAVs for product delivery, such that, the delivery of hot pizzas by a UAV is now a reality, the world's largest pizza chain Dominos successfully delivered first ever delivery of food by drone to its customer. Furthermore, to provide deliverables even faster, the online merchant company Amazon had tested its prime air drone delivery in December 2016. United parcel service started testing UAVs to provide medicine in an emergency or congested cities and remote areas. Nowadays, numer-

ous online merchants are also looking for the approval of UAVs as a regular delivery option. DHL, the world's largest logistics company has started its delivery of goods and logistics using UAVs. Besides this, many start-ups, which are using UAVs for commercial activities, make it more famous by introducing the UAVs to ordinary people.

1.4 Role of Data Offloading and Energy Efficiency in UAV

Due to emerging applications of UAVs, communication is becoming a crucial issue in current time. The requirement of a capable communication architecture for these aerial machines is the need of the hour. Taking steps in this direction, the National Aeronautics and space administration and the European organization are developing a separate communication system for UAVs networks. For the integration of UAV networks with the national airspace system, standard control and non-payload communication (CNPC) links are established. The CNPC carries the information from BS to a UAV and status report is carried from UAVs to the BS. It also senses and avoids interference among the UAVs. The two allocated spectrum's used by this scheme are L-band (960977 MHz) and C-band (50305091 MHz). The limitation with this scheme is the uplink speed and downlink speed, which are 6925 bps and 13573 bps respectively. These speeds are not enough for real-time, video capturing based applications [14]. The data link between UAV networks and BS need to support all the mission related information [14]. These data links must provide higher tolerance in terms of lower latency and security in context to CNPC. Usually, UAVs data link share the same spectrum meant for LTE band while assisting cellular coverage. Hence, there is the absolute requirement of offloading to effectively handle the spectrum and bandwidth in multiple available networks. Data offloading is a popular technique to utilize available networks when the host network is limited.

Table 1.3 shows the comparison of CNPC link with data links.

Table 1.3: Different types of communication links

Communication Link	Uplink Speed	Downlink speed
CNPC	2424 bps*	4008 bps*
CNPC	6925bps**	13575 to 234,134 bps**
IEEE 802.11 n	6 Mbps to 54 Mbps	6 Mbps to 54 Mbps
Cellular 3G	144kbps to 42 Mbps	144kbps to 42 Mbps
Cellular 4G	300 Mbps to 1Gbps	300 Mbps to 1Gbps

Note: * for small UAVs, ** for medium and large UAVs

The data offloading technique in UAV network helps to solve the communication and data transfer challenges. Instead of burdening a single channel, data can be offloaded to the underutilized channel using various suitable techniques. This can increase the resource utilization exponentially, which in turn helps to decrease the latency and waiting time for data transmission. Moreover, less processing time for data transfer helps to save the energy consumption of UAVs. The main objective of data offloading is to maintain the QoS for bandwidth hungry services at various levels. The classification of various data offloading techniques is presented in Fig. 1.10. These data offloading techniques are discussed as below:

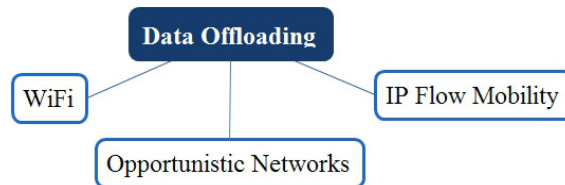


Figure 1.10: Various data offloading techniques

- WiFi Data Offloading:** The most popular data offloading technique is WiFi offloading, due to its widespread diffusion, low cost, and satisfactory performance. Mostly, it consumes radio access hot-spots for indoor broadband services. Moreover, the transfer speed of Wi-Fi is much better than that of cellular networks with a limited coverage area. However, nowadays, WiFi is experiencing a transformation towards ubiquity and city-wide coverage. Mainly, there are three methods by which operators divert the data from the cellular net-

work to free unlicensed IEEE 802.11 network. The first method is unmanaged WiFi offloading and network bypassing. In this method, the data services of a user are shifted to the closest accessible Wi-Fi network by passing around the cellular network, whereas the voice services of the users remain with the cellular (core) networks. The second method is managed WiFi offloading in which an intelligent session-aware gateway is implemented to control the network access by different subscribers. The last method is the integrated data offloading, which is achieved by the unification of cellular and WiFi networks by loosely and tightly coupled networks.

- **IP Flow Mobility:** IP flow is a sequence of IP packets with encapsulated information such as-IP addresses, port number, and transport protocols. There are two types of IP flow mobility, i.e., host-based and network-based IP flow mobility management. In host-based IP flow mobility, mobile IPv6 is utilized and it enables the transmission of multiple IP flows such as- file download, VoIP, and video sharing on the wireless link at the same time. Moreover, mobile IPv6 authorizes the IP flow switching from one wireless link to another, while provisioning desired QoS on the move. On the other hand, proxy mobile IPv6 protocols are utilized by network based IP flow mobility.
- **Opportunistic Data Offloading (ODO)** DO between various available networks can help to manage the issue of limited bandwidth and channel access problems in different networks. In most of the cases, the communication between two devices faces the problem of shortage of spectrum bandwidth. In this context, the 5G network is new and leading edge technology that delivers reliable and faster transmission. Various wireless transmission methods such as-millimeter-wave (mmWave), massive Multiple Input Multiple Output (MIMO) technology and small cells are being used by the 5G network architecture to provide opportunistic offloading mechanisms.

After analysis of the above mentioned data offloading techniques, it is evident that

ODO can handle the challenges of the multi-UAVs network in a better way by utilizing various available cellular networks such as 5G, LTE and WiFi. The amalgamation of cellular networks with the Wi-Fi network creates a heterogeneous network, which needs an efficient ODO scheme to handle the challenge of load balancing. Besides, relieving the single infrastructure network load, offloading of data to a heterogeneous network leads to numerous improvements such as increased network availability, coverage and throughput. Moreover, it also reduces the content delivery time and latency [28]. However, limited energy availability remains one of the biggest challenges for multi-UAV networks.

Energy-efficiency is the utmost need of UAVs for its functioning, flight time enhancement, and endurance. Conversely, UAVs are fitted with conventional Lithium batteries which dissipate energy much faster to handle the energy thirsty processes such as generation of lift to move around and computational work. Moreover, devices like sensors and cameras add to the energy load. Additionally, the need to provide a high data rate for transfer of the considerable amount of data generated put a significant load on the onboard energy. Thus, due to low battery life, these UAVs need to recharge frequently [29–31]. This either confines the mission or may result in the failure of a mission or network traffic overhead. So, in order to overcome above mentioned issues and add more time to fly, two recent methods for energy replenishment are discussed below.

- **Solar energy harvesting** : In solar energy harvesting, the thin film of photovoltaic solar cells are installed on the top surface of wings of UAV. The photovoltaic energy is produced by capturing the radiant heat on PV panels and it is converted into energy. As solar energy is not available all the time, the energy produced by such cell may not be enough for UAV operations [32].
- **Wireless charging**: Another method for energy replenishment is wireless charging. This method is getting popular in various other fields such as wireless sensor networks and electric vehicles. Low power devices can charge

energy from a distance through the geo-located wireless charger points. Hence, using this concept, UAVs can perform communication while charging wirelessly from charging points located at cellular towers. This can increase the hover time of UAVs and avoid mission failures [33].

1.5 Challenges in Multi-UAVs Networks

- **Deployment:** To serve a larger geographical area, it is a challenge for the service provider to find an appropriate site for deployment of UAVs that could provide maximum connectivity to a large geographic area. Moreover, to cater to the demand of mobile ground users, rigorous network planning is required. The number of UAVs and their respective geographical locations have a high impact on various factors such as latency, bit rate, and energy consumption. Hence, a systematic approach is required to take self-coordinated decisions related to the deployment of UAVs [34, 35].
- **Data Offloading and Bandwidth:** Generally, the UAVs are deployed in different terrains where only limited bandwidth is available. As a result, the UAVs network has to face congestion, improper resource utilization and increased energy consumption. The data offloading to alternative available network shifts the load from the core network, which requires timely traffic monitoring, filtering, and updating of network policies [28]. It is essential to tackle such situations by devising strategies or data offloading mechanism so that inadequate availability of bandwidth should not hinder the functionality of any consumer application.
- **Power Consumption:** UAVs require energy for a number of processes such as propulsion, sensing, data processing, and to communicate. Due to the limited battery capacity, it is tough to increase the hover time while providing desired QoS. Due to the higher dissipation of energy, UAVs may have to be grounded

without completing its mission. Maintaining an optimal balance between QoS parameters and energy consumptions becomes an vital task [31,36].

- **Location Accuracy:** For successful delivery of a parcel or a product at consumer location, GPS is popularly utilized as navigation tool. The GPS navigation system provides the pinpoint information such as-velocity, timing and position coordinates to receivers based on satellite coordinates. The GPS satellites broadcast signals as plaintext. This may lead to various attacks such as GPS jamming, spoofing and beaconing. A tampering or change in the GPS coordinates by an attacker may lead to inconvenience and wrong delivery. Further, with the limited energy availability, such misleading coordinates can extend the hover time or travel time of UAVs, which may lead to mission failure or unsuccessful deliveries [37].
- **Energy-Efficiency:** The energy-efficiency has a vital role in the success of UAV-assisted product delivery because UAVs are equipped with a battery which is having limited energy storage capacity the battery impacts the flight endurance like speed, coverage, and payload. Due to such restrictions, UAVs are not able to deliver the product at distant locations and have to cater to a limited area. Moreover, inefficient location tracking may extend the travel time of UAVs and may end in higher energy consumption. Such a situation can lead to the grounding of a drone or unsuccessful deliveries.
- **Latency:** One of the major requirements of the time is critical applications of lower latency. However, the traditional off-the-shelf communication equipment and protocols used by UAVs networks may lead to an increase in the latency. Moreover, sharing of common communication band and spectrum may lead to interference in on-going conversations and higher latency.

1.6 Research Gaps

After the detailed analysis of the aforementioned existing proposals concerning the current requirements, the following research gaps have been identified.

- **Lack of location aware centralized control:** With an increase in the number of UAVs, there is an urgent requirement to establish a centralized controller to check and prevent the various type of malicious activities. Moreover, the central controller will help to provide a complete network view that helps in collision avoidance by sharing the coordinates and location of operating UAVs in the vicinity.
- **UAVs deployment as aerial base station:** The several research work focuses on the path planning, positioning of UAVs for data relaying services but, such work fails to provide clear details of how to optimally deploy the UAVs as ABS. Moreover, the existing literature lacks in pointing out the maximization coverage problem using UAVs, which should be the primary consideration for UAVs based ABS.
- **Energy-efficiency:** The primary focus of the majority of the work is on the applicability of the UAVs. Even the proposed methods, models, schemes, and protocols mainly focused on the path selection and wireless communication using UAVs considering the QoS parameters such as- throughput, and latency, while ignoring the most crucial parameter, i.e. energy-efficiency. The adoption of energy-efficiency in the UAVs network will enhance the overall performance of a network by optimizing the flight time constraints of UAVs.
- **Renewable & wireless energy charging scheme:** While developing an energy-efficient UAVs network, there is an urgent need to consider the renewable and wireless energy charging scheme for the UAVs. In renewable energy, the UAVs can be charged using solar energy panel installed on the UAVs, while

the wireless energy transfer will provide energy during night operating hours. This will enhance the overall flight and operation time of the UAVs.

- **Limited utilization of latest technologies:** The existing proposals have neither being fully utilized nor made the use of the latest technologies for the design of location aware UAVs and to expand networking application domains. Some of the recent proposals have utilized SDN and but not to a great extent for networking in UAVs. Moreover, the existing proposals have not considered the support of UAVs for IoT and machine-to-machine (M2M) networks. In order to maximize the benefits of UAVs assisted networking, the integration of the latest technologies with UAVs network is required.

1.7 Objectives of the Research Work

From reported challenges and research gaps, it is observed that research work on UAVs is mainly focused on their applications. But, the challenges associated with these applications still require attention in specific areas such-as MAC layer, routing and energy. To address the aforementioned challenges or research gaps, the work is carried out through the following objectives:

- To design an efficient location aware protocol for multi-UAVs network.
- To allow QoS provisioning for the proposed protocol.
- Performance validation and comparison with existing protocols on the basis of various QoS parameters.

1.8 Research Methodology and Contributions

The methodology and the contribution to achieve the various objectives are summarised as follows :

Design an efficient location aware protocol for multi-UAVs network

- The requirement of efficient location-aware Medium Access Control for collision and congestion free transmission for UAV network has been identified as a core problem .
- An efficient access control strategy is formulated to consider the energy requirements along with the location of each drone in the network to avoid the failure of the entire network.
- The mathematical model is formulated to facilitate efficient control as well as the provisioning of applications at high quality of service.
- An algorithm based on firefly optimization is formed for efficient timing slot mechanism where UAVs are modelled as fireflies. The flies produces and utilize the fluorescence flashes as communication signals to communicate with other fireflies
- The optimization accounted the variation in light intensity and attractiveness among fireflies.
- The effectiveness of the formulation was tested numerically and through network simulations.

Allow QoS provisioning for UAV Network

- An SDN-enabled location-aware opportunistic offloading scheme for multi-UAVs ecosystem is designed.
- The UAVs are used as forwarding nodes in SDN model. The data traffic is offloaded to other available channel in an opportunistic manner for the congestion free communication.
- The strategies for location-aware offloading and network selection are formulated.

- The algorithm is developed to provide an optimal channel as per the migration request received by the task manager.
- The effectiveness of the proposed algorithms are investigated on account of handover latency, end-to-end delay and throughput.

Development of SDN-enabled location-aware opportunistic wireless energy charging scheme

- A solar harvesting technique is presented wherein UAVs are equipped with photovoltaic solar panels.
- The charging of UAVs battery from the geo-located charging point using the wireless charging is investigated.
- The strategy is formulated for the path planning and sharing the charger coordinates with the UAVs.
- The effectiveness of the proposed scheme is investigated through simulated deployment of charging points in a city.

1.9 Organization of Thesis

After accomplishing the objectives stated above, the thesis is organized into six chapters, the brief description of these chapters is as follows:

- **Chapter 1: Introduction**

This chapter describes the UAVs background and UAV-assisted consumer applications. It also highlights the various challenges associated with the UAVs network. The integration of new technologies with UAVs is also discussed as possible solutions to the challenges faced by UAVs network. In last, the research gaps identified from the existing literature is also presented in the chapter, accompany with the objectives of the research work. It laid the foundation for the research work.

- **Chapter 2: Literature review**

This chapter presents comprehensive and illustrative literature review for multi UAVs network. Firstly, a comparative analysis of UAVs based applications is performed considering different parameters. A detailed review and comparison of various existing MAC protocols for UAVs is presented. The analysis and review of the SDN, data offloading and energy charging scheme based literature is also provided in the chapter.

- **Chapter 3: ELMAC for QoS Enhancement in UAVs Network**

In this chapter, the technique based on the properties of the firefly optimization algorithm are utilized to forms an Energy-efficient and Location aware Medium Access Control (ELMAC) for Quality of Service Enhancement in UAV networks. This technique helps to provide location aware, congestion free, collision free and energy-efficient MAC for UAVs. The fireflies produce and utilizes the fluorescence flashes as communication signals to communicate with other fireflies. The variation in light intensity and attractiveness among fireflies are primary considerations. Basically, the less brighter firefly will get attracted toward the more brighter firefly. The brightness(light intensity) is therefore seen as an objective function to be maximized. However, in our proposed model, the fire-fly optimization algorithm is operated to minimize the light intensity. This approach helps in collision-avoidance over the defined timing cycle.

- **Chapter 4: SLAO Offloading Scheme in Multi UAVs Ecosystem**

In this chapter, an efficient SDN-enabled Location Aware Opportunistic (SLAO) Offloading scheme in the multi-UAV ecosystem is designed. In this scheme, the UAV which wants to offload its data over a channel sends the migration request to the centralized controller. After which the instruction sets provided by central controller matches the input requirements. The successful verification of matching rules leads to the forwarding of the request to the

offload manager. Further, the radio link controller maintains the records of UAVs and provide suitable waypoints for network selection. This technique help to handle congestion and data transfer issue in UAVs network. Moreover, the proposed technique increases resource utilization exponentially and help to maintain QoS for bandwidth hungry services. The results obtained show the superiority of the scheme in terms of end-to-end delay, throughput, and hand-over latency.

- **Chapter 5: SLAO Energy Charging Scheme**

This chapter presents SDN enabled location aware opportunistic energy charging scheme. This scheme provides a solution to the significant challenge faced by UAVs, i.e., energy replenishment while performing a task. To sustain the flight of UAV throughout the mission, a sufficient amount of energy is required to be maintained in UAVs battery. However, with limited battery capacity, it becomes a tough challenge. Moreover, deploying additional batteries can increase the weight of the UAV's. It is not possible to ground a UAV during its flight to charge the battery, as it may hinder the mission. Therefore, to handle the issue, an opportunistic solar energy harvesting and wireless charging schemes are designed in order to sustain the energy of a UAV. By adopting this scheme, the flight time of a UAV can be extended while performing its tasks. In a case, where sufficient solar energy is not available to charge the UAV's battery, a location aware wireless charging scheme is used to sustain the life of a UAV.

- **Chapter 6: Conclusions and Future Scope**

This chapter concludes the thesis by providing a brief overview of contributions made towards proposed approaches and provides an insight into the future directions of the research work. Moreover, the future directions in this area are presented using two case studies. The case studies depict the current and future trends of UAVs as a location aware on demand delivery and an internet

service agent.

1.10 Summary

This Chapter highlights the challenges associated with the UAVs network and UAVs-assisted applications. This chapter also provides an overview of the utilization of latest technologies in UAVs network such as-SDN, data offloading, and energy replenishment. It also presents the reason and the need for considering the congestion, collision, and location aware UAV techniques. In last, this chapter presents the thesis organization.

Chapter 2

Literature Review

In order to provide the solutions to the challenges faced by UAVs and UAVs network, various authors have proposed numerous frameworks, methods, and algorithms which are highlighted herein. The applicability of these flying machines varies with change in scenarios, that arise the various concerns and challenges, and it is for the researcher to address present and upcoming challenges. The existing literature is mainly focused on the application, routing, and cooperative network for the multi-UAVs network. There exists very limited literature on MAC protocols, data offloading and WET for UAVs. Therefore, a comprehensive review of all available literature has been made with an emphasis on MAC protocol, SDN, data offloading and WET.

With the popularity of the UAVs networks, it is observed that the UAVs are being used for various monitoring and SAR applications and their usage is expected to increase in the times to come because of their enhanced utility. Tripicchio and Dabisias [38] utilized the concept of drones in smart farming. They developed algorithms that effectively categorized the ploughing technique by using an RGB-D sensor. The sensors detected the color of leaves, insect and harvesting phases. In another application, Caska and Gayretli [39] designed an algorithm based on the integration of both types of unmanned vehicles, i.e. unmanned ground vehicle and unmanned air vehicle for patrolling of area, where human intervention is consid-

ered dangerous. The algorithm computed the number of UAVs required to patrol the respective area by using the battery level of a UAV. The information gathered by UAVs is shared among UGV for surveillance of the suspicious area. Giitsidis *et al.* [40] designed a scheme to detect fire and human from high altitude using multi-UAVs. For detection, the multi UAVs were armed with a thermal and optical sensor which was equipped with a computer vision algorithm and image processing software. The authors expected the UAV to fly about 2 K.M above the ground, and used blob detection algorithm to achieve accuracy in human recognition. Coifman *et al.* [41] presented a model to use multi UAVs for traffic monitoring. They are provided with RWIS (road weather information system) and night vision cameras to work well in bad weather or bad light. The gathered information is sent to ground stations linked with the geographic information system. The UAVs are deployed for monitoring the photovoltaic plants and oil pipeline inspections [42, 43]. The use of UAVs is reliable, cost-effective and time saving method in comparison to conventional methods.

One of the most striking applications of UAVs is product delivery. In recent years, it has been noticed that the trend of utilizing UAVs for delivery of goods, essential commodities and articles, and construction material is increasing exponentially. The UAVs are employed to act as a guiding principle in designing and construction of the building and are utilized for lifting the small building elements and placing them accurately as indicated in the digital blueprints [44]. Evan Ackerman [45] exploited the benefits of UAVs for delivering of goods purchased from online merchant Amazon. Moreover, Amazon started its delivery service by the name of prime air services utilizing UAVs. Such applicability of UAVs alleviates the challenges faced by delivery services in rural and urban areas. Nowadays the products can primarily be delivered faster and securely to consumers. On similar trends, the authors in [46–48] discussed how big players in the market are ready to utilize the drones for various delivery services. For example, as DHL started the delivery of parcels by engaging the services of utilizing the drones in specific regions.

The biggest pizza chain Domino's have also started the delivery of pizzas through UAVs. Delivery through the drones helps to cut the delivery charges for providers and waiting time in delivery for customers. This is more likely a win-win situation for both the providers and the customers.

The drones are being utilized to save human lives in critical situations. Claesson *et al.* [49] investigated on utilizing the UAVs for delivery of an automated external defibrillator (AED) for cardiac arrest patients. The results suggested that in 93% of cases, the UAVs arrived earlier than traditional transport methods with 19 minutes of saved mean time. Scott and Scott [50] provided models for utilizing UAVs for the delivery of blood, vaccines, medicines, and other healthcare items, to the area where inaccessible roads hinder the delivery of such urgent products. Moreover, by utilizing the UAVs, the delivery of vaccines and medicines at the time of floods or other natural disasters prove extremely useful.

The UAVs are also found effective for post disaster area management and to serve the large number of ground users as ABS. Mukherjee *et al.* [52] developed a scheme by deploying a group of UAVs over the total area (say X), to serve the area with stationary UAVs. The area was divided into small zones X1, X2, and X3. With this the updated information of disaster situation is obtained and simultaneously, these aerial vehicles also utilized as ABS, which serves the UE when cellular towers are destroyed due to natural calamities. Further improvement in the deployment of these vehicles leads to the solution for next-generation networks. Zhan *et al.* [51], in his study, employed UAVs as data relaying nodes which help to extend the communication range between UE and BS. An algorithm was developed for maintaining and enhancing the uplink data rate while providing each UE with data rate above the threshold rate. Han *et al.* [53] proposed an algorithm to serve the maximum number of users with a minimum number of UAVs by utilizing multi-layer UAVs architecture and time slot based transmission to serve the user with the maximum data rate. In [54], drones were utilized as a data relay between the satellite and base station to overcome the communication overheads. TDMA based two level

Table 2.1: Comparison analysis of existing application for UAVs network

Existing applications	Year	Focus	N/w type	Data rate	Range	Energy-Efficiency
Coifman <i>et al.</i> [41]	2004	Traffic Monitoring	Multi-UAVs	L	M	-
Hausmann <i>et al.</i> [43]	2005	Gas pipeline Inspection	Multi-UAVs	M	M	×
Zhan <i>et al.</i> [51]	2011	Data relaying	Multi UAVs	H	H	×
Willmann <i>et al.</i> [44]	2012	Construction	Multi-UAVs	L	M	×
Evan Ackerman [45]	2013	Delivery	Multi-UAVs	M	H	×
Quater <i>et al.</i> [42]	2014	Photovoltaic Plant Inspection	Multi-UAVs	L	M	×
JK Stolaroff [47]	2014	Delivery	Single UAV	M	H	×
Mukherjee <i>et al.</i> [52]	2014	Disaster Management and Wireless coverage	Multi UAVs	H	H	×
Tripicchio and Dabisias [38]	2015	Smart Farming	Single UAV	M	M	×
Caska and Gavrethi [39]	2015	Patrolling	Multi-UAVs	L	M	✓
Gitisidis <i>et al.</i> [40]	2015	Fire Detection	Multi-UAVs	L	M	×
Dominosite	2015	Delivery-Pizza	Multi-UAVs	L	H	×
Dane Bamburry [46]	2015	Delivery	Multi-UAVs	M	H	×
Brar <i>et al.</i> [48]	2015	Delivery	Single UAV	L	H	×
Claesson <i>et al.</i> [49]	2016	Delivery-AED	Single UAV	L	H	×
Scott and Scott [50]	2017	Delivery-Medicine	Single UAV/ Multi UAVs	M	H	×
Han <i>et al.</i> [53]	2018	Wireless coverage	Multi UAVs	H	M	×
Joo & Choi [54]	2018	Data relaying	Multi UAVs	H	M	×
Zhang <i>et al.</i> [55]	2019	Data collection and relaying	Multi UAVs	H	H	×
Google loonsite	2019	Wireless coverage	Multi-UAVs	H	H	×

Notations-✓: considered, ×: not-considered, -: No information provided, L: Low, M: Medium, H: High.

relay structure, was utilized where communication between base station to UAV was performed under a random access scheme and UAV to satellite with either a coordinated or uncoordinated access scheme. The model for IoD, [55] used one UAV as a data collector, and another UAV for data relaying services in a network. For data transmission, was carried out by cellular tower or UAV on the basis of SNR threshold value. It helped to minimize the competition time, and to remove the congestion and collision problem. The comparative review on the applicability of UAVs is described in Table 2.1.

2.1 MAC Layer for UAV Networks

The MAC layer protocols are responsible for the provisioning of fair and efficient allotment of available bandwidth. This also assists in the collision avoidance and congestion control in UAVs networks. The detail of the UAV's MAC protocols and their functionality reviewed as follows and summarized in Table no 2.2.

Gu *et al.* [56] a **Centralized Intelligent Channel Assigned MAC protocol** (C-ICAMA) for UAVs. The C-ICAMA is the first contention based on channel reservation protocol designed for UAVs. This protocol utilizes the phased array antennas technology to penetrate multiple beams on the ground in the typical cellular patterns. Single channel is utilized to transmit and receive information from/to UAVs or UAVs to ground base station. The protocol allows the nodes to contend with getting access of the channel. The node who successful to make a reservation will join the polling queue and wait for his turn to poll ground base station nodes. According to the scheduling algorithm, the communication channel is divided into time slots which are equal to the transmission time of a data packet. To regulate the bandwidth ratio, these time slots are sub-divided into frames. Where frames consist of downlink data and up-link data sub frames, the data transmitted from ground to UAV or vice-versa is stored in the two links. The reservation packets receive by UAVs from ground station are stored in up-link queue, whereas the pack-

Table 2.2: A comparison of various MAC protocols on the basis of different problems with high applicability to UAV scenarios.

Protocols	Year	Antenna	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
C-ICAMA [56]	2000	-	-	-	-	-	-	-	✓	×	✓	-	-	✓	✓	✓	×	✓	×
AMUAV [57]	2010	Omni & Dir	×	×	✓	×	×	GPS/IMU	×	✓	✓	✓	-	-	-	×	×	×	×
Cai. <i>et al.</i> [58]	2012	Full-Duplex Radios	-	-	-	-	-	-	✓	✓	✓	-	-	×	×	×	×	×	×
Token-Based [59]	2013	-	-	-	-	-	-	-	✓	×	✓	-	-	✓	✓	✓	×	✓	✓
LODMAC [60]	2015	Dir.	✓	-	✓	-	✓	GPS, Location Vector	✓	✓	×	×	×	×	-	-	✓	✓	✓
CF-MAC [61]	2016	Omni	-	-	-	-	-	Sensing	✓	×	✓	-	-	×	×	×	×	×	×
CT-MAC [62]	2016	-	-	-	-	-	-	GPS	✓	✓	✓	×	×	✓	✓	×	×	×	-
DFRA [63]	2017	-	-	-	-	-	-	Sensing	✓	×	✓	×	×	×	✓	✓	×	✓	×
PPMAC [64]	2018	Dir	✓	×	✓	×	✓	GPS	✓	×	×	-	-	×	-	✓	×	✓	×
LDNMAC [65]	2018	Omni	-	-	-	-	-	-	-	✓	✓	-	-	×	×	×	✓	×	×
FM-MAC [66]	2018	Dir.	×	-	×	×	×	Location Vector	-	✓	✓	-	✓	×	×	×	×	×	×
IoD-MAC [67]	2019	-	-	-	-	-	-	Deep Learning Mechanism.	×	✓	✓	×	✓	×	×	✓	×	✓	✓
Cognor-MAC [68]	2019	Omni	-	-	-	-	-	Scanning phase	-	✓	✓	-	-	×	×	×	×	×	✓
Time Mirroring [69]	2019	-	-	-	-	-	-	Search phase	-	×	×	-	-	-	-	✓	×	×	×

Note- 1: Deafness-unheard of RTS/CTS, 2: Deafness- beam blockage, 3: Hidden Terminal- Unheard RTS/CTS, 4: Hidden Terminal- Asy Gain, 5 : Head of Line, 6: Neighbor Discovery, 7: MAC Capture Layer, 8: Throughput, 9: End to End delay, 10: Bit error rate, 11: Energy, 12: Scalability, 13: Reliability, 14: Jitter, 15: Latency, 16: Fault tolerance, 17: Fairness Index.

ets generated from the UAVs are stored in down-link queue. Where, size of these queues represents the traffic load on the channel, it helps the scheduling algorithm to adjust queue size according to bandwidth availability. The main aim of this C-ICAMA protocol is to maintain bandwidth ratio between up and down link in the heterogeneous multi-UAVs systems.

Alshbatat and Dong [57] have proposed in their research work **Adaptive Medium access control protocol for Unmanned Aerial Vehicle (AMUAV)**. In this protocol, each and every UAV is equipped with two adaptive (primary and secondary) and two omni directional antennas. The utilization of these directional antennas helps to extend the communication range of a UAV, lower the end-to-end delay, and increase throughput. On the other side, the omnidirectional antennas cater to the initial handshaking and share the current location and orientation of the UAV. The primary and secondary adaptive antennas are distinguished on the bases of their placement on a UAV. The antenna which is located on the top side of UAV is termed as primary, and the antenna which is lied at the bottom in UAV is termed as secondary. Moreover, for providing the exact location of UAVs in the vicinity, all UAVs are equipped with two location estimators, i.e. GPS and IMU. Moreover, a new kind of heartbeat message is proposed in AMUAV. This message will only be broadcasted when there is no activity for the time period of 1 second. The heartbeat message contains the location, orientation details of the sender UAV. On the receiver side, when a heartbeat message is received by a UAV, it is to reply back with same heartbeat parameters. After the successful completion of the handshaking process between two UAVs, the UAVs will update their target information tables. Subsequently, AMUAV examines the distance between the two UAVs. If the UAVs are within the approach of omnidirectional limit, data will transmit using the omnidirectional antenna. Otherwise, adaptive antenna is utilized to transfer data. For this, AMUAV inspects the altitude of the receiver UAV. Accordingly, it decides which directional antenna i.e primary or secondary is to be utilized for transmission. Once the data packet is received by receiver UAV, it updates its target table and

sends ACK using omnidirectional antenna along with UAV parameters. For error-free transmission, the antennas are beamformed on the base of destination location as well as the source.

Another token based MAC scheme is proposed by Y. Cai *et al.* [58]. This MAC scheme is specifically designed for UAV ad hoc network with full duplex radio and Multiple Packet Reception (MPR) capabilities. The working of scheme is designed to overcome the higher packet loss ratio and interference due to the utilization of half duplex antennas in UAV networks. The main objectives of this scheme are (a) to maximize the system throughput, (b) minimize the delay. It consists of two channels, i.e. common and data channel. The common channel is used for token passing, where the data channel is utilized for data transmission. The node which has information to share, it will hold a token to fetch the code out of token and pass immediately to the next neighbor node. Even holding of token for a longer time in such a highly mobile network leads to the latency. The code list, the channel gain list, and delay requirement list all are encapsulated in the token fields. The code list contains the codes to fetch the data frames from the nodes where the information about the channel gain is provided in the channel gain list. The delay list consists of the average waiting time that a transmitter has been waiting for its turn. The channel state information (CSI) and the delay requirements are the main two parameters on which every node re-lie for data transmission, that information can be taken from token passing. However, each node that has a data packet to transmit has to decide first where to send data based on these parameters. It is assumed that with the help of token passing, the CSI and delay information is with each and every node who participated in token passing. This enables nodes to make a selection to whom they can transfer the data with minimum delay.

J. Li *et al.* [59] proposed in his study a **token based MAC** scheme which utilizes the CDMA method for UAV ad hoc network. As per the author, this scheme help to identify the new and lost neighbors of a UAV in its vicinity. For data transmission, each UAV is fitted out with half duplex antennas with the same communication

range. One antenna is utilized for data transmission where other antenna is dedicated for token passing. In this scheme, each UAV has to maintain two buffers (a) a code list (CL) (b) the neighbor list (NL). The code list of a UAV contains the code which is assigned to the UAVs for data transmission. On the other hand, the neighbour list contains UAVs identification and address information. The CL and NL help to decide to which node the token should be passed. The UAV which is on the top of NL will be selected as the destination to which the UAV will transmit the token first. For interference free delivery, the source UAV maintains a timer which is used to determine that token send by the source UAV is received successfully, before initiating another transmission. The value of the timer is higher than the twice of one side transmission time plus the processing time is taken by receiver UAV in one hop network. In case of busy channel, it is assumed that the UAV will overhear the transmissions of other UAVs. On the other hand, in case of clash of the token message at the receiver end, this scheme will wait and rebroadcast the token. This scheme helps to identify the lost and new neighbors and can be admitted as a novel technique for information to be given using the token scheme.

Temel and Bekmezci [60] proposed in their research work a **Location Oriented Directional MAC protocol (LODMAC)** for UAV networks. Each UAV is equipped with two switched beam directional antennas. The first antenna is utilized to transmit control packets and location estimations, which is also known as the probing phase. The Second antenna performs the data transmission; this is known as the data transmission phase. In addition, to get updates of neighbours location LODMAC protocol uses GPS signals. To initiate the communication, the sender node (UAV) broadcasts its location using location vector (LV). LODMAC, utilizes all sectors of a switched beam antenna to transmit LV packet over one hop transmission following round robin algorithm procedure. After receiving LV packet, the nodes update their directional neighbour database (DND), with current antenna orientation and ID of communication. After successful location estimation, the exchange of control packets is conducting using the first antenna. Contrarily, for data

transmission LODMAC utilizes the second transceiver. Before a node starts data transmission, the location information of the receiver node is captured from the DND table. Using this information, the antenna beamformed toward the receiver. After finding a receiver node in idle state, source UAV sends DRTS packet to a destination UAV. On accepting RTS packet receiver node wait for SIFS time and response back with DCTS packet. Subsequently, when source UAV obtains the DCTS for receiver node, it begins the data transmission utilizing the second transmitter. A new Busy To Send (BTS) control packet is introduced along with traditional RTS and CTS packets to encounter the deafness and HoL problem. The BTS packet is used to alert the requesting node about the ongoing transmission between two UAVs.

In [61] Jiang and Mi have proposed in their study a hybrid CSMA/TDMA based collision free MAC protocol for the UAVs ad hoc networks. The author proposed a protocol using the half duplex radio without MRC, to eliminate the directional antenna problems the author uses region marking scheme using omni-directional antennas. For collision avoidance, CF-MAC divides the region into one hop and two hop neighbor. In order to provide contention free access to nodes, the time is divided into slots, which is further subdivided into the frames, when a node tries to access the channel it first chooses the free slot by checking the frame information of a node. In the case of collision, the CSMA method with random backoff time is used to solve it. The region marking scheme helps to improve the performance and avoid collisions but the use of omni directional antennas with half duplex functionality even without MRC leads to poor throughput and communication range limitations.

Another MAC protocol for UAV ad hoc network is proposed by Wang and Dong [62]. The CT-MAC protocol is designed to help the switching of MAC protocol between CSMA and TDMA according to their position of UAVs in reconnaissance missions. The aim of designing such a protocol is to verify an adaptive framework for UAV ad hoc network to consider whether it can switch MAC protocols mutually or not. Moreover, for selection of appropriate MAC protocols to work under various network condition, an adaptive MAC layer is attached to the present MAC

layer. For efficient switching CT-MAC rely on the GPS location of respective UAV. Moreover to avoid collision and blockage TDMA assign slots to each node and every node can only allow transmitting data in that slot. For clock signal synchronizing GPS signal is used, so all nodes have the same timing accuracy. However, this can be admitted as exciting work, but switching between CSMA and TDMA on the bases of GPS is not an appropriate solution. As the delay in GPS signal affects the working of UAV in reconnaissance missions, even it may lead to failure of the whole mission.

In [63] Wang *et al.* in his study proposed a Demodulation-free Random Access (DFRA) scheme for UAVs network. To help the UAVs to join in the UAV network without demodulating the attribute field of MAC protocol header. Moreover, the authors propose an adaptive feature extraction algorithm, which helps to find the MAC protocol identification utilizing machine learning. To evaluate the proposed scheme DFRA, authors also implement testbed USRP N210. The results show that the proposed scheme can guarantee access accuracy over traditional methods.

Zheng *et al.* [64] in his study has designed a MAC layer protocol **Position-Prediction-based Directional MAC protocol (PPMAC)** for UAVs by utilizing directional antennas. PPMAC works in three phases, 1) position prediction, 2) communication control and 3) data transmission. Firstly, it shares the GPS coordinates vector to its surrounding UAVs, which includes its current location, transmission status, and route information. Moreover, to deal with HoL and network overheads, the transmission of nodes are restricted to one hop only. Secondly, for reliable communication and to avoid deafness problems due to unheard control packages, PPMAC employs RTS, CTS and WTS control packets. Similarly, to enhance the network capacity, the position and control packets are shared using transceiver named as TS1, while data communication place over separate transceiver TS2. For data transfer, this protocol retrieves location coordinates from TS1. After that, it points its TS2 in the direction of the receiver. Similarly, after finishing the hand-shaking process, the receiver points its directional antennas towards the sender for

transfer of data.

Chen *et al.* [65] has in his study designed a **propagation Delay-Aware MAC scheme for Long Distance UAVs (LDMAC)**. LDMAC is based on the combination of random access and collision-free time slot allocation for UAVs. This scheme is based on Irregular Repetition Slotted Aloha (IRSA), which motivates the authors to consider the propagation delays in UAVs. For further improvement of the scheme, they have utilized the skilfully adopted scheme of LTE and GSM network, i.e. timing advance mechanism. Additionally, a time slot allocation scheme is also presented for UAVs. A collision of a data frame at either end can lead to propagation delay. To counter this, each frame is subdivided into equal sized time slots so that the forwarding of packets can be restricted to one at a time slot only. Furthermore, a greedy approach is also proposed which works on the omitting of frame index to get maximum throughput from the scheme.

Choudhary *et al.* [67] designed a MAC protocol considering the security of UAV trajectory and channel accessibility. Moreover, the authors have designed a deep neural network model which provides updated information of any wrong maneuvers. The conditions of Macaulay duration helps to generate the timing slot for the designed protocol. To make the secure and non overlapping trajectories, the MAC output verify at every procedure matching step, afterwards feedback model checks and reverify the correctness of the UAV's configuration. Such measures help to protect the UAVs from an attacker. When an attacker tries to modify the hardware configuration of a UAV, the suitable waypoints will be found by the deep learning module. By this method, the authors believe that they can provide security to UAVs from the attacks. Eventually, which results in public safety and more secure SAR applications.

Wu *et al.* [66] proposed a multi-channel MAC protocol with a directional antenna for UAVs (FM-MAC). The authors believed that the combination of the multi-channel scheme with a directional antenna can have a significant impact on the improvement of QoS parameters. In this, each and every node hold an idle slot

and using TDMA, mechanism they have to broadcast the security packets on the network. Meanwhile, all one hop neighbour nodes will ping with their locations, position and velocities. In this scheme, for data transmission, the data streams are divided into high priority and low priority category. FM-MAC provides a higher data rate to the higher priority category. For this, the proposed scheme utilized the directional antennas. The proposed scheme performs very well in terms of PDR for service packets and low end to end delay.

Feng *et al.* [68] proposed **cognitive multi-channel opportunistic reservation MAC** for multi-UAVs. The proposed scheme is divided into two types of users, i.e primary and secondary. The secondary user is equipped with channel sensing transceivers. This can help to identify the primary user activities on all available channels. Even in the proposed scheme, all idle channels that are not currently used by the primary user can be utilized by the secondary users as transmission channels, which is known as channel pool. Meanwhile, the channel identifier is assigned to the channels for unique identification. This scheme executes under six type of control frames such as- Prepare To Send (PTS), Prepare To Receive (PTR), beacon B1, beacon B2, ACK, and CX. PTS and PTR contain the information regarding channel identifier, transmitter, and receiver MAC address. Beacon B1 and B2 are the subtypes of unicast and broadcast transmission in a neighbour about on-going communication. The utilization of proposed scheme helps to reduce the signal collision and waiting time for users.

Baek & Lim [69] proposed a **time-mirroring CSMA/CA(TM-CSMA/CA)** for the UAV-relay network systems. The proposed scheme states that communication and data transfer between UAV and BS (in LOS) is always guaranteed without any bit error. Moreover, NLoS UAVs cannot communicate with UAVs or BS while their position is stationary. Firstly, the UAV-relay network system utilizes only physical layer information to avoid unnecessary relay without the support of the MAC layer. Secondly, TM-CSMA/CA gives assurance of UAV relay repeatedly that wins the contention utilizing the MAC layer. The numerical results show that the pro-

posed scheme can provide better results in terms of higher saturation throughput and lower end-to-end delay than conventional CSMA/CA.

2.2 Software Defined Networks with UAVs

In recent years, various existing proposals have utilized SDN as an alternative to conventional networks in multi-UAV systems. There are numerous benefits of utilizing SDN with UAVs such as- decoupling of control plane and data plane, centralized management, network virtualization, and improving resource utilization. All these benefits induce authors to discover the utilization of SDN with UAVs. In this regard, Iqbal *et al.* [70] designed a SDN-based prototype system for aerial networks to predict and optimize the aerial node orbits path selection. The major findings of the proposed scheme is to provide an optimal selection of the network and radio link to these flying robots. Moreover, such finding and optimization of route prediction and network selection methods result in better results from the traditional routing approach. For this, authors have divided the functionality of the whole process in the three major parts, i.e. aerial systems, controllers, and control application. The aerial system contains all related information such as UAV position, orientation, antennas direction, which help in the working of network control. Similarly, the controller consists of two sub controllers, SDN controller and radio controller. These controllers are also worked as a backup controller to sustain the network in case of the failure of a controller. The application control is having an aerial control of applications and SDN control applications. These applications provide the initial step in the prediction of the route to the controller. Accordingly, the controller provides the best optimal path to UAV. This will also help to reduce the end to end network delay and control packet exchange between controller and UAV.

In similar direction, Rahman *et al.* [71] has explored the benefits of SDN based UAV deployment in emergency scenarios as ABS. Authors, proposed the optimal placement of the SDN controller in UAVs network to reduce the end to end delay in

exchange of control packages, transfer between the UAVs and the controller. As per the scheme, the controller should be placed at the center of a network to minimize the multi-hop communication. In this approach of Rahman the nearby UAVs can send or communicate directly to the controller by sending their control packets directly to the controller. On the other side, the farthest UAVs can relay their packets to other UAVs nearer to the controller. The details of all UAVs in the vicinity will be stored with the controller; the position of UAVs also gets acknowledged using GPS signals. The controller helps to compute the shortest and optimal path based on these criteria after which the forwarding rules will be installed on the UAVs. Even this scheme provides updated information to UAVs about topology changes in the network.

In another work by Yuan *et al.* [72], it is proposed a mobile sensor network scheme for the micro UAVs using SDN. The proposed scheme aims to improve the data transfer between the data plane and micro UAVs. It also supports the advanced routing policies with dynamic topology change. Moreover, to provide reliable communication and management, this scheme utilizes two SDN controllers. The swarm SDN controller controls the routing policies by maintaining the global routing table. On the other side, the SDN MAV manages the communication between UAVs and UAV to SDN controller using Wi-Fi and LTE links. The proposed scheme helps to improve the data transfer but does not consider energy consumption. Similarly, Qi *et al.* [73] have proposed a clustering technique based on the SDN cluster controller and collaborative controller. The main finding of the technique is the implementation of a centralized traffic-differentiated routing in each cluster. The aim of this routing is to maintain the traffic, moreover to check on delay sensitive and reliability require services. Even to help the traffic-differentiated routing the authors introduce prediction model.

Based on a similar trend, Ramaprasath *et al.* [74] has authors proposed a UAV to UAV communication scheme using the SDN controller. In this scheme, an SDN controller acts as a central repository where all the processing and storage takes

place in order to improve network resource utilization, throughput, and delay. However, to maintain the stability of a network, the priority of packets is controlled as per different priority levels. The priority is sub divided into four categories viz:-, priority and non priority control packets, and priority and non priority data packets. To segregate control and data packets, the controller is used as a central hub. Moreover, it is also used to calculate the routes and scan all network nodes. The free route is utilized to transfer the non priority control and data packets. The authors believe that this will increase network traffic throughput.

In another work, Barritt *et al.* [75] has proposed an application based SDN for UAV networks are known as Temporospatial SDN (TS-SDN). For this, the authors have built SDN operating system at Google for topology management, radio resource management, and scheduled operations. The major findings and functionality of TS-SDN is to predict the future state of the lower level networks by utilizing the physical positions and trajectory of UAVs knowledge available with the SDN controller. The position awareness of these flying vehicles help to avoid interruption avoidance. Additionally, TS-SDN ensures that the network supports the traffic with its full capacity and have the capability to convey the traffic between eNodeB and eNodeBs.

Moving ahead, in another case of White *et al.* [76], authors have proposed an SDN and Network Function Virtualization (NFV) based architecture for UAV systems. They have utilized SDN and NFV for the monitoring of network services and anomaly detection. The proposed architecture helps to migrate faster information and maintain continuity in high mobility environment such as moving vehicles (opposite direction), and ships. For this, the author has applied the middlebox approach at GCS to use it as UAV VNF server, at which they can implement routing at Open vSwitch. According to which all connected nodes route their information to GCS and vice-versa.

Zacarias *et al.* [77] has exploited the benefits of SDN in video streaming application for military surveillance using UAVs. The surveillance of an area required

higher bandwidth data transfer between the host and destination. Moreover, when it is linked with the national security issue, then security, and relay of data pose new requirements on traditional methods. To address these issues the authors have proposed a self-guiding method based on SDN to maintain QoS. The OpenFlow architecture in the proposed scheme provides the global view of the network with information about congestion and deteriorated links. Further, the proposed scheme is tested on three metrics 1) Video playback start time, 2) Number of interruptions, 3) Total no. of interruption at user end.

The authors in [78] have proposed an architecture that collaborates with the UAVs and WSNs using IoT model. In this architecture, the control plane consists of the UAV controller to control the UAVs and WSN controller to control the wireless sensor nodes at the data plane. Moreover, to take benefits of the cloud services, the upper layer of the architecture is integrated with the cloud. These strategies help the authors to present better results in the irrigation scenario. The WSN used to check the land humidity level, on the other side, the UAVs are utilized for irrigation. Additionally, the control plane can take advantage of residing in the cloud or massive data servers, such as- Cloud services, Ubiquity, Mobility, and elasticity. Similarly, Kirichek *et al.* [79] has proposed a routing control function based on the SDN for WSNs using UAVs. In this proposed function, a flying controller is placed at the centre of the network. This controller controls, and manages the traffic, localisation of its nodes, and provides a route to forwarding UAVs. The forwarding UAVs or flying switches perform the function of the data plane. They forward all the data to the WSN. In such a way, a self organising routing function is presented by the author.

Zhang *et al.* [80] have designed a monitoring framework in SDN for UAVs networks. The monitoring system will help to manage the UAVs network and provide network statistics to the succeeding layers. The author also presents a load balancing algorithm which utilizes the network statistic to analyze the results. The analysed results further, validate the traffic balancing in the designed approach. In

addition, the author considers battery power consideration.

Secinti *et al.* [81] have proposed in his work an aerial network management protocol for the UAVs network on the head of SDN architecture. According to this, UAVs will act as forwarding devices on the guidance of the central controller. The controller utilizes 3D spatial coverage to perform localization, so the location unawareness among UAVs do not hinder the operations and network performance. The controller updates all connected UAVs about the directive from time to time through flow entries in OF v1.5 protocol. This helps the UAVs to switch between best path available.

In another work [82], the authors have utilized the SDN based architecture for fast handovers and efficient management in UAVs. The authors have proposed this scheme to handle the traffic shifting policies and network management using two centralized approaches and distributed controller approach. In this, the UAVs and AP will act as forwarding devices at the data plane. On comparison with LTE handover, the results in the papers show significant improvement by using SDN based handover scenario for UAVs.

The comparative description of above mentioned SDN based network model for UAVs is provided in Table 2.3.

2.3 Data Offloading in UAV Ecosystem

The capability of UAVs to act as an aerial base station and the ability to serve mobile users with on-demand data services make UAVs a promising solution for offload data from BS to ABS. The deployment of these ABS, also makes it easier for reconfiguration, better traffic rate, and short-range LoS communication which decreases the end to end delay. Even the utilization of UAVs will also help to reduce the channel congestion in overloaded BS.

Bor-Yaliniz *et al.* [83] have in his study presented a drone cell placement model. The model aims to cover the maximum number of users to increase the revenue

of the service provider. Even, the proposed model also helps to find the where-to-deploy location with the size of a minimum coverage region. Moreover, the altitude of the UAVs can also be adjusted as per the requirement of users. To perform all these events effectively the authors have provided solutions of the quadratically-constrained mixed integer non-linear optimization problem used for optimal placement of drones. Similarly, to serve the wireless connectivity of UE, Lyu *et al.* [84] proposed a UAVs mounted mobile base station. The major finding of the proposed technique is the deployment of a minimum number of UAVs based mobile base station for serving the UE. For this, the authors design a polynomial-time algorithm for the optimal placement of the mobile base stations. The placement of these mobile base station follows the spiral path coverage, to cover all the uncovered UEs. In a similar direction, in [85], proposed a model for UAVs deployment as a wireless BS. For efficient connectivity and coverage, the downlink coverage probability of UAVs is found based on the altitude and antenna gain. Moreover, the circle packing theory based location prediction of UAVs is performed to increase the coverage area of UAVs cells and to maximize the network lifetime of the users. It also helps to determine the minimum number of UAVs required for target coverage probability in a specific region.

In another work, Cheng *et al.* [86], has utilized the convex optimization technique for the UAV trajectory optimization. To provide effective data offloading the proposed scheme considers the three adjacent cells in a network. The best cell with the least interference is chosen to serve the end users by maximizing the sum rate. Rohde and Wietfeld [87] have in their study proposed the utilization of UAVs as temporarily offload traffic data agents from nearby overloaded LTE/4G networks. The proposed technique uses the femtocell technology caters to the decode-and-forward relaying utilizes user devices as the backhaul. For optimal data offloading, the authors positioned the UAVs at the centre of the connecting device and the overloaded cell. This significantly helps to reduce the system and signal loss of an overloaded cell. Moreover, it also reduces the free resource block ratio. In similar

Table 2.3: Comparison of existing proposals for UAVs based on SDN

Proposal	Focus	Description
Iqbal <i>et al.</i> [70]	Path selection	SDN-based prototype system for aerial networks to predict and optimize the aerial node orbits path selection
Rahman <i>et al.</i> [71]	UAV deployment	The optimal placement of SDN controller in UAVs network to reduce the end to end delay
Yuan <i>et al.</i> [72]	Data transmission	To improve the data transfer between the data plane and micro UAVs by utilizing wifi and LTE links on two different controllers
Ramaprasath <i>et al.</i> [74]	UAV-to-UAV communication	Control and data packets are segregated on the basis on priority for resource utilization
Barritt <i>et al.</i> [75]	Proactive packet routing	TS-SDN predicts the future state of the lower level networks by utilizing the physical positions and trajectory of UAVs knowledge available with SDN controller.
White <i>et al.</i> [76]	Anomaly detection	SDN and NFV based model used for the monitoring of network services and anomaly detection at GCS.
Zacarias <i>et al.</i> [77]	Video streaming	SDN connected UAVs acts as data provider to ensure the security and maintain QoS for video streaming service in military networks
Mahmoud <i>et al.</i> [78]	Network softwarization	Authors collaborates the UAVs and WSNs in Cloud based SDN architecture.
Kirichek <i>et al.</i> [79]	Routing control function	Flying controller introduce to control the management of traffic and route data.
Qi <i>et al.</i> [73]	Clustering technique	The implementation of a centralized traffic-differentiated routing in each cluster to maintain the traffic, moreover to check on delay sensitive and reliability requite services
Zhang <i>et al.</i> [80]	Load Balancing	Monitoring system with load balancing technique is designed in SDN
Secinti <i>et al.</i> [81]	Aerial network management protocol	The controller utilizes 3D spatial coverage to perform localization and provide UAVs with best shortest paths
Sharma <i>et al.</i> [82]	Fast Handover	SDN based centralized and decentralized approach present for fast and efficient handover in SDNs

work, [88], proposed the hybrid network architecture to offload the data from GBS. In this technique, the UAVs fly around the cell edge in a circular way, to offload data from the overloaded GBS. The authors also utilize the orthogonal spectrum between UAVs and GBS and the reuse of spectrum for bandwidth, requirement helps to provide throughput gains. Similarly, Lyu *et al.* [89] have proposed another technique to offload the data from the cell-edge mobile terminals. This scheme is the extension of the previous scheme. On similar trends, the authors have utilized the circular trajectory for data offloading.

As the UAVs have limited energy and computation power, some of the authors proposed the offloading of these computation powers to energy sufficient UAVs or to the cloud based solutions. In this direction, the authors in [90] utilized the theoretical game strategy, to decide the offloading computation tasks for UAVs. In this game strategy all UAVs act as a player, where possible strategies in case, UAVs can compute the tasks itself than no offloading is required. If it is unable to handle to compute the load which can be offloaded either using the cellular network to a server or the tasks can be offloaded to BS via wireless local network. The introduction of such offloading techniques assists to meet the challenges of energy consumption in UAVs network. In a similar direction, in [91], the authors have proposed two offloading algorithms for the UAVs. These algorithms help in determining the location and offload suitable algorithm when required. The first algorithm is utilized to offload the UAVs computational tasks to another UAV in the vicinity having efficient computing and energy resources. Another algorithm manages the ground offloading, which comes in execution after the failure of the first algorithm. It is constructed on the multi-level MEC system. It enables the offloading of tasks to the cloud servers connected to the GBSs. These algorithms are selected on the basis of energy and latency constraints. Zhao *et al.* [92] has proposed a framework of caching UAV-enabling SCN. This framework helps to offload the data from the overloaded small cell BSs. For, faster and congestion free transfer of data, the most common data is saved in the local cache of the UAVs which are free to use when it

is required. This will enhance the QoE and also reduces the energy computation of UAVs. In the framework, the authors have also discussed the distributed caching strategy of UAVs. Moreover, it also leverages the energy constraints to some extent. The comparative description of above mentioned data offloading techniques for UAVs is provided in Table 2.4.

Table 2.4: Comparison of existing proposals for data offloading in UAVs

Proposal	Focus	Description
Cheng <i>et al.</i> [86]	UAV trajectory	Best trajectory is selected on the basis on minimum interference in adjacent three cells.
Lyu <i>et al.</i> [84]	3D placement	Optimal placement of UAVs mobile base station to cover all UE by following spiral path coverage algorithm.
Bor-Yaliniz <i>et al.</i> [83]	3D placement	The better coverage means better revenue for service provide. For this, solution of quadratically-constrained mixed integer non-linear optimization is provided by author for placement of UAVs.
Mozaffari <i>et al.</i> [85]	3D Deployment	Maximize the downlink coverage by optimizing the UAV deployment.
Rohde and Wietfeld [87]	Data offload	To increase the operation range of tower and simultaneously to reduce the overload
Lyu <i>et al.</i> [88]	Data offloading	UAVs flies in the circular trajectory to offload the data from BS
Lyu <i>et al.</i> [89]	Data offloading	UAVs flies in the circular trajectory to offload the data from cellular hotspot
Zhao <i>et al.</i> [92]	Data offloading	Caching enabled UAVs are utilized to serve UE for performance improvement in SCNs.
Ateya <i>et al.</i> [91]	Energy aware offloading	Air-offloading and ground-offloading two algorithm work to offload computation load for UAV to near by full charged UAVs.
Messous <i>et al.</i> [90]	Game theory based offloading	Game theory approach utilized to offload data either via cellular data or via wireless local network.

2.4 Energy-Efficiency in UAV Ecosystem

To accomplish a mission, the long battery life in UAVs plays a crucial role. Due to the lightweight and size constraints in UAVs limits them not to carry large, and heavy batteries. It also restricts the coverage range capability and endurance. In some kinds of literatures, authors have proposed the energy-efficient and wireless transfer methods to provide time to time energy for battery charging. It will increase the overall time span of the UAV applications. The following literature highlights the various proposed schemes/framework proposed for UAVs charging is also depicted in Table 2.5.

Simic *et al.* [93] in his study considered a wireless energy transfer scheme for wireless charging in UAVs. This model is developed for UAVs who are involved in the inspection of power transmission lines and towers. The UAVs are equipped with wireless energy transfer receivers. These receivers get activated when coming closer to the high voltage power transmission lines. In a similar direction, Campi *et al.* [94] have designed an automatic wireless charging system for batteries of small UAVs. This WPT system is based on the magnetic resonant coupling system. To charge a UAVs wirelessly it is equipped with WPT receiving circular coil and the charging coil is placed on the ground having a connection with electronic feeder. On the same trend, [95] proposed the wireless charging pad for energy transfer in UAVs. To make this scheme different and better from other conventional schemes, the authors have utilized GPS and on board available camera for a perfect landing on charging pad. This scheme helps to charge the UAVs via WPT, but landing and take-off of these aerial vehicles during the alive operation leads to various delays. In other work [96] presents an asymmetric coupled WPT system for wireless charging in UAVs. The new structure and parameters of these charging coils are designed to improve the QoE.

To meet the need of wireless charging of UAVs, Long *et al.* [97] proposed a WPT based opportunity charging for UAVs. This proposed concept is already im-

Table 2.5: Comparison of existing proposals for energy replenishment in UAVs

Proposal	Focus		Description
Simic <i>et al.</i> [93]	Wireless transfer	energy	UAVs inspecting the power transmission lines get wireless charging from the power lines through wireless receivers equipped in UAVs
Campi <i>et al.</i> [94]	Wireless transfer	power	A charging receiver is placed on the UAV, and transmitting coil is placed on the ground for wireless power transfer
Junaid <i>et al.</i> [95]	Wireless transfer	power	A charging pad for wireless power transfer is build for UAVs.
Long <i>et al.</i> [97]	Wireless transfer	power	Renewable energy is used to top-up UAVs batteries.
Jashnani <i>et al.</i> [98]	Solar energy		Solar energy is utilized to charge the UAVs.
Mortan <i>et al.</i> [99]	Solar energy		Solar power UAV is designed by implementing PV panel on UAV.
Kate J Duncan [100]	Laser guided energy	en-	Narrow and concentrated laser beam used to charge UAVs battery.
Chen <i>et al.</i> [101]	Laser beam guided		To acquire, pointing and tracking of laser beam technology for UAVs power transfer.

plemented in EVs for range extension. In this UAVs comprises of the receiving and transmitting coils. However, the energy which is used to top-up wireless energy in UAVs is harvested from renewable sources. The solar energy is the best source of renewable energy. The charging scheme by utilizing PV arrays on UAVs also presents a robust solution for energy replenishment. In [98] proposed two models to utilize the solar power for charging batteries of UAVs. The first model works at low altitude(2.5KM), and the second model works above the mentioned altitude. The authors have also provided the details of the minimum area required for this energy generation. Similarly, Mortan *et al.* [99] has also presented a prototype in his study of solar powered UAV. They developed a small scale solar powered UAVs. It got the energy from solar radiation and could work only due to insufficient sunlight. This prototype was tested for low altitude UAV's sensing applications. In another work Kate J Duncan [100] has presented a model to either charge or run the UAVs from

a distance by using a laser beam. The laser beam produces a straight, concentrated and narrow beam of light at a defined frequency and specific wavelength. This laser light is directed on special designed PV cells placed on UAVs. Further, the working of PV cells is the same as of solar PV cells and helps to recharge the batteries of UAVs. Similarly, [101] considered the laser beam based wireless charging for UAVs. The authors have provided the acquiring, pointing and tracking study for wireless power transfer to UAVs. Moreover, in order to control the system at the same, the fast scan mirrors control program is also executed.

2.5 Summary

The chapter 2 emphasize on the existing literature related to the UAVs network. The existing proposals have been studied independently and categorizes according to various parameters considering the different modules and functionality. Each and every category is explained for effective understanding of the problem. In last, the research gaps identified from the existing literature is also presented in the chapter, accompany with the objectives of the research work, this will laid the foundation for the design of proposed techniques.

Chapter 3

ELMAC for Quality of Service Enhancement in UAVs

3.1 Overview

In this Chapter the properties of the fire-fly optimization algorithm are utilized to form an efficient timing slot mechanism. It results in the creation of an energy-efficient and location-aware MAC for UAV networks. The term optimization is associated with finding an optimal solution of the objective function(s) where, objective functions, variables, and constraints are three major components of the well-formulated optimization problem. It helps to find an optimal solution during optimizing (minimize or maximize) the objective function subject to the constraints satisfaction. Such solutions generally utilized to solve analysis and design problems of communication, transport and manufacturing networks. The mathematical formulation of the optimization problem is defined below:

$$\begin{aligned} & \text{Minimize } p_0(x) \\ & \text{subject to } r_i(x) \leq b_i, i=1,2,\dots,m \\ & p_0 : Q^n \longrightarrow Q : \text{objective function} \\ & x = x_1, x_2, \dots, x_n : \text{design variable} \end{aligned}$$

$r_i(x) : Q^n \rightarrow Q : i=1,2,\dots,m$: inequality constraints.

3.1.1 Firefly Optimization

In this chapter, the properties of the firefly optimization algorithm are utilized to form EL-MAC in UAV networks. This helps to provide location awareness, congestion-free, collision-free and energy-efficient MAC for UAVs. In the firefly optimization, the fireflies produce and utilize the fluorescence flashes as communication signals to communicate with other fireflies. However, the two major considerations of this optimization are i) the variation in light intensity and ii) attractiveness among fireflies. As attractiveness in fireflies is proportional to the brightness of fireflies. So, in case of two flashing fireflies, the less bright firefly will attract towards the more brighter firefly, according to which, the brightness(light intensity) can be seen as objective function that is utilized to maximize the optimization problem. But in our proposed model, the fire-fly optimization algorithm is operated in reverse pattern as the actual algorithm works to increase the light intensity, but for the proposed model, the higher intensity may result in a collision, and by operating in reverse, the proposed approach efficiently accounts for collision-avoidance over the defined timing cycle.

To satisfy the maximum optimization problem, the light intensity (I) or brightness of a firefly at location x can be seen as $I(x) \propto p(x)$. Although the attractiveness \hat{A} is corresponding to other fireflies i.e. it varies with the distance between two fireflies (say k and l) and coefficient of light absorption. Where to determine the distance, attractiveness and movement of firefly k which is attracted towards more brighter firefly l is given as below:

$$z_{kl} = \|x_k - x_l\| = \sqrt{\sum_{m=1}^d (x_{k,m} - x_{l,m})^2}, \quad (3.1)$$

The distance between two fireflies k and l can be calculated using Cartesian or Euclidean formula. eq. (3.1), where $x_{k,m}$ is the m^{th} component of spatial coordinate

and d is the number of dimensions.

$$\dot{A} = \dot{A}e^{-lz_{kl}^b} \quad (3.2)$$

In eq. (3.2) the attractiveness function value is calculated, where $b \geq 1$.

$$x_k = x_k + \dot{A}e^{-lz_{kl}^2} (x_l - x_k) + \varepsilon \quad (3.3)$$

The movement of a firefly k towards l is given as eq. (3.3), the first value x_k is the current position of firefly k , l is the light absorption coefficient, z_{kl} is the distance and ε is the random movement of firefly if there is no brighter firefly.

3.1.2 MAC Layer for UAV Networks

A key feature of considering the MAC layer protocol for UAV networks is its capabilities of systematizing the sharing of the limited available medium. The MAC protocols come into action when a node is permitted to transmit its packets, so it doesn't cause a collision at the receiver side and consistently controls all access to the physical layer [16]. However, when a common physical channel in a network is utilized by all nodes, then MAC protocols play a decisive role to control and coordinate channel access among the different nodes so that information can be passed through one node to another [102]. As per the recent studies, the use of such conventional MAC protocols which are designed and implemented for mobile, and vehicle ad hoc networks are not found appropriate for UAVs networks [60]. The design of MAC protocol such as time-varying propagation characteristics, higher complexity, and distributed MAC constraints of UAVs network. The requirement of UAV networks such as location awareness and energy conservation pose significant challenges on MAC protocols.

In particular, MAC protocols extended to UAVs, are classified on the basis of their channel access methods, i.e. contention based (Random access) and contention-

free (reservation-based). In contention based methods, nodes compete with each other to win the access of shared medium for a specific duration of time. During this time, other nodes remain silent and continuously scan to find their turn to access the channel [16, 103]. The most often the MAC mechanism used to avoid a collision in contention based method is the CSMA/CA. On the contrary, contention-free methods, experience transmission delays and scalability issues because the nodes are allocated with the pre-decided schedule and do not compete to access the channel.

The Distributed Coordinated Function (DCF) in IEEE 802.11 [104] is a primary MAC mechanism which works on the CSMA/CA technique to access the channel. It gained consideration due to its simplicity. The data transmission in a wireless medium using CSMA is based on Physical Carrier Sensing (PCS) and Virtual Carrier Sensing (VCS). In CSMA, a node senses the shared channel before initiating transmission. As a result, the transmission is carried out only when the channel is found idle. However, the execution of CSMA in multi-hop network degrades the performance of a network due to the hidden terminal problem [103].

Keeping such a problem in mind, the protocol with collision avoidance is proposed with the Request To Send (RTS) and Clear To Send (CTS) handshake mechanisms [105]. When a sender wants to initiate data transmission, firstly it has to send RTS packet to the intended receiver. After receiving a successful RTS packet, the receiver responds with the CTS packet if the channel at the receiver side is idle for Short Interframe Spacing (SIFS) period. Both RTS and CTS frames both are encapsulated with the duration field used to set the Network Allocation Vector (NAV) values. The NAV preserves the forecast of future data traffic on the channel on the basis of duration field provided by RTS and CTS frames. All nodes within the reception range, update their NAV periodically.

The primary difference between DCF and CSMA is the use of a backoff/ rescheduling mechanism when confronted with a collision in the network or a busy channel. In the IEEE 802.11 DCF MAC protocol, each node performs both physical and virtual carrier sensing. If the channel is sensed idle and NAV is not set, then node defers

its transmission for the DCF Interframe Spacing (DIFS) period. However, if the channel is busy, then the node selects a random backoff interval from $[0, CW]$ and waits for a particular time before initiating the channel access. However, in the case of collision, the Binary Exponential Backoff (BEB) algorithm is used to retransmit packets. In this BEB algorithm, after every collision, the value of CW is doubled until it reaches the maximum contention window (CW_{max}), after which the packet is discarded.

The directional version of IEEE 802.11 was proposed by Choudhury *et al.* [106] under the name of “Basic DMAC”. This Basis DMAC protocol is considered as the benchmark for directional MAC protocols. With the use of MAC protocols for beamforming antennas, the problem of hidden and exposed terminals arises. A hidden terminal problem may lead to a collision, and the exposed terminal problem can introduce low throughput efficiency.

MAC protocols play a significant role in successful UAV-transmissions. Multiple UAVs can operate autonomously and collaboratively that can be used for defining a sustainable MAC, which can provide high reliability for maintaining control and command over transmissions. Table no 2.2 illustrates the comprehensive review of various MAC protocols for UAVs; it also describes the reservation and access methods used by MAC protocols for UAVs networks. The superiority of MAC protocols can be evaluated from Table no 2.2, in term of various problem handling capabilities. Although for ad hoc networks, there are several ways to classify the MAC protocols for directional antennas, for a different type of classification [17, 19, 102, 103]. Here, we classify the MAC protocols on the bases of the antennas used to nullify the interference during the ongoing transmission. As UAV network works under critical conditions, where human life may be the concern in that communication between UAV to any architecture should be able to restrict the interference from the surrounding. Moreover, multi-UAVs works collaboratively and autonomously, the interference at either source node or the receiver node leads to a failed interpretation of conversations. It is observed that the ability of adaptive array of antennas

to nullify the interference is much higher than that of the switched beam antennas. However, the energy constraints in UAVs hinder the performance of these antennas. Moreover, the utilization of these directional antennas requires time for switching of antenna direction according to the BS. The working of both directional antennas is provided below.

Generally, it is observed that MAC protocols for switched beam antennas are not as complicated as those of adaptive antennas, but due to directional reason, they have to counter with more complex issues than omni-directional antennas. In switched beam antenna, when a node has packets to transmit, it must first choose a beam from its various sector in the direction of the intended receiver. In case where the location of the receiver node or destination is unknown, the RTS packets may transmit on all beams (sectors) periodically. When nodes are ideal and have no packets to transmit at this time they scan the incoming signals on all the sectors and beamform one of its beams only when the direction of the signal is determined. This may limit the advantage gained from the switched beam antennas as the transmission range may be mitigated to Directional-Omnidirectional (Dir-Omni) or even Omnidirectional-Omnidirectional (Omni-Omni) range. The MAC protocol for ad hoc networks which are based on the use of switched beam antennas include Nasipuri's protocol [107], DMAC [108], CADMAC [109], DMAC-DACA [110], Tone DMAC [111], DBTMA/DA [112], CDMAC [113], and etc. MAC protocols for UAV ad hoc network that assume to use switched beam antennas are AMUAV [57] and LODMAC [60].

The Adaptive Array Antenna (AAA) in UAV ad hoc networks shows better capabilities than those of switched beam antennas due to the reduced interference and reduced multipath fading. The nulling capabilities of these are much higher than those of switched beam antennas. Firstly, to receive data from an unknown source the estimation technique such as Direction of Arrival (DoA) is used by AAA. Secondly, after calculating DoA, it beamforms its main lobe in the direction of the intended source to receive the data. Furthermore, during an ongoing trans-

mission, the main lobe of AAA is consistently focused on the intended source and receiver, which made it unaware of ongoing transmission in its neighbor. It results in severe problems: hidden terminal problem, deafness, HoL, which already described in the previous section. The MAC protocols use the adaptive array antennas are SCSMA [114], NULLHOC MAC [115], DVCS [116], SpotMAC [117], WACnet [118], Smart 802.11b [119], FFT-DMAC [120], DMAC-PCDR [121], DOA-MAC [122], LiSL/d [123].

It is observed that the exchange of DATA and ACK packets in all proposed MAC protocols are performed directionally to utilize the benefits of directional antennas. However, the transmission of RTS/CTS packets observes variations. Some protocols prefer omni directional transmission of RTS/CTS to avoid hidden terminal and deafness problems. On the contrary, to exploits extended transmission and spatial reuse various MAC protocols have used directional RTS/CTS transmission. Although, this handshaking scheme lends to various problems such as hidden terminal problems, deafness, and HoL problems. While some of the MAC protocols utilize the switched beam antenna to transmit the control packets circularly, one direction after the other. Although, this scheme helps in avoiding deafness and hidden terminal problem its large control overhead can degrade the performance. Some MAC protocols use tone instead of RTS/CTS packets. Tones are normally transmitted directionally using a dedicated control channel to avoid collision or interference with the current on-going transmission. It is also observed that to avoid deafness problem tones are transmitted omni directionally to aware all its neighbours about the start and end of a transmission. To Tackle the MAC challenges, another approach is used to perform synchronized access instead than random access methods. The synchronized access protocols require the synchronization of the nodes with the time slot, where time slots are further sub-divided into the frame and subframes. However, the transfer of control and data packet in subframes leads to the global synchronization problem in the multi-hop network.

3.2 System Model

The considered model comprises a set D of drones, which are used as on-demand nodes for supporting-transmission in the range of a network that cannot be covered through the traditional networks. The network with drones uses an omni-directional antenna with a view to support communication without much effect because of drone's drifts. However, as stated in existing works, height does affect the performance of the network. At first, the system model accounts for drones that are available to support the transmission between $|E|$ number of end users and the base station. This decision is based on the interference issue of the network and the link based energy consumption. For a network with a different altitude of drones, the Signal-to-Interference Noise Ratio ($SINR$) observed by each drone at j^{th} location is expressed as follows and depicted in Figure 3.1.

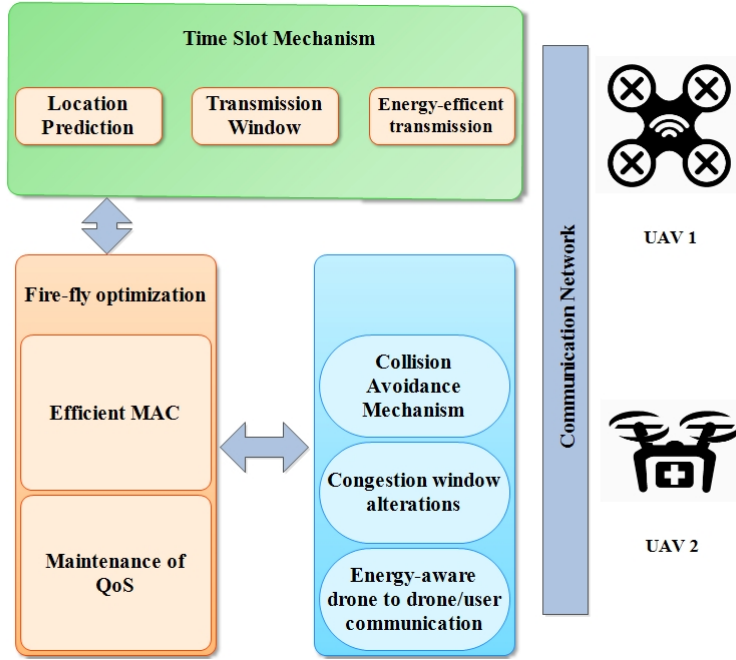


Figure 3.1: System model for the ELMAC

$$SINR = \frac{\mathcal{P}\mathcal{K}h^{-\varphi}}{\sum_{i=1, i \neq j}^{|D|} \mathcal{P}\mathcal{K}h^{-\varphi} + N_0}, \quad (3.4)$$

where \mathcal{P} is the transmission power, \mathcal{K} is the antenna characteristics, h is the height of drone, φ is the path loss, and N_0 is the noise power spectral density.

If $SINR_t^{(N)}$ is the signal to interference noise ratio for the required network then

$$\frac{1}{|D|} \sum_{|D|} SINR \geq SINR_t^{(N)}. \quad (3.5)$$

The above eq. (3.5) can be expressed in the form of a continuous model for the drones flying at same altitude and same configuration, such that $\frac{1}{|D|} \int_{|D|} SINR dt \geq SINR_t^{(N)}$.

The total connections in the network are given as $(\frac{|D|(|D|-1)}{2} + 1)$ and at a time t , these connections are given as $(\frac{|D'|_t(|D'|_t-1)}{2} + 1)$, where D' is the set of drones that obey the conditions in eq. (3.5).

If L' and L are the minimum and maximum links that are inactive in the network, respectively, the possibility of the network to sustain is expressed as eq. (3.6). Which means that the duration of links should be minimum from the required number of connections, but the number of a link should also be greater than equal to L' . The minimum duration help to better recoverability of drones in case of failures.

$$\min \left(\lim_{T_{max} \rightarrow \infty} \sqrt{\frac{1}{T_{max}} \sum_{i=1}^{T_{max}} \left(\left(\frac{|D'|_i(|D'|_i-1)}{2} + 1 \right) - \left(\frac{L'+L}{2} \right) \right)^2} \right). \quad (3.6)$$

For energy modeling, if the transmission speed of each link is K bits per second and assuming that each bit consumes E_0 amount of energy, then the energy consumption of each link can be given as following eq. (3.7)

$$\frac{|D'|(|D'|-1)}{2} \times K \times E_0. \quad (3.7)$$

The above equation can be modelled to a much realistic scenario as $\int KE_0u(D) du$, where $u(D)$ denotes the function of network describing the connection at a given instance. This model can be used for predicting the continuity of the network through its average lifetime, which is given by τ' that denotes the time duration up to which the network can operate with the existing connections and bit rate, such

that $\tau' \leq T_{max}$.

3.3 Network Model and Problem Formulation

The network of UAV focuses on the use of energy-modeling to decide on the time slot for Request to Send/ Clear to Send (RTS/CTS) signals. Once a set of drones is available for transmission, the network model helps to formalize the conditions that are used by the proposed model to support efficient transmission without any congestion as well as the collision between signals and vehicle movements. Here, collision is referred to in the context of physical overlapping of way-points. The network model is categorized into three parts, namely,

- dynamic location window,
- transmission window, and
- energy-aware transmission rate.

In the given model, the time slot for RTS/CTS is governed by the set of metrics which includes network fly time, current position of drones and predictive location.

Let t denote the time during which any entity intending to transmit must receive a CTS signal from the receiver. Assuming that a drone is always in a dynamic maneuver, the drone must maintain a particular link for this much time. If $C_{x,y,z}$ is the location of the receiver and $C_{x',y',z'}$ is the location of transmitter, then at any given instance $\frac{f(C_{x',y',z'}, C_{x,y,z})}{\vartheta} \leq t$ for no-loss communication, where ϑ is the relative speed between two drones. If the model is available to operate in No Line of Sight (NLoS) scenarios, then the condition to communicate over given slots changes to $\vartheta \times t \leq R$, where R is the radio range.

Once the signals are received as per the initial constraints, and if the drones are in the radio range, for transmission to begin, the time changes to nt where $(n-1)$ is the number of unique transmissions that can be carried out between two drones.

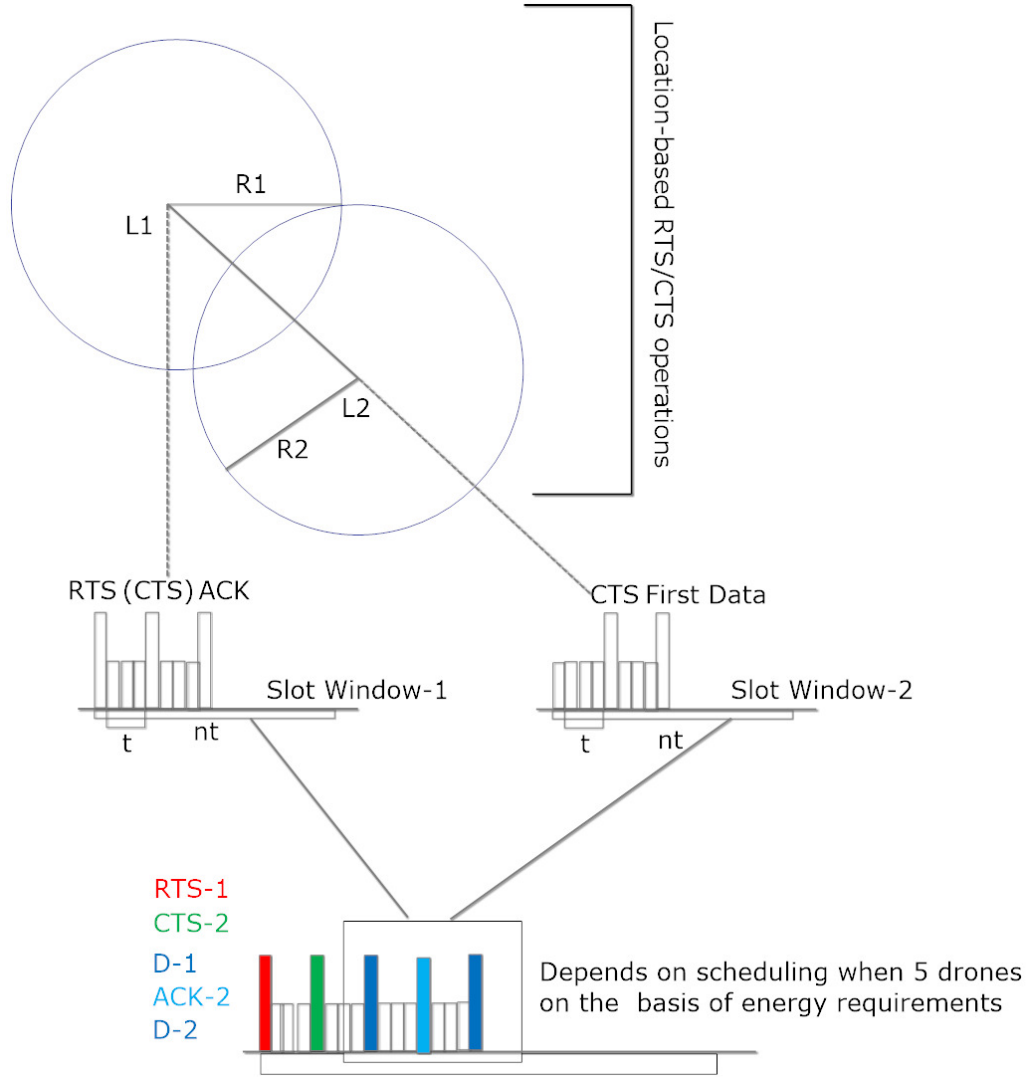


Figure 3.2: Illustration of the time slot diagram based on location and arrival rate.

This can be understood from the timing diagram presented in Figure 3.2.

From the time slot diagram, it is clear that each drone will have a series of slots depending on the location of other drones, LoS or NLoS model and availability, which is defined on the basis of $SINR$ in the given model. However, the final decision on selecting a route will depend on the core metrics such as energy, congestion and collision policies.

3.3.1 Current Position and Location Prediction

The network model always comply with the rule of having at least minimum number of UAVs active throughout the connectivity. For this purpose, let θ_i be the current

Table 3.1: List of symbols

Parameter	Description
D	Set of drones
$ E $	End users
$SINR$	Signal to Noise Ratio
\mathcal{P}	Transmission power to calculate $SINR$
\mathcal{K}	Antenna characteristics for $SINR$
h	Height of drone
φ	Path loss factor
N_0	Noise power spectral density factor
$SINR_t^{(N)}$	SINR for the required network
$(\frac{ D (D -1)}{2} + 1)$	Total connections in the network
$(\frac{ D' _t(D' _t-1)}{2} + 1)$	Total connections in the network at a time t
L'	Minimum that are inactive in the network
L	Maximum links that are inactive in the network
K	Transmission speed of each link in bits per second
E_0	Amount of energy each bit consumes
$u(D)$	Function of network describing the connection at a given instance of the network
τ'	Time duration up to which the network can operate
$C_{x,y,z}$	location of the receiver at any instance for no-loss communication
$C_{x',y',z'}$	location of transmitter at any instance for no-loss communication
$\frac{f(C_{x',y',z'}, C_{x,y,z})}{\vartheta} \leq t$	for no-loss communication, where ϑ is the relative speed between two drones.
θ_i	The current position of a drone at i^{th} location
v_i	Velocity of a drone at i^{th} location
w	Way-point of nearby drone that act as a relay in transmission window
T_x	Total time required for transmission from current location to new location
$T_x^{(w)}$	The average wait time w.r.t each available way-point.
$\min(t_w)$	Minimum time for which a drone must be in the transmission range of another drone
$\frac{1}{\mu}$	The mean packet size of each request coming from any entity in the network
λ	Arrival rate of requests coming from any entity in the network
L_T	Total connections in average connectivity of network
L_A	Actually used connections in average connectivity of network
C_H	Number of channels for the connected components in average connectivity of network
$P_C^{(R)}$	Probability that $\frac{\lambda}{\mu}$ for a given connection is greater than equal to $\left(\frac{\lambda^{th}}{\mu^{th}}\right)$
$L_T^{(0)}$	Initial active links at the present state of the network
\mathcal{P}_c	Power consumption of each bit by drone to run entire processing
t_k	Time for which the drone transmits
T_f	Time for which the drone flies between the two way-points
\mathcal{P}_k	Power consumed by drone in flying
\mathcal{P}_{Tx}	Power consumed by drone in transmissions of control messages
$E_{i,k}$	Energy to maintain a connection between the UAVs at location i and k
$E_L^{(C)}$	Required link state energy between two drones
$\mathcal{P}_L^{(D)}$	Power rate for the distance between the two drones
$E_A^{(t)}$	The maximum energy available per charge of a UAV
$\frac{E_{N,t}}{E_A}$	Mean energy consumption of the network up to a given time instance t
$\mathcal{L}_{A,i}^{(R)}, \mathcal{E}_{i,j}^{(R)}$	Collision avoidance intensity
$\omega_i^{(t)}, E_A^{(t)}$	Attraction value between the two drones from i 's perspective to calculate $\mathcal{L}_{A,i}^{(R)}, E_A^{(t)}$
$\omega_{i,0}^{(t)}, E_0^{(t)}$	Initial value for attraction to calculate $\mathcal{L}_{A,i}^{(R)}, E_A^{(t)}$
γ	Density of drones in its neighbor to calculate $\mathcal{L}_{A,i}^{(R)}$
η	Rate of change of current heading to calculate $\mathcal{L}_{A,i}^{(R)}$
β	The constant defined as the inverse of the probability of connectivity to calculate $\mathcal{L}_{A,i}^{(R)}$

position of a drone at i^{th} location and v_i be its velocity, then the next location $i + 1$

can be defined on the basis of θ and v itself, such that in eq. (3.8)

$$L_{i+1} = (v_i \times t')_{(\Theta_i)}, \quad (3.8)$$

where t' is the time after which the location is to be predicted, and Θ_i is the angle opted to head forward at the previous instance.

3.3.2 Transmission Window

The transmission window refers to the slots which are available for each drone during its shifting from the current location to the predicted location after the time t' . Transmission window helps to identify the number of chances which a drone can use to share the signals with any of the connected entity of the network. For t' slots if w denotes way-point of nearby drone that act as a relay, the possibility that a particular signal will be transmitted before the drone reaches its new location is given in the following condition:

$$\sum_{k=1}^w \left(T_x^{(w)} \right)_k \geq T_x, \quad (3.9)$$

where T_x is the total time required for transmission and $T_x^{(w)}$ is the average wait time w.r.t each available way-point.

Moreover, this condition also accounts for a $\min(t_w)$ which refers to a minimum time for which a drone must be in the transmission range of another drone to establish a connection. All these conditions help to set transmission windows that are available to be utilized by a drone during its heading from θ_i to θ_{i+1} .

3.3.3 Energy-Efficient Transmission

The efficiency of MAC lies in the energy conservation of transmission in the case of highly dynamic nodes. In context to efficiency over MAC, there exists a trade-off between energy and QoS. In such a case, the satisfaction of one may result

in the degradation of others. Thus, it is required to provide an intermediate but effective solution to the problem so that energy is also conserved and QoS is also not compromised. For this, let $\frac{1}{\mu}$ be the mean packet size of each request coming from any entity in the network such that the transmission rate is given by $T_s^R = \frac{\lambda}{\mu}$ where λ is the arrival rate of these requests. Now, the probability of connectivity will help to decide whether the network can operate at the given rate or not. This can be done on the basis of average connectivity of the network, according to which,

$$P_c^{(N)} = 1 - \left(\sum_{j=1}^{t'} \prod_{m=1}^{C_H} \left(\binom{L_T}{L_A} \left(P_C^{(R)} \right) \left(1 - P_C^{(R)} \right)^{L_T - L_A} \right) \right), \quad (3.10)$$

In eq. (3.10), t' is the time slots, L_T is the total connections, C_H is the number of channels for the connected components, L_A is the actually used connections and $P_C^{(R)}$ is the probability that $\frac{\lambda}{\mu}$ for a given connection is greater than equal to $\left(\frac{\lambda^{th}}{\mu^{th}} \right)$. This formulation helps to check the failure rate of the network by using the decay policy over the average probability of connectivity such that, for the given number of connections, the rate of declining of the link is expressed as follows:

$$R_{(L_T),0}^{(t)} = L_T^{(0)} e^{-P_{c,0}^{(N)} t_0}, \quad (3.11)$$

$$R_{(L_T),1}^{(t)} = L_T^{(1)} e^{-P_{c,1}^{(N)} t_1} = R_{(L_T),0}^{(t)} e^{-P_{c,1}^{(N)} t_1}, \quad (3.12)$$

$$R_{(L_T),t}^{(t)} = R_{(L_T),t}^{(t-1)} e^{-P_{c,0}^{(N)} t_0}. \quad (3.13)$$

These conditions help to check the intermediate state of the network as MAC protocols rely on multiple states while forming policies for collision and congestion avoiding metrics. Here, $L_T^{(0)}$ is initial active link at the present state of the network.

From the above model, it is evident that despite the continuous mobility of drones, the energy consumption is discrete and should be evaluated separately for every different instance. If E_0 is the energy consumed by the drone to maintain its flight and \mathcal{P}_c is the power consumption of each bit for entire processing, the average

energy consumption can be calculated as:

$$E_c^{(t)} = E_0 + \sum_{i=1}^K (\mathcal{P}_c t_k) + (\mathcal{P}_k T_f) + (\mathcal{P}_{Tx} T_f), \quad (3.14)$$

In eq. (3.14), t_k is the time for which the drone transmits and T_f is the time for which the drone flies between the two way-points, such that $t_k \leq T_f$. \mathcal{P}_k is the power consumed in flying, \mathcal{P}_{Tx} is the power consumed in transmissions of control messages.

For a regulated flow, t_k should be maximized to allow multiple transmissions and load balancing. Note that a higher value of t_k means more way-points will be used by a drone to share its traffic resulting in the use of different routes. This saves energy but may result in some overheads, which can be reduced by using an appropriate strategy for selecting drones based on their way-points and the previously presented timing diagram.

The given model can be used to check the possibilities of connection with its neighboring drones apart from the time slot by using energy-referencing equations. For this, the network model uses distance and degradation rate approach, according to which,

$$E_{i,j} = \left(E_L^{(C)} + E_L^{(C)} e^{-\mathcal{P}_L^{(N)} t} + \mathcal{P}_L^{(D)} \left(\frac{f(C_i, C_j)}{\vartheta} \right) \right) \ll E_c^{(t)}, \quad (3.15)$$

In above eq. 3.15, $E_{i,j}$ is the energy to maintain a connection between the UAVs at location i and j , respectively. $E_L^{(C)}$ is the required link state energy, $\mathcal{P}_L^{(D)}$ is power rate for the distance between the two drones. Note that this model can be directly applied to QoS requirements. According to which, a link may sustain if $\left(\frac{\lambda}{\mu} \right)_L \geq \left(\frac{\lambda}{\mu} \right)_{\min L}$ and $\left(E_{i,j} + E_c^{(t)} \right) \leq E_A^{(t)}$, where $E_A^{(t)}$ is the maximum energy available per charge of a UAV. Now, for efficient MAC, along with the collision and congestion avoidance principles, the proposed approach should also satisfy the

following conditions:

$$\min (E_{i,j} + E_c^{(t)}) \text{ and } \max \left(\frac{\lambda}{\mu} \right), \quad (3.16)$$

$$s.t. \quad \max (P_c^{(N)}) \forall D, \forall E, \quad (3.17)$$

$$\min \left(\sqrt{\frac{1}{|D|} \sum_{i=1}^{|D|} (E_{c,i}^{(t)} - \overline{E_{N,t}})^2} \right) \quad (3.18)$$

where $\overline{E_{N,t}}$ is the mean energy consumption of the network up to a given time instance t .

3.4 Proposed MAC Model

The proposed approach forms an energy-efficient network which ultimately helps to establish an efficient MAC along with the maintenance of QoS metrics. The proposed approach uses light-intensity formation which is inspired by fire-fly optimization algorithm [124] to resolve the above-defined optimization problems. The proposed approach uses this mechanism to form a connection between any two UAVs that have slots formed between them through the initially formed timing diagram. The proposed approach first defines the collision avoidance between UAVs via accurate positioning beacons and then uses the congestion-avoidance strategy to harmonize the transmissions. The collision avoidance is done on the basis average-light intensity received by the two drones at location i and j , such that

$$\mathcal{L}_{A,i}^{(R)} = \omega_i^{(t)} + \omega_{i,0}^{(t)} e^{-\eta\beta^2} (C_i - C_j) + \gamma, \quad (3.19)$$

In eq. (3.19), $\omega_i^{(t)}$ is the attraction value between the two drones from i 's perspective, $\omega_{i,0}^{(t)}$ is the initial value for attraction, γ is the density of drones in its neighbor, η is the rate of change of current position, β is the constant defined as the inverse of the probability of connectivity.

The average light-intensity, $\mathcal{L}_{A,i}^{(R)}$, is calculated for each drone as in most of the

scenarios, the varying factor is γ , which is mostly different due to variation in the number of inter-connected drones. This model helps to set the location-aware policies, which are used for checking the possibilities of collision as below eq. (3.20):

$$\mathcal{L}_{A,i}^{(R)} \leq \left(\mathcal{L}_{A,i}^{(R)} \right)_{(TH)} = \min \left(\overline{\mathcal{L}_A^{(R)}} \right), \quad \forall D. \quad (3.20)$$

Note that the fire-fly optimization algorithm is operated in reverse pattern as the actual algorithm works to increase the light intensity, but for the proposed model, the higher intensity may result in a collision, and by operating in reverse, the proposed approach efficiently accounts for collision-avoidance over the defined timing cycle.

Now, for managing the congestions in the network, the proposed approach uses intensity mechanism for incoming traffic, and it decreases or increases the congestion window by using lower or higher streaks for any given connection. If $\mathcal{R}_{i,j}$ is the traffic rate between any two drones, then the congestion-avoidance operates simultaneously on both while managing their transmissions and receptions. For this, the evaluations is expressed as follows:

$$\mathcal{C}_{A,i}^{(R)} = \mathcal{R}_{i,j}^{(t)} + \mathcal{R}_o e^{-v\alpha^2} \Delta M + C_H, \quad (3.21)$$

In eq. (3.21), ΔM defines the existence of a connection between the drones and ranges between 0 and 1 for any incoming drones. If at any instance, the value of $\mathcal{C}_A^{(R)}$ increases, the network may result in a state of congestion. Thus, the proposed model operates to accommodate traffic by using the eq. (3.22) discussed as below.

$$\mathcal{C}_A^{(R)} \leq \left(\mathcal{C}_A^{(R)} \right)_{(TH)}, \quad (3.22)$$

where thresholds are obtained on the basis of the average rate sustainable over the defined number of channels.

The proposed model, before predicting the next state of UAV network, uses

energy-conservation MAC which can be observed through the similar light-intensity formation of a fire-fly optimization algorithm expressed in eq. (3.23).

$$\mathcal{E}_{i,j}^{(R)} = E_A^{(t)} + E_0^{(t)} e^{-P_c^{(N)} \alpha^2} (C_i - C_j) + C_H, \quad (3.23)$$

and for energy-efficient facilities over the location-aware MAC, $\mathcal{E}_{i,j}^{(R)} = \min \forall t$.

Now, once these models are finalized, the proposed approach uses predictive strategy for governing the conditions related to the collision, congestion, and energy to help to form an energy-efficient and location-aware MAC for UAV networks. The details of these predictive steps are presented in Algorithms 1, 2, and 3. Algorithm 1 operates for continuously checking the possibilities for any collision over the resultant way-points, thus, preventing any unintentional halts in the transmissions. It makes sure that the light-intensity conditions are always satisfied by a drone in view of its neighboring drone and also provide immediate feedback if these conditions do not hold true. This provides sufficient feedback for the MAC timing control while selecting a slot for transmission with the upcoming drone.

Algorithm 1 Collision avoidance mechanism

```

1: Input: Drone network components and entire system model
2: Output: collision avoidance phenomenon
3: Initialize the networks
4: while (Transmission==continue) do
5:   Share beacons and find location
6:   i=1
7:   while (i≤|D|) < parallel > do
8:     Calculate  $\mathcal{L}_{A,i}^{(R)}$ 
9:     Input metrics from neighboring drones
10:    if ( $\mathcal{L}_{A,i}^{(R)} > \left(\mathcal{L}_{A,i}^{(R)}\right)_{(TH)}$ ) then
11:      Collision possibilities=true
12:      Update incidence and adjacency matrices
13:    else
14:      Continue with the present state
15:    end if
16:    i=i+1
17:  end while
18: end while

```

Once the collision conditions are figured out, Algorithm 2 is used for managing the congestion by controlling the size of the congestion window. This helps to regulate the entire traffic without any bottleneck as well as traffic-overloading. Note that with trivial decay principle, this algorithm can be operated towards prediction of congestion after certain time slots. After evaluations of the network through both these algorithms, Algorithm 3 checks for route while maintaining conditions of minimum consumption of energy along with the QoS requirements. All these algorithms together form the basis of energy-efficient and location-aware MAC, which are then easily accommodated over the timing diagram previously presented in Figure 3.2.

Algorithm 2 Congestion window alterations

```

1: Input: Drone network components and entire system model
2: Output: Congestion window control
3: Initialize the networks
4: while (Transmission==continue) do
5:   Share beacons and find location
6:   Initialize traffic and set timing diagram
7:   i=1
8:   while ( $i \leq |D|$ ) < parallel > do
9:     Calculate  $\mathcal{C}_{A,i}^{(R)}$ 
10:    Input metrics from neighboring drones
11:    if ( $\mathcal{C}_{A,i}^{(R)} > \left(\mathcal{C}_{A,i}^{(R)}\right)_{(TH)}$ ) then
12:      congestion_window=congestion_window-1
13:    else
14:      congestion_window=congestion_window+1
15:    end if
16:    i=i+1
17:  end while
18:  Recheck conditions and continue
19: end while

```

The operational complexity of the proposed algorithms depends on the number of drones in the neighborhood of every drone over which these algorithms are operated. For the maximum number of connections and full-time transmissions, the operational complexity of each algorithm is of the order $O(t |D|)$. The complexity is reduced by the parallel run of the model and depends on the current state of UAVs. The proposed approach is highly scalable and low-complex with an ef-

Algorithm 3 Energy-aware drone to drone/user communication

```

1: Input: Drone network components and entire system model
2: Output: Route for transmission
3: Initialize the networks
4: while (Transmission==continue) do
5:   Share beacons and find location
6:   Initialize traffic and set timing diagram
7:   Check for timing diagram and available slots
8:   set energy metrics and approve Algorithms 1 and 2
9:   i=1
10:  while (i≤|D|) < parallel > do
11:    Calculate  $\mathcal{E}_i^{(R)}$ 
12:    Input metrics from all the channels
13:    if ( $\mathcal{E}_i^{(R)} < (\mathcal{E}_A^{(T)})_{(TH)}$ ) then
14:      add connected channels to route matrix route[]
15:    else
16:      remove connected channels from route matrix (route[])
17:    end if
18:    i=i+1
19:    Ready for transmission (route[])
20:  end while
21:  Operate for all channels and recheck conditions
22: end while

```

fective application for the drone to drone or even drone to user communications. The proposed schemes were evaluated using a simulated environment with respect to various performance metrics. This chapter presents the results obtained after evaluation of all the proposed schemes with respect to various performance metrics.

This section presents the analysis of the proposed protocol through numerical evaluations and simulation case study. Further, a comparison is drawn with the existing state-of-the-art MAC protocols, which are specially developed keeping in view the architecture of UAV-assisted networks.

3.5 Simulation Results and Discussion

This section presents the numerical analysis of the proposed approach by using the system and network modeling of the network. The values are obtained by using the configurations given in Table 3.2. The results are recorded for the metrics which

affects the performance of any MAC strategy which focuses on the location as well as energy-efficient computations in the network. The choice of metrics is based on the standard metrics, which are also used by existing MAC strategies irrespective of their domain of applications.

Table 3.2: Input parameters

Parameter	Value	Description
\mathcal{P}	30 dBm	Transmission power
\mathcal{K}	-11 dB	Antenna characteristics
h	100 - 300 feet	Height
α	4	The path loss factor
N_0	-174 dBm/Hz	The noise power spectral density
$ D $	5 - 20	Set of Drones
$ E $	100 - 500	End Users
t_k, T_{max}	1000 s	Time for which drone transmits
E_A, E_0	2500 J	Energy consume
v	5 - 35 mps	Velocity of drone
n	1-10	Number
t, t'	1-10 s	The time after which the location is to be predicted
Θ	± 45 deg	The angle opted to head forward at the previous instance.
C_H	1-4	Channels
$\left(\frac{\lambda^{th}}{\mu^{th}}\right)$	256 kbps	Velocity
$E_L^{(C)}$	1-2 J	The required link state energy
ω, ω_0	10	The attraction value
η	0.1	Rate of change of current heading
γ	5-20	Density of drones

At first, the results are traced for average SINR in the network as shown in Figure 3.3. The results show that the average variation in permissible height of a drone has a huge impact on the performance and the SINR decreases as a drone fly beyond its allowed radio range. It is to be noted that the number of drones possesses similar SINR if interfered with an equal number of drones. However, in case the drones are operating in excessive distance from each other the average SINR increases due to lower interference. Results show that with an increment in the altitude from 100 to 300 feet for each drone, the average SINR shows a variation of 59.04% on the decreasing side. These can be controlled by deploying the proposed strategy, which helps to accommodate only those connections which do not cause much interference as well as are free from congestions as predicted using the light-intensity formulations of the fire-fly optimization algorithm.

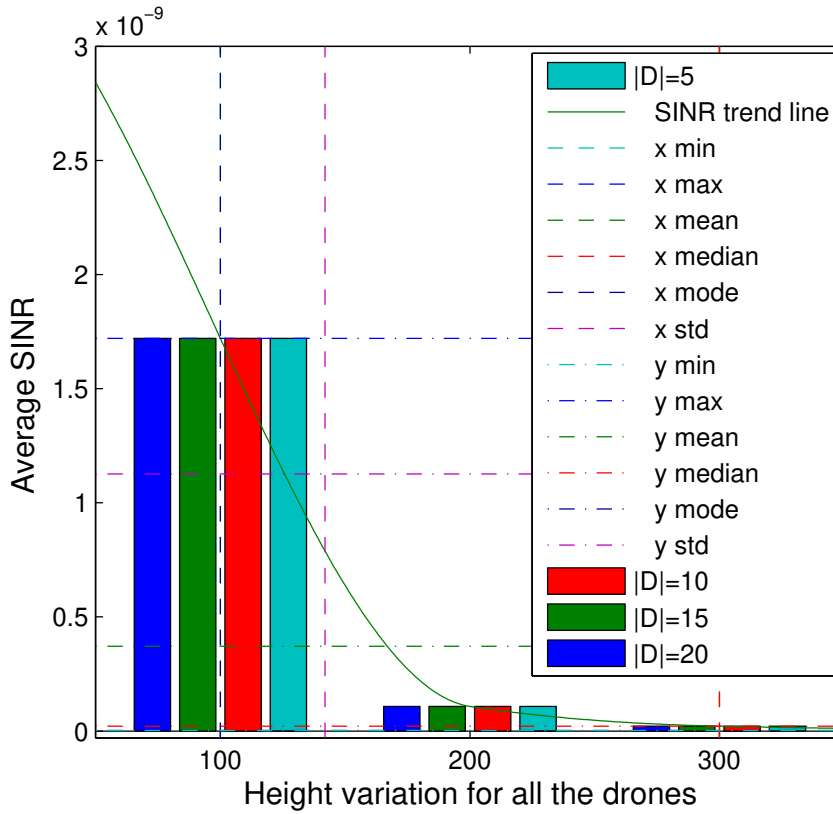


Figure 3.3: Effect of height variation on SINR.

For evaluations, the RTS, CTS and ACK packet lengths are of the order 170

Table 3.3: Parameter configurations

Parameter	Value	Description
Area	2500x2500 sq. m.	Area under evaluations
Maximum speed	70 Kmph	Maximum Speed of drones
$ D $	5-20	Number of drones
$ E $	100-500	Number of users
Simulation Time	1000s	Operational time
Agent	TCP New Reno	TCP agent between nodes
Pause time for drones	0	Halts for drones
Pause time for users	2-5s	Halts for users
Routing Agent	Link state	Routing strategy

bits, 120 bits, and 120 bits, respectively. Default packet lengths, such as physical layer header, busy to send and congestion notifications are of similar size to that of 802.11b with a pause of 2 s for each packet. This is used to analyze the proposed approach on the available configuration of the NS-2. Other metrics which are used in

the system model are kept similar to the ones used for numerical evaluations, except for those presented in this table. The results are recorded for different metrics as explained below:

- **Packet Delivery Ratio (PDR):** It denotes the ratio of the number of packets successfully received at a node to the total packets transmitted to it. It allows checking the number of drops that may be induced due to incorrect timing cycles of the configured MAC.
- **Network Throughput:** Throughput should be more close to the offered rate of the network. A network must provide stable and reliable connectivity between the nodes through high throughput. Here, the average throughput is trivially calculated as the number of bits actually transferred per unit time over the channel under operation.
- **End-to-End (E2E) Delay:** E2E delay is computed which is the sum of the propagation delay, transmission delay, queuing delay and processing delay. It allows analysis of QoS obtained while managing traffic between the end nodes. Highly delayed traffic represents possibilities of congestion, which is undesirable while forming an efficient MAC-based drone network.

The simulation study suggests that the proposed MAC strategy is able to provide high PDR even with a varying number of users for each UAV in the given region of interest as shown in Figure 3.4. It is evident from the simulations that with a constant number of UAVs and an increasing number of network users, the overall PDR decreases due to immense load over a single UAV. However, with the proposed timing cycle based on the energy and the location of drones, the number of channels are efficiently utilized which helps to attain a high PDR of 99.9% with a variation between 2.8% to 9.8% for number users increasing between 100 and 500. The lowest PDR is only when the number of users on the ground increases abruptly beyond the capacity of all the drones. QoS is guaranteed if the network is able to utilize

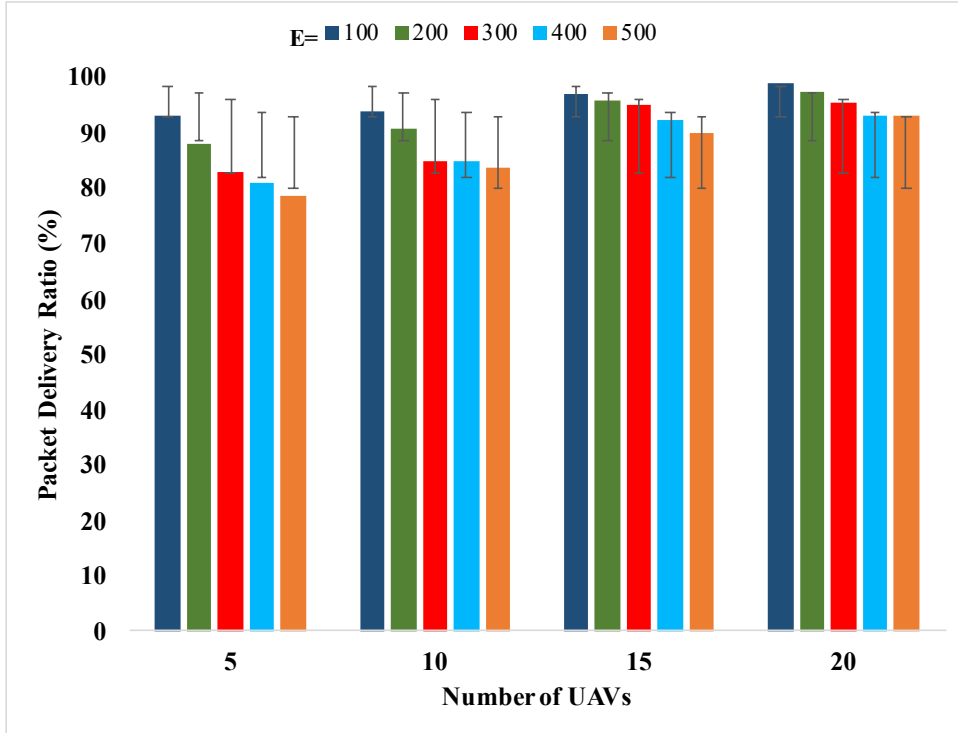


Figure 3.4: The variation in PDR with varying number of UAVs for varying users

a maximum of its resources while increasing the average transmission rate. When the attained rate is closer to the permissible rate, the average network throughput increases. However, if the number of users is increasing, the average throughput of the network will decrease and may cause a failure. But, in the proposed approach, the average network throughput is maintained at a sufficiently high value even for a lesser number of UAVs and an extremely high number of users as shown in Figure 3.5. These results show that the proposed approach provides average network throughput of 32 Mbps with a variation rate between 5.9% and 21.7% for the number of users increasing between 100 to 500 and the number of UAVs between 5 and 20.

In a network, it is entirely difficult to curb all sort of delays while transmitting over a link between the UAV and the ground users. There are certain types of losses which affect the transmission and cannot be controlled. However, the queuing and the processing delays can be controlled via an efficient MAC strategy as provided in this objective. The proposed MAC is capable of reducing the traffic burden of

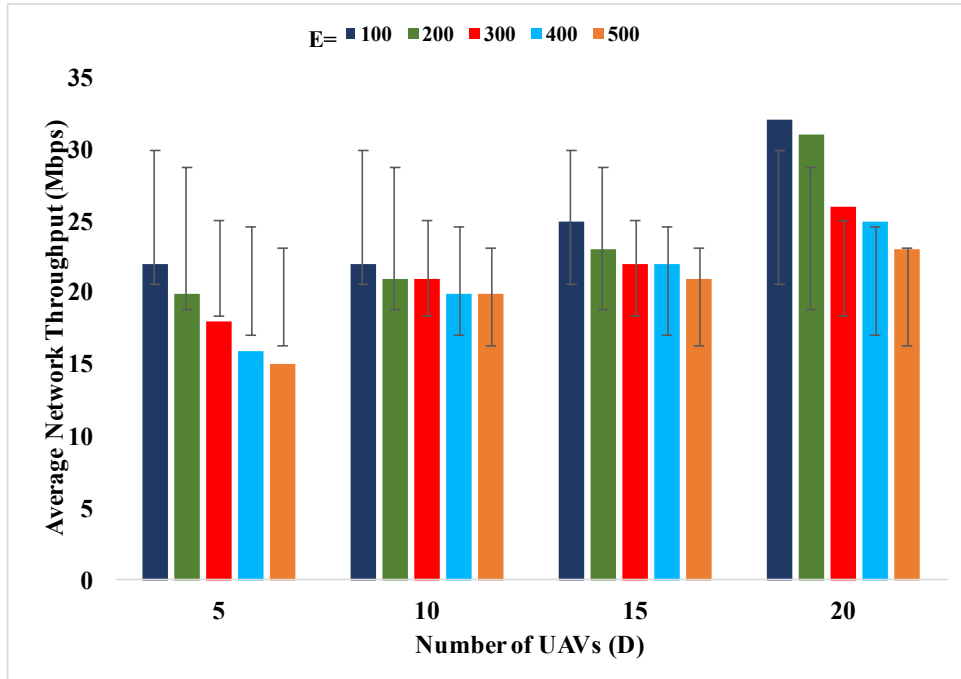


Figure 3.5: Effects on average network throughput with varying number of UAVs and users

each node as well as manages the congestion window which helps to prevent any bottlenecks that ultimately results in a lower end to end delay. The results for delays as shown in Figure 3.6 show that the increasing number of nodes causes more delays compared with a network with a low number of users and a high number of drones. The maximum end to end delay obtained by the proposed approach is 17.03 ms while the minimum is 2.00 ms. This shows that as the numbers of UAVS increases, the end to end delays decreases. The reason behind such improvement is that the proposed scheme provides better resource allocation which reduce the congestion and collision.

Apart from the results presented in the previous parts, some other details are also traced to the proposed model as shown in Table 3.4. These results indicate the average number of messages recorded between the UAVs and the ground nodes and the average delay observed during these transmissions. It is to be noted that the proposed model allows efficient MAC, thus, sustaining of the network at the desired QoS is of much importance. To demonstrate this, the results are traced for the average sustaining time of the network. It is evident that the number of UAVs

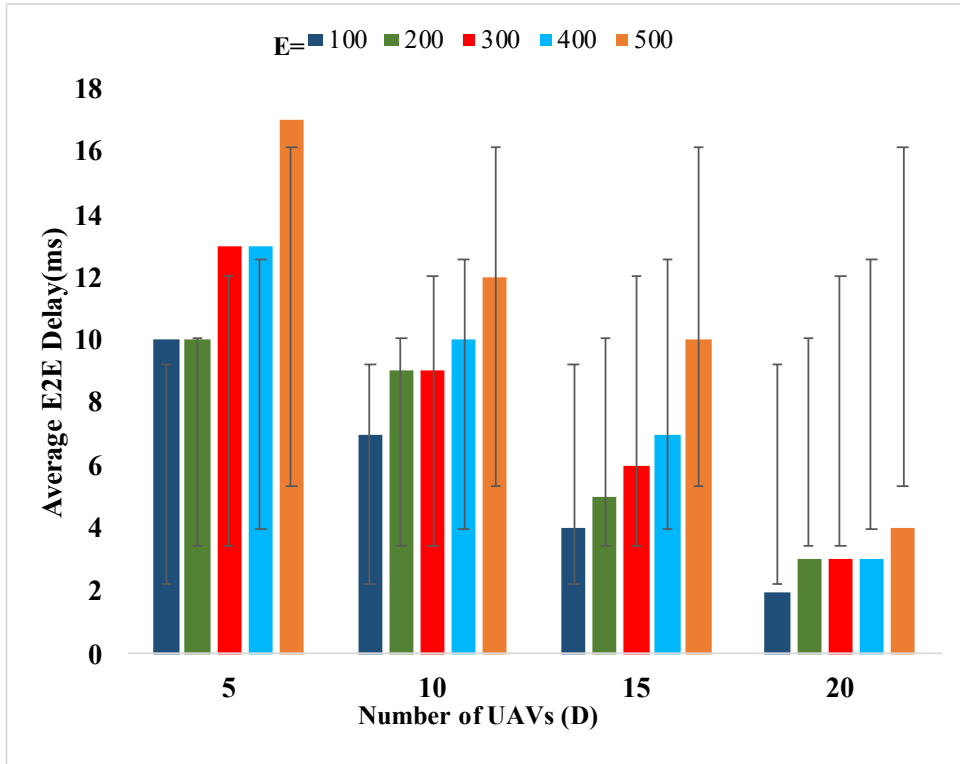


Figure 3.6: Effect on average end to end delay with varying number of UAVs and users

Table 3.4: Simulation evaluation of the proposed model for ground users.

$ D $	$ E $	Messages Ex- changed	Observed Average Delay (s)	Sustaining time of the network (s)
5	100	103	0.0145	995.32
	200	143	0.0189	994.24
	300	155	0.0233	993.16
	400	186	0.0277	992.07
	500	211	0.0321	990.99
10	100	115	0.0101	996.14
	200	159	0.0108	996.50
	300	203	0.0115	996.86
	400	247	0.0122	997.22
	500	291	0.0129	997.58
15	100	144	0.0095	997.22
	200	190	0.0100	997.25
	300	225	0.0105	997.28
	400	270	0.0110	997.31
	500	305	0.0115	997.34
20	100	355	0.0040	997.45
	200	395	0.0045	997.85
	300	410	0.0050	998.25
	400	445	0.0055	998.65
	500	480	0.0060	999.05

causes considerable effects on these metrics, but the average fluctuations for these metrics are low, and most of the time, these metrics observe pretty high value, which

demonstrates the high performance of the proposed MAC strategy.

3.5.1 Result and Discussion

The proposed approach supports energy-efficient and location-aware QoS enhancement through an efficient MAC strategy. The proposed approach provides collision-free and congestion-free data dissemination between the users and the UAVs. Also, the evaluations suggest that with the defined criteria of light-intensity of the fire-fly optimization algorithm, Algorithms 1- 3 help to determine the pre-congestion, pre-collision or pre-consumption of energy over an active link of a UAV. This helps to maintain the timing cycle and avoid any bottlenecks by adjusting the congestion window without affecting the performance.

Table 3.5: Comparison of the proposed model with the state-of-the-art MAC approaches (*Data gathering phase, **Network throughput).

Approach	Ideology	Location-Aware	Energy-Efficient	UAVs	E2E Delay	Throughput	Channel Utilization
Adaptive MAC [62]	MAC for UAV ad hoc networks	✓	✓	-	0.186s	6.18Kbps*	-
PFSC Based MAC [125]	Evaluations of PFSC Based MAC	-	-	✓	-	-	-
CF-MAC [61]	Collision - free MAC	-	×	✓	-	-	-
LODMAC [60]	Location-oriented directional MAC	✓	×	✓	0.0014s	-	>70%
Adaptive MAC [57]	Directional antenna-based MAC	✓	×	✓	1.85s	2.7Kbps*	-
Proposed	Location-aware, energy-efficient MAC via fire-fly optimization	✓	✓	✓	0.0125s	22.25Mbps**	>90%

Over the years, MAC has been actively researched by different researchers for different types of network. However, very few of them have relatively targeted it for UAV networks. The high dynamics and issues related to LoS make it difficult to set any existing MAC strategy on such a network. Further, the existing approaches work for energy-efficiency or QoS and mostly ignore the impact of both as discussed in this chapter. To further understand the significance of the proposed approach, a comparison is drawn between the existing solutions and the proposed approach as shown in Table 3.5. This comparison suggests that the proposed approach is competitive in significantly enhancing the network performance keeping in control the delays and latency over varying number of nodes.

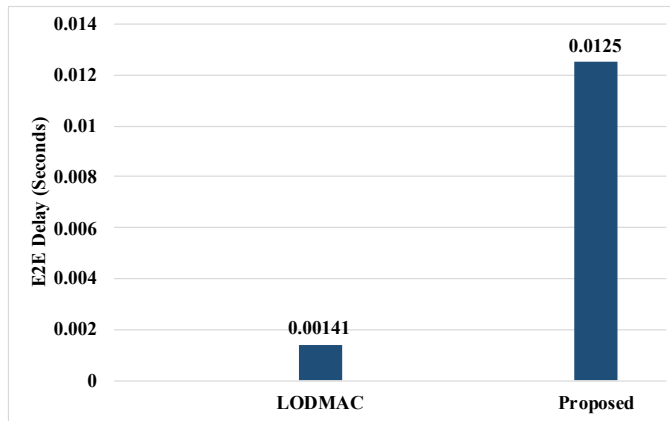


Figure 3.7: End to End Delay comparison of proposed model with existing techniques

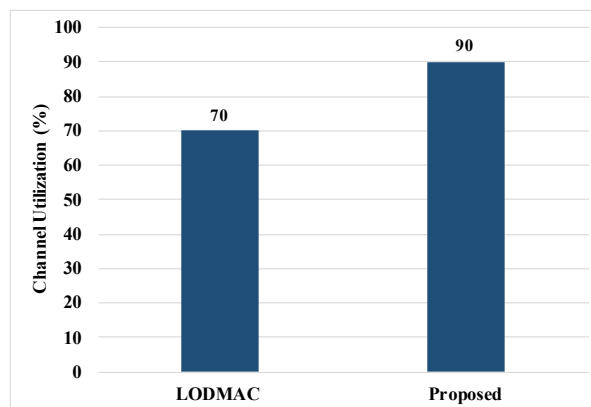


Figure 3.8: Channel Utilization comparison of proposed model with existing techniques

3.6 Summary

In this Chapter, the properties of the fire-fly optimization algorithm are utilized which help to form an efficient timing slot mechanism that results in the creation of an energy-efficient and location-aware MAC for UAV networks. The simulation results and comparative analysis suggest that the proposed approach is capable of providing congestion-free, collision-free and energy-efficient MAC with signalling quality amended up to 59.04% along with 80.1% conservation of energy. The proposed technique is also able to attain a high PDR and throughput, where it helps to counter the network delay. This technique accomplishes all the objectives, which include the design of an efficient location aware protocol for the multi-UAVs network, QoS provisioning, performance validation, and comparison with existing protocols.

3.6.1 Future Work

This work can be extended to routing layer of UAVs network to provide a cross layer solution to enhance various QoS parameters.

Chapter 4

SLAO Offloading Scheme in Multi-UAV Ecosystem

4.1 Overview

In this chapter, an efficient location aware scheme is designed to build the over utilized channel congestion free. In this scheme, the data traffic is offloaded to another available channel opportunistically. UAVs are used as forwarding nodes in SDN model, wherein the location aware and network selection algorithm finds an optimal flow path for offloading of data and forwarding it to the destination. This increases the resource utilization exponentially and help to maintain QoS for bandwidth hungry services.

4.2 Software Defined Network Architecture

As the applicability of UAVs is increasing exponentially day by day, there is an urgent need for network abstraction to simplify and automated network management in UAVs. For this, SDN emerged as the best choice, due to its fundamental characteristics. SDN architecture is based on the three architectural characteristics, (1) the decoupling of the forwarding plane from the control plane, (2) the logical

centralization of the controller at the control plane, (3) programmability of network functions. These combined features would make networks more simple, clear and efficient to control and manage its operations.

Inspired by the computing systems, the SDN consists of three planes, from the top plane to the bottom plane viz: 1) the application plane, 2) the control plane, and 3) forwarding or data plane. The interface, utilized to link the application plane with control plane, is known as NorthBound Interface (NBI), while the SouthBound Interface is utilized to link control plane with forwarding plane. The application plane lies above the control plane, as shown in Figure 4.1. Through this SDN applications, can easily access global network. Moreover, it also covers an array of applications focusing on network services and software applications communicating with the control layer. For an example, the application plane acts as the software application which uses the computing strategies to finish its tasks, whereas control plane acts as computer's operating system, which can easily interact with applications and devices(forwarding plane). The control plane lies between application and forwarding plane. It is also referred as the brain of SDN architecture, because it consists of a centralized controller. It provides and maintains the global and dynamic view of the entire network. Moreover, it is responsible for collecting network state information and make decisions accordingly. Thereafter, it passes on the instructions and configurations to the forwarding plane about time to time implementation of required policies. In this way, SDN makes perfect balance with network status, and user defined policies. It results in the optimization of network configuration and improving the performance of a network. The plane where all these policies get implemented is referred to as the forwarding or data plane. The significant motive of this plan is to forward the traffic to the next hop guided by the upper plane. It consists of the forwarding devices such as-OpenFlow (OF) switches, OF routers and OF gateways.

In SDN architecture, the transfer of control logic to an external entity and logical centralization, offers numerous benefits that are listed below.

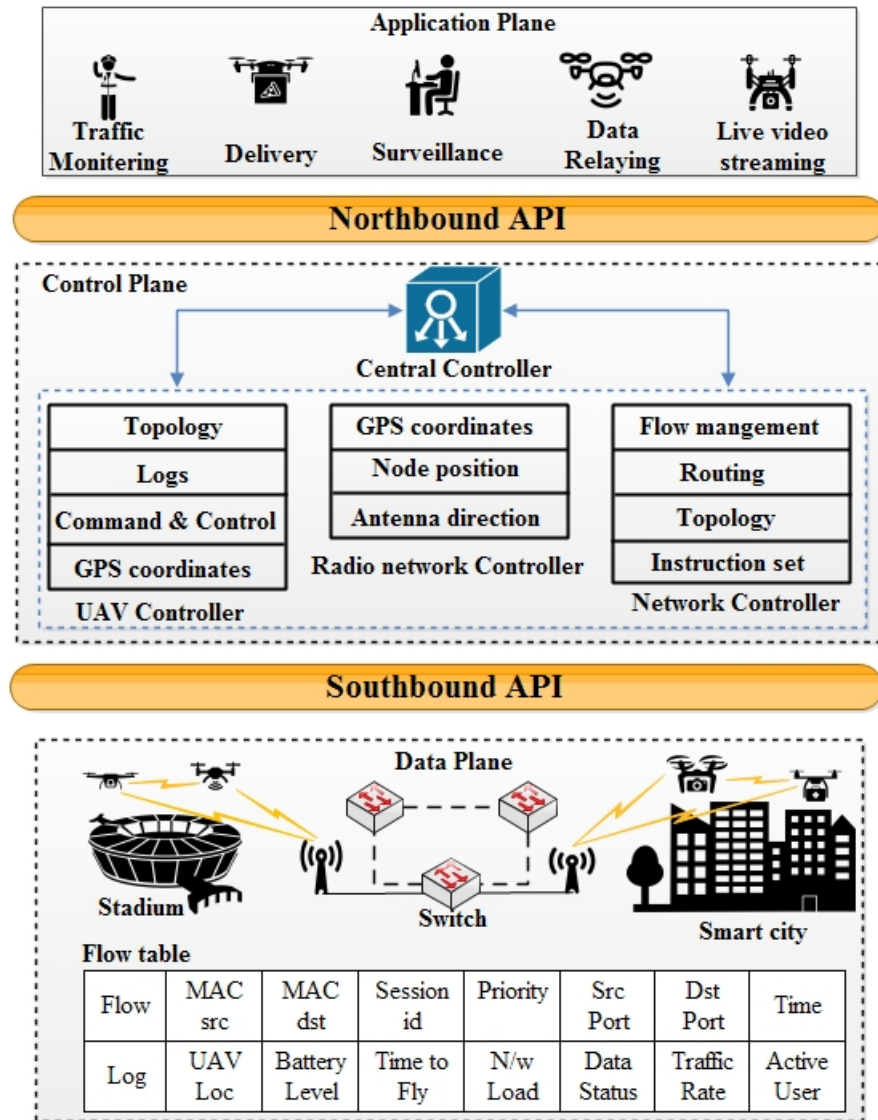


Figure 4.1: Architecture of SDN

- Unlike the traditional network, in SDN, the control functionality from network forwarding devices such as- routers, gateways, and switches are removed. In this way, these devices can flexibly adapt to new policies and functionalities updated by the SDN controller.
- The adaptability of policies and functionalities offers excellent control of the network through remote programming, configuring, and forwarding rules.
- A control program can automatically react to the suspicious change of the network state. In this way, it maintains a high level of security in the entire network.

- It simplifies the development of more sophisticated services, network functions, and applications by centralizing the control logic in a controller with a global knowledge of network state.
- Integration of virtualization with SDN caters manifold benefits such as maximization of resource utilization and network slicing, which results in delay minimization and performance improvement.

In SDN architecture, communication infrastructure follows OF protocol. With the help of interfaces and APIs, the OF protocols, the communication between two similar and dissimilar network devices are allowed. Inside an OF device, there is predefined path sequence based on the flow tables which guide the incoming packets [126]. Moreover, SDN allows the creation of multiple virtual instances of resources hosted at control stations, which in turn increases the resource utilization. These multiple instances can be placed at different geographical locations and can act as a backup when required.

4.3 System Model

With a continuous increase in numbers of the users within the coverage area of a particular network, it becomes difficult to sustain the connectivity without any loss of data or compromising QoS. This is one of the problematic issues for UAVs networks, where demand is set to be higher than the available network capacity. Therefore, a SDN-based control model is presented, which aims at provisioning continuous connectivity using the heterogeneous network. Moreover, the heterogeneity of networks also comes with several opportunities to transmit a similar amount of data with lesser network cost. The proposed model leverages an energy-efficient framework which uses SDN architecture. In this, the radio towers (LTE, WiMax and radio transmitter) act as the decentralized controllers and UAVs act as SDN switches. These decentralized controllers are managed by a single global con-

troller using two managers, (1) radio link manager, and (2) status manager. The radio link manager maintains the records of available networks and the number of active users with their updated location information, whereas the status manager handles the network load and queuing information. Figure 4.2 shows the system model comprising of N UAVs deployed in a typical smart city scenario. For better understanding, Table 4.2 presents the notation table.

An incoming flow F composes of n type of flow paths to be processed in multi-

Table 4.1: List of symbols

Parameter	Description	Parameter	Description
F	Incoming flow	t_a	Arrival time
t_d	Deadline time	f_s	Flow size
$\lambda_i^n(t)$	Number of type n flows routed to i^{th} UAV.	T_R	Transmission rate
C_c	Channel capacity	$SINR$	Signal to noise ratio
B	Bandwidth	\mathcal{P}	Transmission power
K	Antenna characteristics	h	Height of drone
γ	Path loss	N_0	Noise power spectral density
L	Latency	τ^{pro}	Propagation delay
D	Distance between the two nodes	W_i	Decision variable for two flows
\mathbb{C}	Binary variable constant	d_{med}	Medium propagation delay
τ^{que}	Queuing delay	$ Q(t) $	Ready queue
O	Occupancy ratio	τ^{ser}	Serialization delay
$P_{size}(t)$	Size of the packet	τ^{pcs}	Processing delay
$l_{bs}(t)$	Delay due to processing at BS	$l_{uav}(t)$	Delay due to processing at UAV
τ^j	Jitter	d_j	Deterministic jitter
R_j	Random jitter	\hat{n}	Link bit error rate
T_{u_i}	Throughput	E_i^{to}	Total energy consumption
E_i^{tr}	Transition energy required by UAV	E_i^{ho}	Energy required to hover an UAV
E_i^c	Energy required by an UAV to communicate	U_i, U_k	Utility function for i^{th} and k^{th} CC
U_{ijk}	Combined utility function	T_i^{avg}	Average anticipated throughput
L_i^{avg}	Average anticipated latency	$D_{i \rightarrow k}$	Distance between i^{th} and k^{th} CC over flow path j
E_i^{thr}	Threshold energy required for i^{th} UAV to accomplish its mission	\mathcal{L}_{of}	Load which is to offloaded to the selected destination channel
\mathcal{L}_{thr}	Threshold load	L_{av}	Average load
L_i	Total load	B_{n+i}	Bandwidth allocated after adding i^{th} user
T_{n+i}	Throughput of the network after adding i^{th} users	U_{mass}	UAV mass (kg)
g	Gravity (m/s^2)	ρ	Air density (kg/m^3)
ν_p	Radius of the propellers	ς_p	Number of propellers in UAV
R	Solar radiations	α	Radiation angle of sunlight
ρ	Conversion efficiency	S	Size of panel
E_i^{pv}	Energy generated by PV panels	P_r	Source transmission power
P_i	Power available at receiver	G_t	Source antenna gain
G_r	Receiver antenna gain	L_{po}	Polarization loss
η	Rectifier efficiency	λ	Wavelength
β	Constant to adjust Friis free space equation	C_p	Charging points
C_r	Charging range	E_i^{prs}	Energy available with the i^{th} UAV at time t
E_i^{rt}	Rated capacity of i^{th} UAVs battery	R_{thr}	Threshold value of radiations
E_i^{def}	Energy deficit	δ	Probability of successful handover
T_f	Time taken to retry in case of failure of a handover	T_h	Handover time

UAV environment, wherein a single flow is described as $f : (t_a, t_d, f_s)$, where, t_a , t_d , and f_s are arrival time, deadline time and flow size, respectively. At time t , type

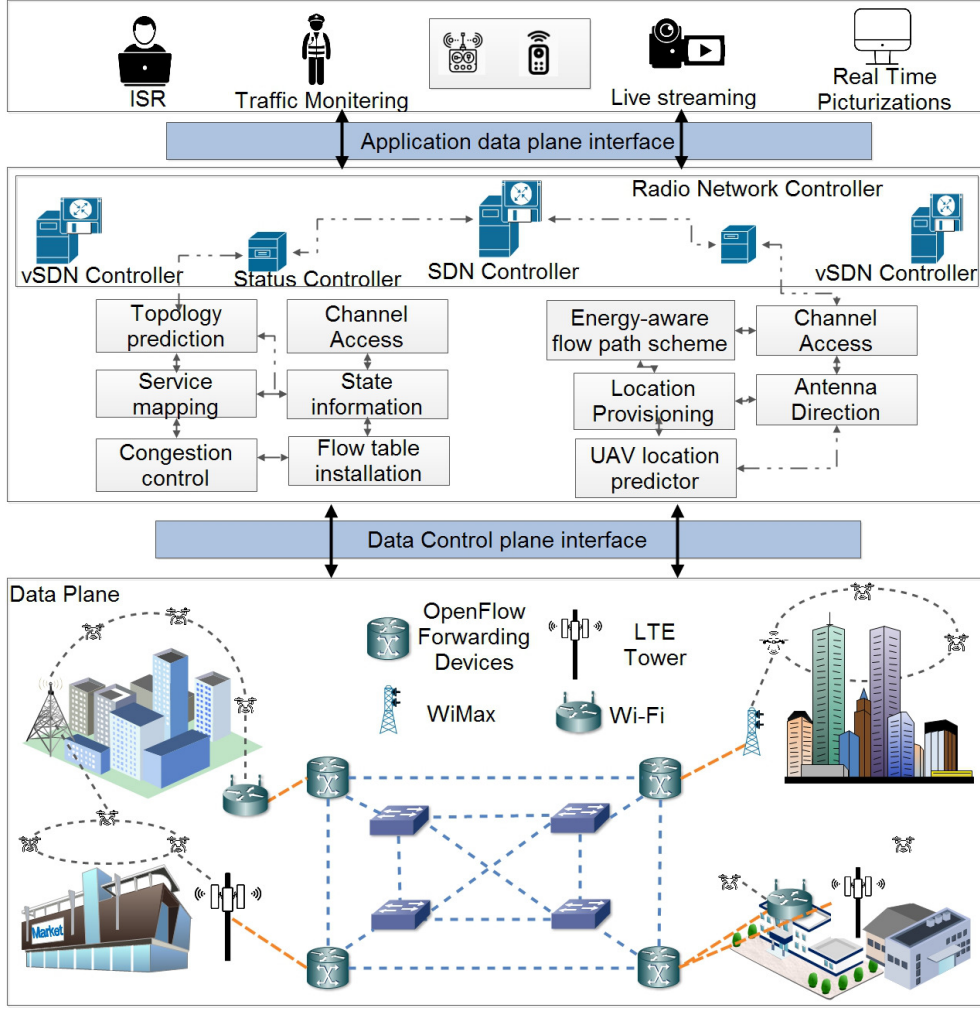


Figure 4.2: SDN based system model and architecture

n flows are modeled using Poisson distribution with an arrival rate, $\alpha(t)$ [127, 128]. The type n flows scheduled at i^{th} UAV follow the queues dynamics [127–129] as below eq. (4.1)

$$\Theta_i^n(t+1) = \max[\Theta_i^n(t) - \Theta_i^{pr}(t)] + \lambda_i^n(t), \quad (4.1)$$

where $\lambda_i^n(t)$ is the number of type n flows routed to i^{th} UAV.

The traffic model for QoS provisioning plays an important role. Considering that the transmission rate T_R of the network, the traffic model is defined as the maximum transmission rate over the channel capacity C_c , which is given in eq. (4.2):

$$C_c = B \log_2(1 + SINR), \quad (4.2)$$

where SINR is the signal-to-interference noise ratio and the B is taken as available bandwidth. Using the above factors, the SINR is derived as eq. (3.4).

The other important QoS parameter on which traffic model or transmission is directly dependent is known as the latency (L). The latency in a UAV network depends on various types of delays (such as-propagation, queuing, serialization, processing) and jitter. The L is defined is given as follows.

$$L = \tau^{pro} + \tau^{que} + \tau^{ser} + \tau^{pcs} + \tau^j. \quad (4.3)$$

In Eq. (4.3), the propagation delay (τ^{pro}) is calculated as follows.

$$\tau^{pro} = \sum_p \frac{D \times W \times \mathbb{C}}{d_{med}}, \quad (4.4)$$

where in eq. 4.4, D is the distance between the two nodes, W is the decision variable for two flows, \mathbb{C} is the binary variable constant and d_{med} is the medium propagation delay.

Now, the queuing delay (τ^{que}) is derived as follows in eq. (4.5).

$$\tau^{que} = \sum_{uav} \sum_{infra} \frac{|Q(t)|}{B \times O}, \quad (4.5)$$

where $|Q(t)|$ is ready queue and O is the occupancy ratio.

The serialization delay (τ^{ser}) is given as below eq. (4.6).

$$\tau^{ser} = \sum_{uav} \sum_{infra} \frac{P_{size}(t)}{B \times O}, \quad (4.6)$$

where $P_{size}(t)$ is the size of the packet.

Similarly, the processing delay (τ^{pcs}) is defined as.

$$\tau^{pcs} = \sum_{bs} l_{bs}(t) \times \sum_{uav} l_{uav}(t), \quad (4.7)$$

where $l_{bs}(t)$ is the delay due to processing at BS and $l_{uav}(t)$ is the delay due to processing at UAV end.

Jitter (τ^j) is also an important parameter in data transmission and is defined as follows.

$$\tau^j = d_j + 2 \times R_j \times \hat{n}, \quad (4.8)$$

where in eq. (4.8), d_j is the deterministic jitter, R_j random jitter and \hat{n} is the link bit error rate.

Throughput (T_{u_i}) is one of the most desirable factor to measure the performance of a network. T_{u_i} observed at UAV (U_i) is defined as below.

$$T_{u_i} = T_{bs} - \sum (T_i + B_i), \quad (4.9)$$

where in eq. (4.9) T_{bs} is the maximum throughput offered by a BS to a U_i , T_i is the flow peak rate at which the traffic send by U_i and B_i is the average bandwidth of traffic flow sent by U_i .

The total energy consumption (E_i^{to}) of a UAV depends on the transition (E_i^{tr}), hover (E_i^{ho}) and communication (E_i^c) energies, which required by an UAV to accomplish its operational goal. E_i^{to} required by i^{th} UAV to accomplish its mission is given as below in eq. (4.10).

$$E_i^{to} = \sum_i E_i^{tr} + E_i^{ho} + E_i^c. \quad (4.10)$$

4.3.1 Problem Formation

In order to select a significant heterogeneous network or a suitable communication channel (CC) for data offloading in a multi-UAV network, the following entities that play an important role, 1) source CC (i), 2) flow path (j), and 3) destination CC (k). On the basis of these entities, there may exist multiple choices, out of which an optimal pair need to be selected for data from i^{th} CC to j^{th} CC on the basis of

different available flow paths. For this purpose, a mapping ($U_{i,j}^{map}$) of these entities is shown as a function of utilities in eq. (4.11).

$$U_{ijk}^{map} = f(U_i, U_j, U_k). \quad (4.11)$$

On the basis of various network models, the combined utility (U_{ijk}) is defined as below eq. (4.12).

$$U_{ijk} = \frac{B \times T_i^{avg}}{(n+1) \times L_i^{avg}} \times \frac{1}{\frac{D_{i \rightarrow k}}{j}}, \quad (4.12)$$

where the average anticipated throughput and latency on adding new load is T_i^{avg} and L_i^{avg} , respectively, $D_{\frac{i \rightarrow k}{j}}$ is the distance between i^{th} and k^{th} CC over flow path j .

To select an optimal pair (ijk) on the basis of eq. (4.12), a decision variable ($\chi_{ijk}, \forall t$) is defined as below in eq. (4.13).

$$\chi_{ijk} = \begin{cases} 1, & U_{ijk} > U_{ijk}^*, \\ 0, & otherwise. \end{cases} \quad (4.13)$$

Now, using the aforementioned factors, the objective function is formulated as below eq. (4.14)

$$max \left[\sum_{j=1}^{j_n} (U_{1j_1k_1}) \chi_{1j_1k_1} + U_{1j_2k_1} \chi_{1j_2k_1} + \dots + U_{1j_nk_n} \chi_{1j_nk_n} \right], \quad (4.14)$$

subject to following constraints

$$\chi_{ij} \in [0, 1], \quad (4.15)$$

$$U_i(j) > U_i(j^*), \quad (4.16)$$

$$U_k(t) > U_k(t+1), \quad (4.17)$$

$$D_{\frac{i \rightarrow k}{j}} < D_{\frac{i \rightarrow k}{j^*}}, \quad (4.18)$$

$$E_i \leq E_i^{thr}. \quad (4.19)$$

Where $U_i(j)$ is the utility of i^{th} CC with respect to j^{th} CC, $U_i(j^*)$ is the utility of i^{th} CC with respect to CC other than j , $U_j(t)$ and $U_j(t+1)$ are utilities of j^{th} CC at time t and $t+1$, respectively, $D_{i \rightarrow k}^*$ indicate the distance between all pairs other than ijk , and E_i^{thr} is the minimum threshold energy required for i^{th} UAV to accomplish its mission.

To achieve the above defined objective function, *SDN-based Location Aware Opportunistic Offloading Scheme using Adaptive Controller is proposed*

4.4 SDN-based Location Aware Opportunistic Offloading Scheme using Adaptive Controller

The proposed scheme works in three phases 1) SDN-based adaptive control scheme for location aware data offloading, 2) Location aware Offloading control scheme, and 3) Network selection scheme.

4.4.1 SDN-based Adaptive Controller for Location Aware Data Offloading

The UAV's applications have been increasing aggressively over the past few years. It can be expected that the number of UAVs will be added to the future network, can create new challenges for UAV communication. As each UAV application demands high quality services, anyhow of location or access type. Besides, traditional UAV network structure depends upon the single overburdened infrastructure, which inherently has the limited wireless capacity. Moreover, it is insufficient to control and manage a large number of network nodes. To fill the gap between availability and demand of communication channel, the heterogeneous network's provisioning can play a crucial role in UAV networks. As a solution for QoS provisioning in heterogeneous UAV network, the proposed SDN-based adaptive control scheme has all the capabilities to caters present and future demands of UAVs communication. Moreover, SDN

empowers easy controllability and manageability by software abstraction of network infrastructure. This abstraction is achieved when the control logic (control plane) is separated from the forwarding devices (data plane). This offers a significant control of the network as it can reconfigure its policies and forwarding rules as and when required. These combined benefits enhance the performance and reduce the complexity of the underlying networks [130]. In this network architecture, the FDs are only limited to traffic forwarding based on the flow rules provided by the centralized controller. OF protocol is used to configure the network element and manage flow control at data plane [131]. Notably, the concept of flow table management delivers numerous advantages such as fast forwarding and flow consideration [132]. Such features help to increase QoS in term of reduced energy consumption, path planning, response time and latency [133]. So in this chapter, an SDN-based framework for adaptive data offloading to avoid congestion in UAVs network is presented. The role of the three decoupled planes of the proposed framework are described as below.

- Data Plane:** At this plane, the core OF switches are located below the edge OF switches, i.e., UAVs (FDs). These FDs act according to the flow entries installed in the flow tables based on the flow rules established by the SDN controller at the control plane. These flow rules are installed on FDs using data-control interface known as the southbound interface (SBI). Moreover, to increase the usability of network resources, virtualization of physical switches is performed by building an instance of OF switches. Even these OF switches contain a set of flow tables and group table for the sake of streamlining the flow table management and fast forwarding of data. These flow tables are interconnected to each other by using a pipeline. Another important function which is performed by the data plane is the verification of the instruction set, created by the centralized controller. This instruction set comprises of the encapsulated header along with data such as priority queue, matching rules and statistics. Based on the flow rules, the FDs can take any of the actions such as forwarding, discarding or resending the packet along with a notification

to the controller. The working of the data plane is explained below with the help of an example as depicted in Figure 4.3.

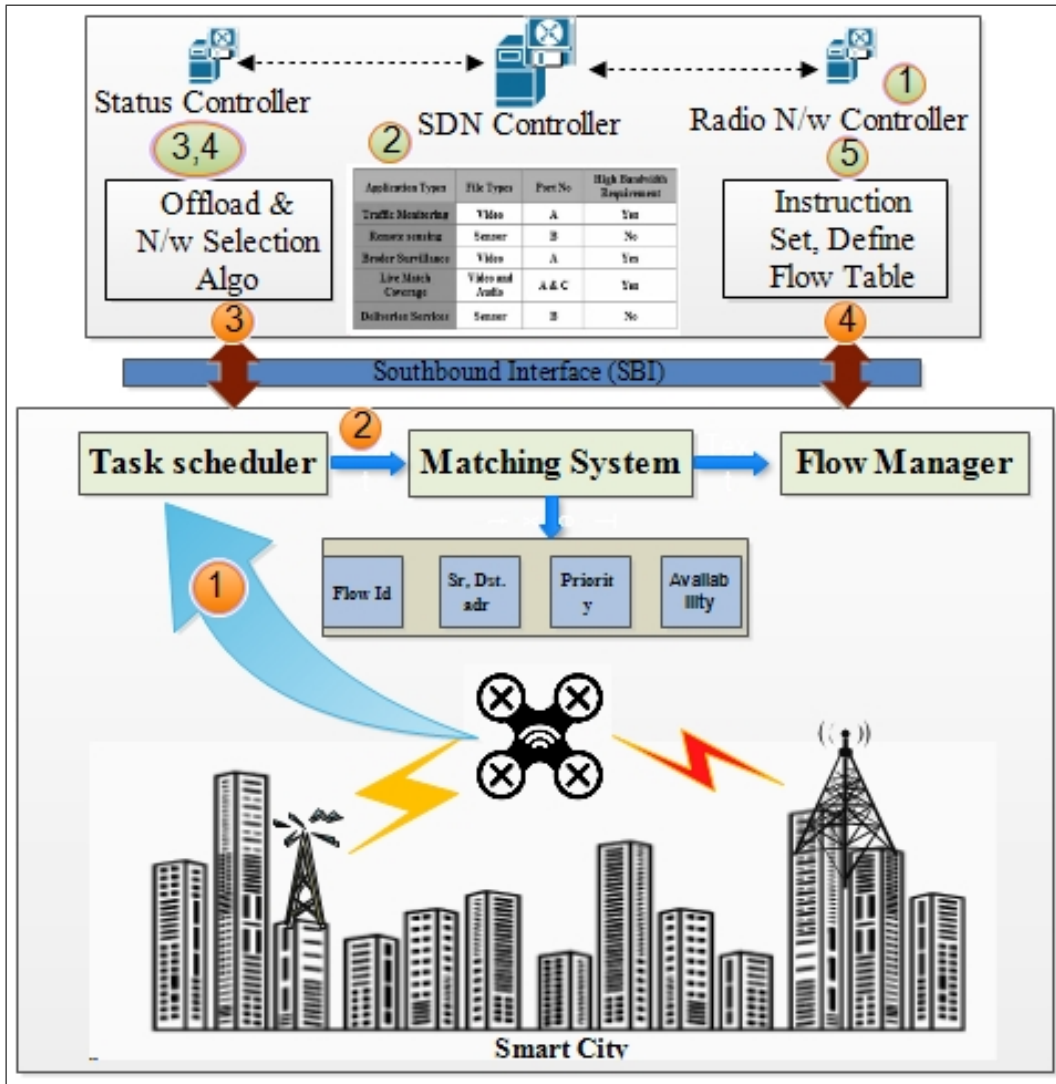


Figure 4.3: SDN-based adaptive controller for data offloading

The incoming data is categorized on the basis of its type (video, audio, sensor, etc.), which is identified from the port address. Each category of the data follows different statistics depending on their bandwidth requirements. Once the data is categorized, then UAV sends the request for offloading. The steps involved in this procedure are explained below:

- Step 1: The UAV that want to offload its data over an appropriate channel sends the migration request. The migration request is received by task scheduler at data plane and queued for further processing.

4.4. SDN-BASED LOCATION AWARE OPPORTUNISTIC OFFLOADING SCHEME USING

- Step 2: The task scheduler matches the input requirements with the instruction set provided by the SDN controller. The instruction set verifies the matching rules, which includes the flow id, source and destination address, priority, traffic rate requirements and availability. Afterwards, a suitable action (forwarding, modifying, discarding, or replicating the request) is taken based on the matched rule.
 - Step 3: The request is now forwarded to the control plane, where the flow manager performs the required execution. Based on the request, flow entries (matching rule, session ID, priority, action and counter) are installed at the flow table. In addition to the flow entries, the proposed scheme includes an additional entry, i.e. a log table, which maintains the log entries with information regarding UAVs route, current location, battery information and when next charging is required.
 - Step 4: Once the flow table is updated, the data packets are offloaded through the selected channel.
 - Step 5: After the entire process is accomplished, the feedback is provided to the controller.
- **Control Plane:** In SDN architecture the control plane comprises of the centralized SDN controller. This centralized controller act as the brain of the architecture. Moreover, it logically maintains dynamic and global network view, receives requests from the application layer and provide instruction sets, control decisions and commands to FD for information passing. Moreover, it takes regular feedback from the FD's and makes changes in the instruction sets if required. All the network policies which are implemented at data plane are created at the control plane. The working of the control plane with the help of an example (as depicted in Figure 4.3) is described below.
 - Step 1: To offload data, the information (such as-UAV's location, and antenna orientation to compute the performance and availability of radio

network in its vicinity) is provided by radio link controller. Using these details, the offload process starts at the control plane.

- Step 2: Status controller identify the data which is to be offloaded on another network channel based on its application type and inputs received from the radio link controller.
 - Step 3: Now, the offload control algorithm is initiated to complete the offload request.
 - Step 4: To accomplish the above step, an appropriate network channel should be selected for offloading the requested data. For this purpose, a network request selection algorithm is initiated.
 - Step 5: Once the destination network channel is selected using algorithm 4. The SDN controller selects a suitable flow path. Based on the selected flow path, appropriate flow entries are established, using which the data is transmitted.
 - Step 6: Finally, to verify the reliability of the flow path, feedback is recorded based on this feedback, the counter is updated.
- **Application Plane:** In SDN architecture, this plane consists of the applications such as energy aware path scheme, security, congestion control, load balancing, channel access, routing and fault tolerance. Besides, it also delivers the QoS statistic to control algorithm based on the feedback received from the application.

4.4.2 Location Aware Offloading and Network Selection Control Scheme

Location aware offloading and network selection control scheme is coordinated by two managers, i.e., priority and network. Initially, the priority manager (\mathcal{P}) sets a threshold value (\mathcal{L}_{thr}). The value of \mathcal{L}_{thr} is calculated using the adjustable threshold

4.4. SDN-BASED LOCATION AWARE OPPORTUNISTIC OFFLOADING SCHEME USING

value calculation process [28] as shown in Algorithm 1. In this algorithm, a random number (p) is assumed as an initial value of \mathcal{L}_{thr} . After this, the average load (L_{av}) is calculated using the total load (L_i) as given in eq. (4.20).

$$L_{av} = \frac{\sum_0^n L_i}{i}. \quad (4.20)$$

Once the L_{av} is calculated, it is compared with p . If the value of p is less than L_{av} , then it is selected as the threshold value otherwise, L_{av} is selected. Based on \mathcal{L}_{thr} , \mathcal{P} classifies the incoming load into low and high priority data. This classification is based on the priority-based scheduling where data streams with high priority are scheduled before data stream with low priority. To decide the priority of respective data, a greedy strategy is known as per-flow priority adjustment and per-router priority adjustment is utilized [28]. The incoming load (\mathcal{L}_i) is calculated as below in eq. (4.21)

$$\mathcal{L}_i = \frac{l(t) - l(t-1)}{l_c}, \quad (4.21)$$

where $l(t)$ denotes the data messages that are arriving at the controller at time t , $l(t-1)$ represents the data messages receives by the same controller at time $t-1$, and l_c is the maximum capacity of the controller to handle total messages.

In the next step, (\mathcal{L}_i) is compared with (\mathcal{L}_{thr}). If \mathcal{L}_i is smaller or equal to \mathcal{L}_{thr} , then the control is passed to the SDN controller, which selects the optimal route for transmitting the data. Now, the data is transmitted using the home network based on the flow statistics set by the SDN controller. However, if \mathcal{L}_i is found to be greater than \mathcal{L}_{thr} , then the control is passed to \mathcal{P} , which sets the priority of \mathcal{L}_i . If \mathcal{L}_i is of high priority, then it is transmitted using the home network based on the flow statistics set by the SDN controller, but subject to, the high priority load should be less than the threshold value. However, if \mathcal{L}_i is a low priority load, then it is offloaded to another available network channel.

To select the destination network channel (N_k), the \mathcal{L}_i is compared with the channel capacity (\mathcal{L}_k^{cp}) of all available channels. If \mathcal{L}_i is less than the \mathcal{L}_k^{cp} , then

Algorithm 4 Location Aware Offloading and Network Selection AlgorithmInput: l_c, p, \mathcal{N}_i Output: \mathcal{N}_k, ijk pair, f_j

```

1: for ( $i = 0; i \leq n; i++$ ) do
2:   Assume:  $p$  as  $\mathcal{L}_{thr}$ 
3:   Compute:  $\mathcal{L}_i = (l(t) - l(t-1))/l_c$ 
4:   Compute:  $L_{av} = \sum_0^n L_i/i$ 
5:   if ( $p < L_{av}$ ) then
6:     Set:  $p$  as  $\mathcal{L}_{thr}$ 
7:   else
8:     Set:  $L_{av}$  as  $\mathcal{L}_{thr}$ 
9:   end if
10:   $\mathcal{L}_{thr}$ 
11:  if ( $\mathcal{L}_i < \mathcal{L}_{thr}$ ) then
12:    Pass control  $\rightarrow$  SDN controller
13:    SDN controller  $\rightarrow$  flow path  $f : s_0 - \dots - s_n$ 
14:    Transmit:  $\mathcal{L}_i$ 
15:    Stop
16:  else if ( $\mathcal{L}_i > \mathcal{L}_{thr}$ ) then
17:    Pass control  $\rightarrow$  Priority manager
18:    if ( $\mathcal{P} == \text{HIGH}$ ) then
19:      Goto Step 12
20:    else if ( $\mathcal{P} == \text{LOW}$ ) then
21:      Set: Selected Network  $\rightarrow \mathcal{N}_k$ 
22:      for ( $k = 0; k \leq n; k++$ ) do
23:        if ( $\mathcal{L}_i < \mathcal{L}_k^{cp}$ ) then
24:          Calculate:  $U_k = \frac{B_{n+i} \times T_{n+i}}{(n+i) \times L_{n+i}}$ 
25:          if ( $U_k(t+1) > U_k(t)$ ) then
26:            Add:  $k$  in destination selection list ( $l_{dst}$ )
27:          end if
28:        end if
29:      end for
30:    end if
31:    Calculate  $U_i = \frac{B_n \times T_n}{(n) \times L_n}$ 
32:    if ( $U_i(k) > U_i(k^*)$ ) then
33:      Sort:  $ik$  pair
34:      Pass control  $\rightarrow$  SDN controller
35:       $\forall ik$  pair, Select  $j$ 
36:      Map: all  $ijk$  pairs
37:      Calculate:  $U_{ijk}$  using eq. (4.12)
38:      if ( $U_{ijk} > U_{ijk^*}$ ) then
39:        Select:  $ijk$  pair.
40:        Set:  $\chi_{ijk} = 1$ 
41:        Offload  $\mathcal{L}_i : \mathcal{N}_i \rightarrow \mathcal{N}_k$ 
42:      end if
43:    end if
44:  end if
45: end for

```

such destination channels calculate their utilities. The utility function (U_k) for the destination channel is calculated as follows in eq. (4.22)

$$U_k = \frac{B_{n+i} \times T_{n+i}}{(n+i) \times L_{n+i}}, \quad (4.22)$$

where B_{n+i} is the total bandwidth allocated to n number of users, T_{n+i} is the throughput of the network and L_{n+i} is the average delay of packets after adding i^{th} users.

The load which is to be offloaded must be less than or equal to the load difference of the controller and forwarding device given as below eq. (4.23).

$$\mathcal{L}_{of} \leq (\mathcal{L}_c - \mathcal{L}_m)/2. \quad (4.23)$$

If the utility at time t is lower than its value at time $t+1$, then the destination channel is added to destination selection list l_{dst} . For all shortlisted channels in l_{dst} , source channel calculates its utility (U_i) as follows in eq. (4.24).

$$U_i = \frac{B_n \times T_n}{(n) \times L_n} \quad (4.24)$$

Based on these utilities, all the ik pairs are sorted, and the control is passed to the SDN controller, which selects flow path j for each pair. Now, map all ijk pairs and compute U_{ijk} for these pairs. Now the value of χ_{ijk} is set to 1 for the best ijk pair. Using the selected pair, \mathcal{L}_i offloads from \mathcal{N}_i to \mathcal{N}_k . Algorithm 4 is designed to depict the entire offloading and network selection process.

4.5 Simulation Results and Discussion

The proposed scheme is evaluated using a simulation-based case study, which is carried out using NS-2 and MiniNet using OF. A simulation setup of Chandigarh city is considered for evaluation wherein random users are arranged using Poisson

distribution. These users are served by 20 UAVs which are configured using random way point model. With an initial network offering at a rate of 256 kb/s, the permissible radio range is set at 200 m. It is assumed that the network service provider is located at the centre of each cell, which is allocated with orthogonal frequency division multiplexing (OFDM) technique to mitigate the inter-cell interference.

The parameters are recorded to understand the efficiency of the proposed scheme

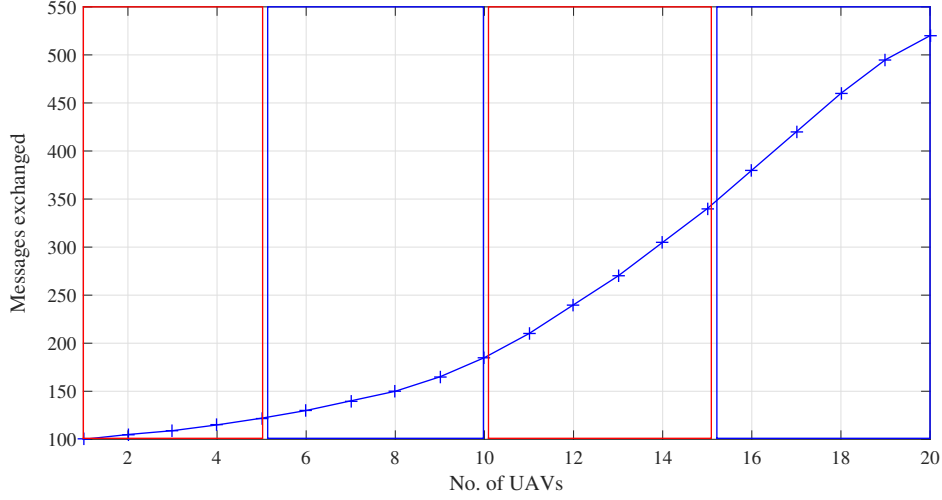


Figure 4.4: Variation of messages exchanged with change in number of UAVs

and compared with two cases, a) only offloading case (without SDN) and b) conventional offloading case (TCP/IP and WiFi). A random operation is used to generate the data traffic for evaluation purpose of the proposed scheme. For evaluation, we have considered 4 cases, i.e., 5 UAVs, 10 UAVs, 15 UAVs and 20 UAVs. Figure 4.4 shows the variation of messages exchanged for all these 4 cases demonstrated as separate boxes.

- **Test Case 1: Handover Latency:** It is defined as below eq. (4.25).

$$H_l = (1 - \delta)(T_f + T_w)\delta T_h \quad (4.25)$$

Where, δ denotes the probability of successful handover, T_f represents the time taken to retry in case of failure of a handover, T_w is the time taken to wait for the establishment of a handover, and T_h denotes the handover time. The

handover latency for the test case 1 is depicted in Figure 4.5. The handover latency for the proposed scheme is show better results in term of lower latency than the conventional scheme such as- TCP/IP, and WiFi. However, it is observed that handover latency increases with an increase in the number of UAVs. This is due to an increase in the number of handovers.

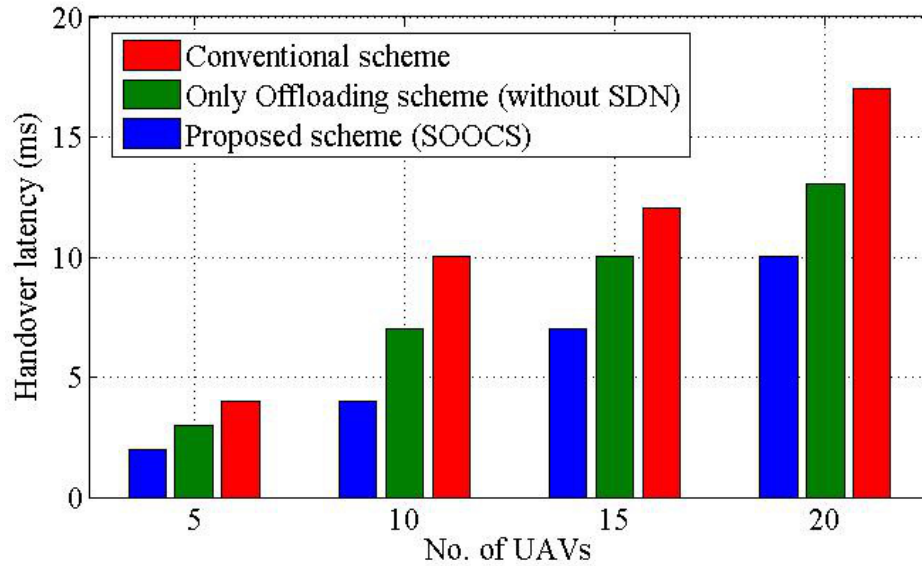


Figure 4.5: Impact on Handover latency w.r.t the numbers of UAVs

Table 4.2: Hypothesis t-Test: Soocs vs Without SDN for Handover Latency

<i>Parameter</i>	<i>Soocs</i>	<i>Without SDN</i>	<i>Analysis</i>
Mean	5.75	8.25	Without SDN is larger
Variance	12.25	18.25	
Observations	4	4	
Pearson Correlation	0.986489669		
Hypothesized	0		
Mean Difference			
df	3		
t stat	-5		t Stat is larger in absolute than the t-critical value
P(T _i =t) one-tail	0.007696219		
t Critical one-tail	2.353363435		
P(T _i =t) two-tail	0.015392438		reject the null hypothesis
t Critical two-tail	3.182446305		

Table 4.3: Hypothesis t-Test: Soocs vs Conventional Scheme for Handover Latency

<i>Parameter</i>	<i>Soocs</i>	<i>Conventional</i>	<i>Analysis</i>
Mean	5.75	10.75	Conventional Scheme is larger
Variance	12.25	28.91666667	
Observations	4	4	
Pearson Correlation	0.969662745		
Hypothesized Mean Difference	0		
df	3		
t stat	-4.629100499		t Stat is larger in absolute than the t-critical value
P(T _i =t) one-tail	0.009493116		
t Critical one-tail	2.353363435		
P(T _i =t) two-tail	0.018986231		reject the null hypothesis
t Critical two-tail	3.182446305		

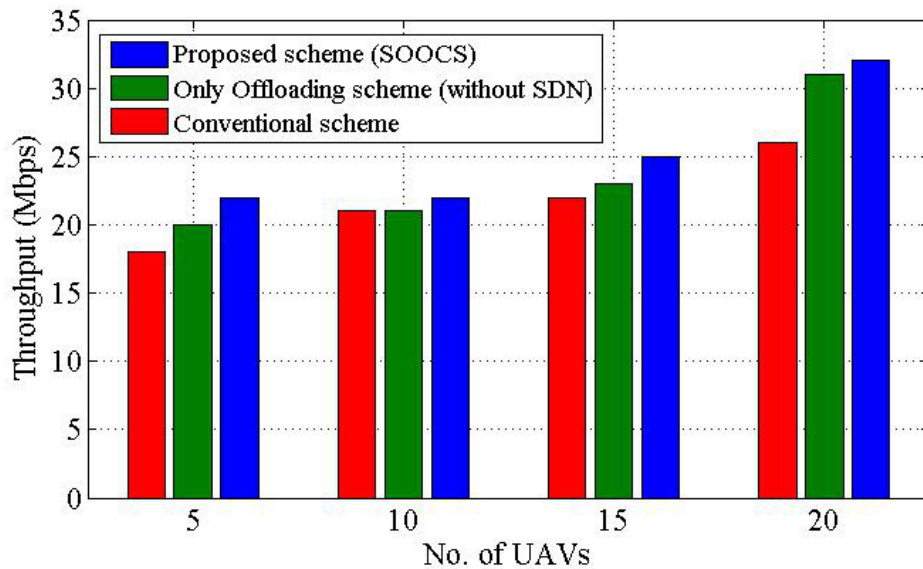


Figure 4.6: Impact on Throughput vs number of UAVs

- **Test Case 2: Network Throughput:** The stability and reliability of a network are measured using throughput. It is desirable that throughput should be high and close to the offered rate of the network. Throughput is defined as the number of bits that are transferred concerning the time taken by the channel over which the traffic is transmitted. The throughput for the proposed scheme is observed to understand the stability and reliability of the connectivity. Figure

Table 4.4: Hypothesis t-Test: Soocs vs Without SDN Scheme for Throughput

<i>Parameter</i>	<i>Soocs</i>	<i>Without SDN</i>	<i>Analysis</i>
Mean	25.25	23.875	Soocs is larger
Variance	22.25	24.72916667	
Observations	4	4	
Pearson Correlation	0.99651048		
Hypothesized Mean Difference	0		
df	3		
t stat	5.74456265		t Stat is larger in absolute than the t-critical value
P(T _i =t) one-tail	0.005		
t Critical one-tail	2.35336343		
P(T _i =t) two-tail	0.01047709		reject the null hypothesis
t Critical two-tail	3.1824463		

Table 4.5: Hypothesis t-Test: Soocs vs Conventional Scheme for Throughput

<i>Parameter</i>	<i>Soocs</i>	<i>Conventional</i>	<i>Analysis</i>
Mean	25.25	21.75	Soocs is larger
Variance	22.25	10.91666667	
Observations	4	4	
Pearson Correlation	0.925027884		
Hypothesized Mean Difference	0		
df	3		
t stat	3.36269123		t Stat is larger in absolute than the t-critical value
P(T _i =t) one-tail	0.021823117		
t Critical one-tail	2.35336343		
P(T _i =t) two-tail	0.043646235		reject the null hypothesis
t Critical two-tail	3.1824463		

4.6 shows the throughput observed for varying numbers of UAVs maintains a high throughput value, which is better in comparison to the other two cases.

- **Test Case 3: End-to-End Delay:** It is defined as the sum of various types of delays (propagation, transmission, queuing and processing delays). It is always desired that the delay incurred should be low as it represents the possibility

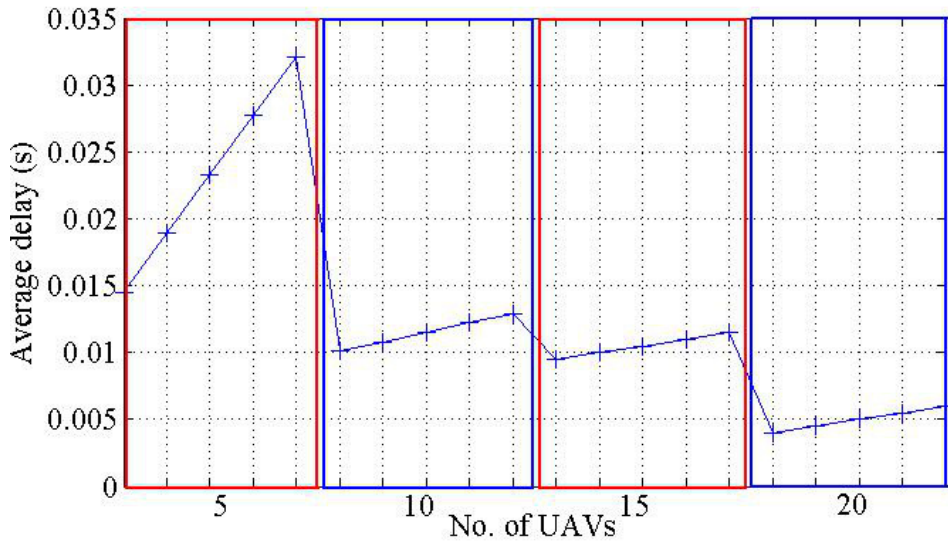


Figure 4.7: Average delay w.r.t the number of UAVs

of the least congested channel, which is most desirable in an efficient multi-UAV network. For these messages exchanged, the observed average delay is shown in Figure 4.7. It is evident from the figure that as the number of UAVs increases, the average observed delay decreases. This is due to the fact that an efficient offloading process is performed which reduces the delay anticipated at the home network. To support this fact, Figure 4.8 shows the end-to-end latency observed in contrast to two comparative cases. It is clear that the end-to-end latency observed decreases gradually with an increase in the number of UAVs.

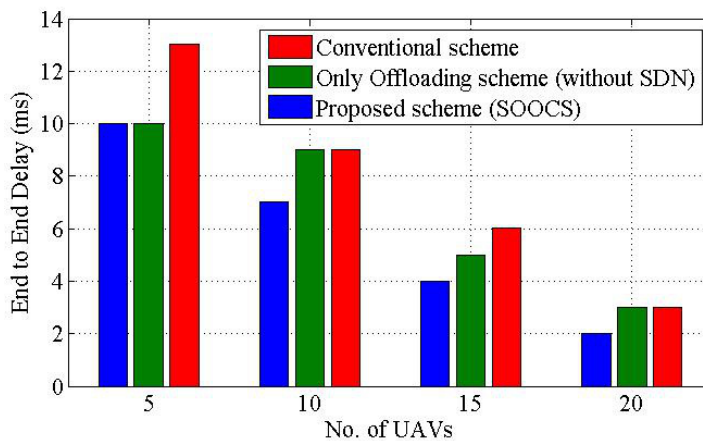


Figure 4.8: Impact on End-to-End delay w.r.t the number of UAVs

Table 4.6: Hypothesis t-Test: Soocs vs Without SDN Scheme for Delay

<i>Parameter</i>	<i>Soocs</i>	<i>Without SDN</i>	<i>Analysis</i>
Mean	5.75	6.75	Without SDN is larger
Variance	12.25	10.9166666	
Observations	4	4	
Pearson Correlation	0.972835597		
Hypothesized Mean Difference	0		
df	3		
t stat	-2.449489742		t Stat is smaller in absolute than the t-critical value
P(T _i =t) one-tail	0.045860557		
t Critical one-tail	2.353363435		
P(T _i =t) two-tail	0.091721113		accept the null hypothesis
t Critical two-tail	3.182446305		

Table 4.7: Hypothesis t-Test: Soocs vs Conventional Scheme for Delay

<i>Parameter</i>	<i>Soocs</i>	<i>Conventional</i>	<i>Analysis</i>
Mean	5.75	7.75	Conventional is larger
Variance	12.25	18.25	
Observations	4	4	
Pearson Correlation	0.997636445		
Hypothesized Mean Difference	0		
df	3		
t stat	-4.89897949		t Stat is larger in absolute than the t-critical value
P(T _i =t) one-tail	0.008138302		
t Critical one-tail	0.016276603		
P(T _i =t) two-tail	0.016276603		reject the null hypothesis
t Critical two-tail	3.182446305		

Therefore, it is evident from the observed results that the proposed scheme performs better in terms of all the evaluation parameters, and hence, it is a promising approach to be deployed in realistic multi-UAV scenarios.

4.6 Summary

In Chapter 4, an efficient location aware scheme is designed to build the home channel congestion free, in which the data traffic is offloaded to another available channel opportunistically. UAVs are used as forwarding nodes in SDN model, wherein the location aware and network selection algorithm finds an optimal flow path for offloading of data and forwarding it to the destination. To evaluate the performance of the proposed scheme, a simulation-based evaluation is performed. This also shows the effectiveness of the proposed scheme for the multi-UAVs ecosystem in term of lower handover latency, end-to-end delay, and higher throughput. This chapter also accomplishes all objectives by developing an efficient location aware technique for the multi-UAVs network. The technique also helps in QoS provisioning, performance validation and comparison with existing techniques.

4.6.1 Future Work

This work can be further extended using some self learning mechanism (transfer learning) for embedding intelligence during the offloading process.

Chapter 5

SLAO Energy Charging Scheme

5.1 Overview

To sustain the flight of UAV throughout the mission, a sufficient amount of energy needs to be maintained in UAVs battery. However, with limited battery capacity, it becomes a tough challenge. Deploying additional batteries can increase the weight of a UAV's, which are not desirable. It is not possible to ground a UAV during its flight to charge the batteries, as it hinders the mission. Therefore, to handle these issues, an opportunistic wireless charging scheme is designed in order to sustain the energy of a UAV's batteries on the flight using charging points deploying at various locations. By adopting this scheme, the flight time of a UAV can be extended. In this chapter, a solar harvesting technique is used to increase the lifetime of the UAV's batteries. If sufficient solar energy is not available to charge the UAV's batteries, a location aware wireless charging scheme is used to sustain the life of a UAV battery.

5.2 System Model

The system model for "SDN-enabled Location Aware Opportunistic Energy Charging Scheme" is same as the system model presented in section 4.2.

5.3 Energy Consumption Model

The total energy consumption (E_i^{to}) of a UAV comprises of three components;

1. Transition energy (E_i^{tr}),
2. Hover energy (E_i^h) which is for the movement of UAVs and
3. Energy required for communication (E_i^c)

The total energy consumption of an UAV is given as below [134]:

$$E_i = \sum_i (E_i^{tr} + E_i^{ho} + E_i^c), \quad (5.1)$$

where E_i^{tr} is dependent on the average speed of a UAV, which is calculated as below.

$$E_i^{tr} = \frac{E_{full}^{tr} - E_{idle}^{tr}}{S_{max}} \times S_{avg} + E_{idle}^{tr}, \quad (5.2)$$

where S_{max} is the maximum speed of a UAV, and S_{avg} is the average speed of an UAV (which remain constant during the operation) E_{full}^{tr} is UAV's hardware energy level when UAV moves at its full speed, E_{idle}^{tr} is when UAV stops in a fixed position to transit the data.

The energy consumed by a UAV while hovering is given as below eq. (5.3).

$$E_i^{ho} = \sqrt{\frac{(U_{mass}g)^3}{2(\pi)\nu_p^2\varsigma_p\varrho}}, \quad (5.3)$$

where U_{mass} , g and ϱ are the UAV mass in (kg), gravity in (m/s^2), air density in (kg/m^3) respectively, ν_p is the radius of the propellers and ς_p is the number of propellers in a UAV.

However, a major chunk of energy is consumed by communication processes E_i^c (receiving and sensing data) [135].

$$E_i^c = m \times (E_{elec} + E_{amp})J, \quad (5.4)$$

where in eq. (5.4), m represents the bits transmitted by UAV, E_{elec} is the energy consumed for actuation, sensing, signal transmission and E_{amp} is the energy consumed for communication which varies with the distance.

5.4 Solar Harvesting Model

In this scheme, it is assumed that UAVs are equipped to harvest energy from the photovoltaic (PV) energy to recharge their batteries. The PV energy is produced by capturing the radiant heat on PV panels, which is converted into energy. However, the energy produced by PV panels varies on the basis of various parameters such as solar radiations (R), radiation angle of sunlight (α), conversion efficiency (ρ), and size of panel respectively (S) [136, 137]. The energy (E_i^{pv}) generated using PV panels by capturing sunlight is given as below:

$$E_i^{pv} = (1 - l_{ex})RS_i\cos(\alpha)\rho \quad (5.5)$$

where in eq. (5.5), l_{ex} denotes the loss occurred due to the temperature exceedance of battery container due to cold weather.

5.5 Wireless Charging Model

Wireless charging can be performed in three ways: resonance, magnetic induction and radio reception. Resonance transfers the energy only when the sender and receiver are at the same frequency, while magnetic induction transfers the energy into electromagnetic phenomena. Radio reception transforms the electromagnetic waves into the current and is preferred to charge low power devices from a distance. According to the requirement of UAV ecosystem, the radio reception technique is an appropriate method for wireless charging.

In the proposed framework, the wireless charging model, which is used to design

the opportunistic energy charging scheme for UAVs, is given as below.

$$P_r = \frac{G_t G_r P_t \eta}{L_{po}} \left(\frac{\lambda}{4\pi(D + \beta)} \right)^2, \quad (5.6)$$

where in eq. (5.6), P_r symbolizes the source transmission power, P_t is the power available at receiver, G_t , G_r is the source and receiver antenna gain, respectively, η denotes the rectifier efficiency, L_{po} is the polarization loss, D is the distance between source transmitter and receiver, λ is the wavelength, β is constant to adjust Friis free space equation for short distance transmission.

The Friis free equation is further simplified as $P_r = \frac{\gamma}{(D+\beta)^2}$ and $\gamma = \frac{G_t G_r P_t \eta}{L_{po}} \left(\frac{\lambda}{4\pi} \right)^2$ and the value of γ and β are 4.32×10^{-4} and 0.2316, respectively [138]. Moreover, the received power of node is dependent upon the distance between the source and the receiver, i.e., if the distance increases, the received power will decrease. Also, if the distance exceeds certain threshold, the received power is negligible at the receiver's side. Thus, the following condition must be satisfied for efficient working of a charging model.

$$P_r = \begin{cases} \frac{\gamma}{(D+\beta)^2}, & D \leq C_r, \\ 0, & D > C_r. \end{cases} \quad (5.7)$$

where in eq. (5.7), C_r indicates the charging range.

5.6 Charging Characteristics

It is assumed that the location-aware UAVs are uniformly distributed in $2A \times 2A$ network with a communicating range (r). For every communication interval (C_s), UAVs relay data and energy information to the controller on the base station. The energy consumption is calculated using the energy model. Now, if a UAV requires to charge its batteries to share energy level and location information to the controller base station. Herein, for ease of path planning the network is divided into numerous uniformly sized grids. Figure 5.1 depicts that the vertices of the grid are taken as

the charging points C_p . To make the calculation easy, the side length D of each grid should be divisible by $2A$. With this, the calculated value of D , the number of charging points required and the coverage of the charging can be found. To determine the size of the charging grids, two cases are possible based on the relation between the side length D and charging range C_r . In the first case, all the UAVs within grids can be charged, wherein the maximum value of D is $\sqrt{2}C_r$. In the second case (D is equal to C_r), the UAVs can only be charged from four charging points in the grid. Moreover, to shorten the path length and optimize charging performance, the value of D must lie between : $C_r \leq D \leq \sqrt{2}C_r$. In this layout, E , F , G and H denotes the charging points and dashed lines shows the charging range.

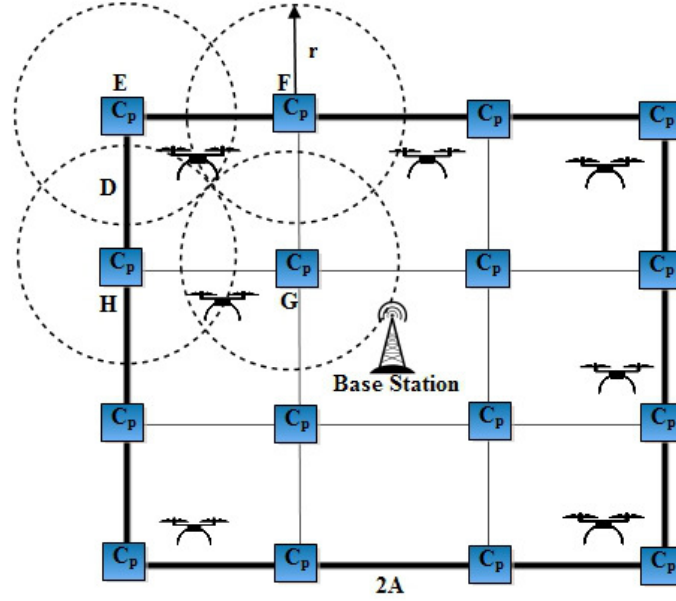


Figure 5.1: Representation of charging points for wireless charging

Following the grid size determination, the controller at the base station broadcasts the position of the charging points to the UAVs. Now, each UAV computes the received power on the distance between itself and its charging points. The Figure 5.1 depicts i^{th} UAV with coordinates (x_i, y_i) and located in E , F , G , H charging points in the grid. However, the coordinates of the charging points are $(\lfloor \frac{x_1}{D} \rfloor \times D, \lfloor \frac{y_1}{D} \rfloor \times D)$, $(\lceil \frac{x_2}{D} \rceil \times D, \lfloor \frac{y_2}{D} \rfloor \times D)$, $(\lfloor \frac{x_3}{D} \rfloor \times D, \lceil \frac{y_3}{D} \rceil \times D)$, $(\lceil \frac{x_4}{D} \rceil \times D, \lceil \frac{y_4}{D} \rceil \times D)$ respectively. The following eq. (5.8) to (5.11) are used to calculate the distance

between i^{th} UAV and the charging points.

$$D(i, E) = \sqrt{(x_i - (\lfloor \frac{x_1}{D} \rfloor \times D))^2 + (y_i - (\lfloor \frac{y_1}{D} \rfloor \times D))^2}, \quad (5.8)$$

$$D(i, F) = \sqrt{(x_i - (\lceil \frac{x_2}{d} \rceil \times D))^2 + (y_i - (\lfloor \frac{y_2}{D} \rfloor \times D))^2}, \quad (5.9)$$

$$D(i, G) = \sqrt{(x_i - (\lfloor \frac{x_3}{D} \rfloor \times D))^2 + (y_i - (\lceil \frac{y_3}{d} \rceil \times D))^2}, \quad (5.10)$$

$$D(i, H) = \sqrt{(x_i - (\lceil \frac{x_4}{d} \rceil \times D))^2 + (y_i - (\lceil \frac{y_4}{d} \rceil \times D))^2}. \quad (5.11)$$

Now, the total amount of energy (E_i^{cp}) received by k^{th} UAV from four charging vertices is given as below.

$$E_i^{cp} = \gamma \left(\frac{1}{(D(i, E) + \beta)^2} + \frac{1}{(D(i, F) + \beta)^2} + \frac{1}{(D(i, G) + \beta)^2} + \frac{1}{(D(i, H) + \beta)^2} \right), \quad (5.12)$$

where γ is a predefined constant.

5.7 Proposed Location Aware Opportunistic Energy Charging Algorithm

To enhance the flight time of a UAV, an opportunistic energy charging scheme is designed. Initially, the controller checks the energy available with the i^{th} UAV at time t (E_i^{prs}). If E_i^{prs} is less than the rated capacity of i^{th} UAVs battery (E_i^{rt}), then the UAV need to charge energy. For this purpose, the energy required by i^{th} UAV is given as below eq. (5.13).

$$E_i^{req} = E_i^{rt} - E_i^{prs}. \quad (5.13)$$

In the proposed scheme, the E_i^{req} is also compared with the E_i^{thr} (it is set by the UAV side based on the minimum amount of energy required by a UAV to the base). Apart from the above comparison, the solar radiations (R) available at time t

5.7. PROPOSED LOCATION AWARE OPPORTUNISTIC ENERGY CHARGING ALGORITHM

are also compared with the threshold value of radiations (R_{thr}) required to generate energy by the solar harvesting plates deployed at the UAV. On the basis of these comparisons, three cases exist for availing opportunistic energy charging, which is depicted below.

$$\varphi = \begin{cases} 1, & \text{if } E_i^{req} < E_i^{thr}, R(t) \geq R_{thr}, \\ 2, & \text{if } E_i^{req} < E_i^{thr}, R(t) < R_{thr}, \\ 3, & \text{otherwise } E_i^{req} \geq E_i^{thr}. \end{cases} \quad (5.14)$$

Based on the above cases, Algorithm 5 is designed, which is given as below.

Algorithm 5 Opportunistic Energy Charging Algorithm

Input: E_i^{prs} , $R(t)$, E_i^{thr} , R_{thr}

Output: φ

- 1: Check E_i^{prs} at time t .
 - 2: **if** ($E_i^{prs} < E_i^{rt}$) **then**
 - 3: Compute $E_i^{req} = E_i^{rt} - E_i^{prs}$
 - 4: **if** ($E_i^{req} < E_i^{thr}$) **then**
 - 5: Check R at time t .
 - 6: **if** ($R(t) > R_{thr}$) **then**
 - 7: SET: $\varphi = 1$
 - 8: Charge E_i^{req} from solar harvester.
 - 9: Compute E_i^{pv}
 - 10: **if** ($E_i^{req} > E_i^{pv}$) **then**
 - 11: Compute $E_i^{def} = E_i^{req} - E_i^{pv}$
 - 12: SET: $\varphi = 2$
 - 13: Reach coordinates $[(i, E), (i, F), (i, G), (i, H)]$
 - 14: Charge E_i^{cp} from charging points.
 - 15: **end if**
 - 16: **else**
 - 17: SET: $\varphi = 2$
 - 18: Reach coordinates $[(i, E), (i, F), (i, G), (i, H)]$
 - 19: Charge E_i^{cp} from charging points.
 - 20: **end if**
 - 21: **else**
 - 22: SET: $\varphi = 3$
 - 23: Ground UAV to charge required energy
 - 24: **end if**
 - 25: **else**
 - 26: No charging required
 - 27: **end if**
-

The three cases depicted in eq. (5.14) are explained as below.

- **Case 1:** The UAV can continue its mission, but it can charge its batteries to maintain its energy level from solar harvested. In this case, the solar harvester is receiving a sufficient amount of radiations to generate E_i^{pv} .

Apart from the above discussed scenario, there exists some special considerations also. If E_i^{pv} generated by solar harvester is less than the E_i^{req} , then the energy deficit (E_i^{def}) is calculated as given below in eq. (5.15).

$$E_i^{def} = E_i^{req} - E_i^{pv}. \quad (5.15)$$

If E_i^{def} exists, then the value of φ is set as 2 and the process explained in case 2 is initiated.

- **Case 2:** The UAV can continue its mission but it cannot charge its batteries to maintain its energy level from the solar harvested. In this case, the solar harvester is not receiving a sufficient amount of radiations to generate E_i^{pv} . Therefore, the UAV travels to some specific location coordinates provided by the controller (as per section 4.4.1) and charge E_i^{cp} from the multiple charging points.
- **Case 3:** ($E_i^{req} \geq E_i^{thr}$): This is an emergency case, wherein the E_i^{req} by i^{th} UAV's battery is higher than E_i^{thr} and there exists no possibility of maintaining sufficient energy to sustain the mission. In such a case, the UAV has to be grounded to charge energy.

5.8 Simulation Results and Discussion

Now, the proposed opportunistic charging scheme is evaluated with respect to a realistic deployment of charging points at various locations as depicted in Figure 5.2.

Moreover, the solar radiations (12 hours) considered have been taken from is shown in Figure 5.3. The solar radiation are varies with the movement of sun such that the radiation is maximum at 1400hrs to 1600hrs. Moreover, clearly depicted as per figure that the radiations above R_{thr} are enough to generate solar energy, which can be used to sustain a UAV on the fly. Table 5.1 depict different types of batteries used in the UAVs for evaluation of the opportunistic energy charging scheme.



Figure 5.2: Deployment of charging points

Now, the proposed scheme is first evaluated for a UAV, wherein, the energy required by UAV at different time slots is shown in Figure 5.4. This energy requirement is based on various activities and performance evaluations of a UAV. To make a UAV fly the required energy has to be replenished from either solar energy (through solar harvesting using solar plates) or through wireless charging from

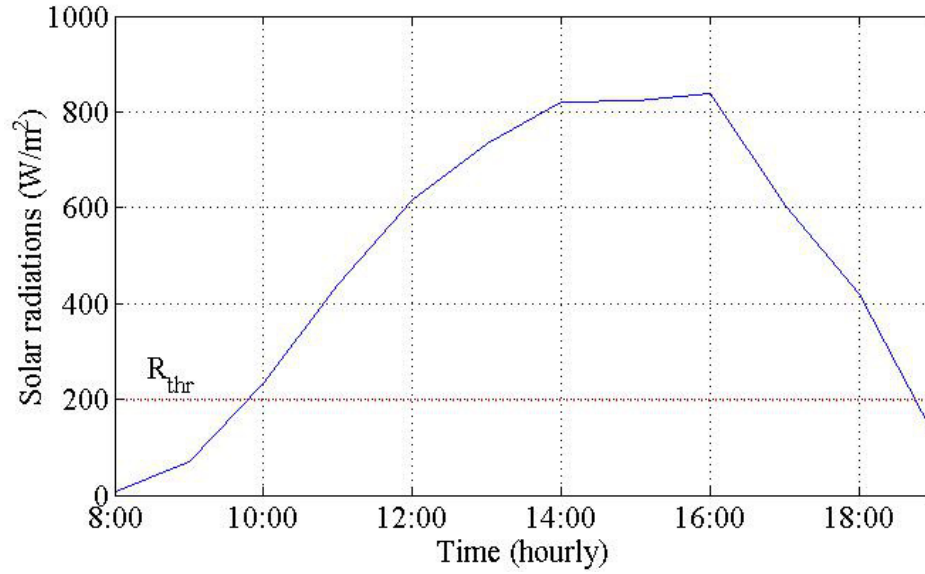


Figure 5.3: Impact on Solar radiations w.r.t time

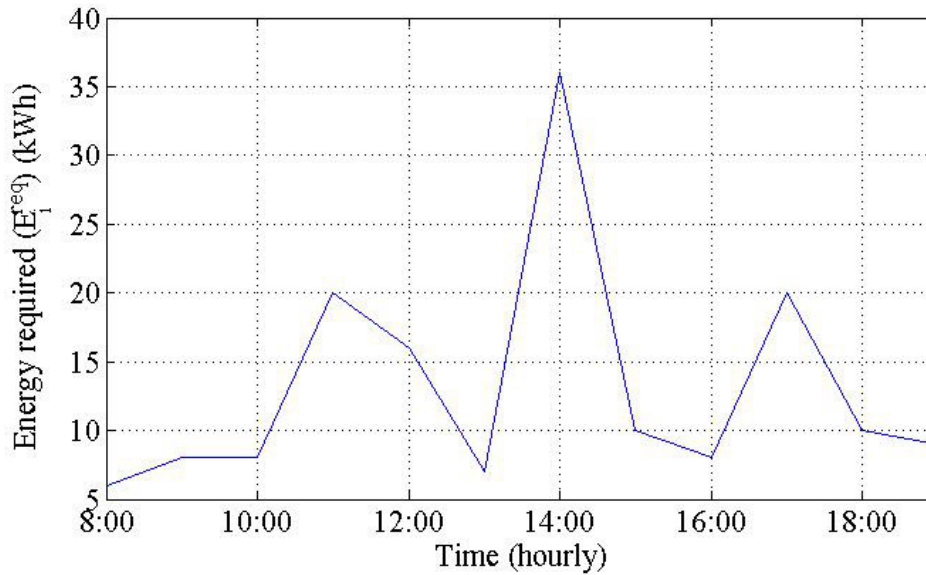


Figure 5.4: Energy required by single UAV

Table 5.1: Battery specifications of EVs

Model	Type	E_i^{rt} (Wh)	Capacity (mAh)	Charging Voltage (VDC)	Mass (g)
Panasonic NCR 18650B	LI	11.2	3.2	3.6	0.047
Zippy Flight Max	LP	111	5	22.2	0.703
MaxAmps MA6S11000	LP	144.2	11	22.2	1.235
MaxAmps MV5450	LP	19.8	5.4	3.7	0.131

Note: LI: Lithium Ion, LP: Lithium Polymer

charging points deployed in the city shown in Figure 5.2.

The mapping of energy required with the energy available from solar plates is

shown in Figure 5.5. It depicts two coloured bars, 1) green colour bars depict the time slots and amount of energy charged from solar plates, and 2) red bar represents the energy deficit that needs to be replenished from charging points using wireless charging scheme.

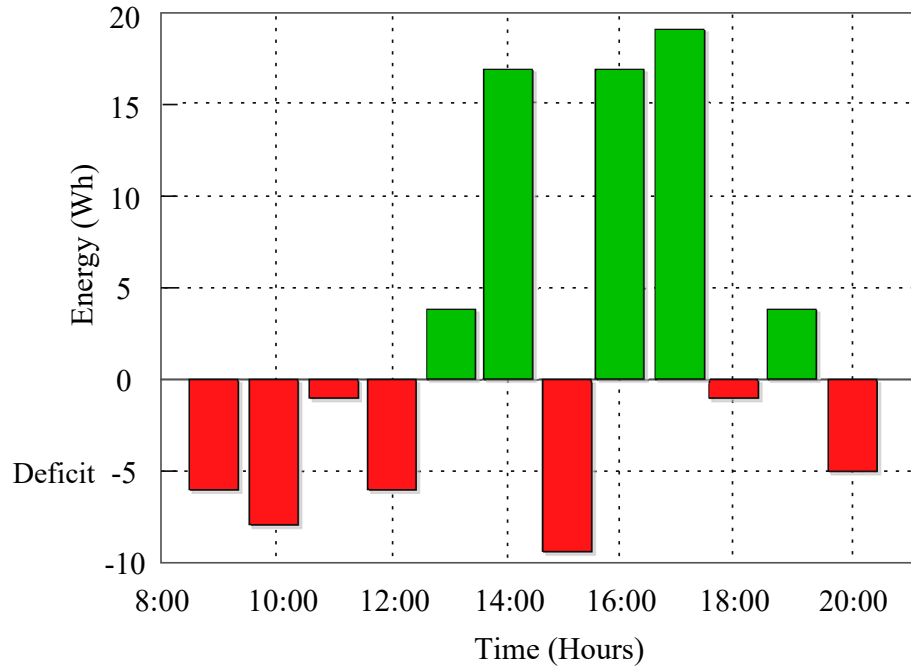


Figure 5.5: Energy map with respect to solar harvester

The deficit in energy after charging using solar plates, which is charged from charging points is shown in Figure 5.6. Therefore, the purpose of the proposed scheme is successfully accomplished. The Figure 5.7 shows a scenario where the number of UAVs increases, the energy consumption of the proposed scheme are 78% and 81.2% less as compared to the existing DD and RIDS (energy efficient routing algorithm) schemes. The performance also impact on the network lifetime as the energy consumption decreases, the network lifetime increases.

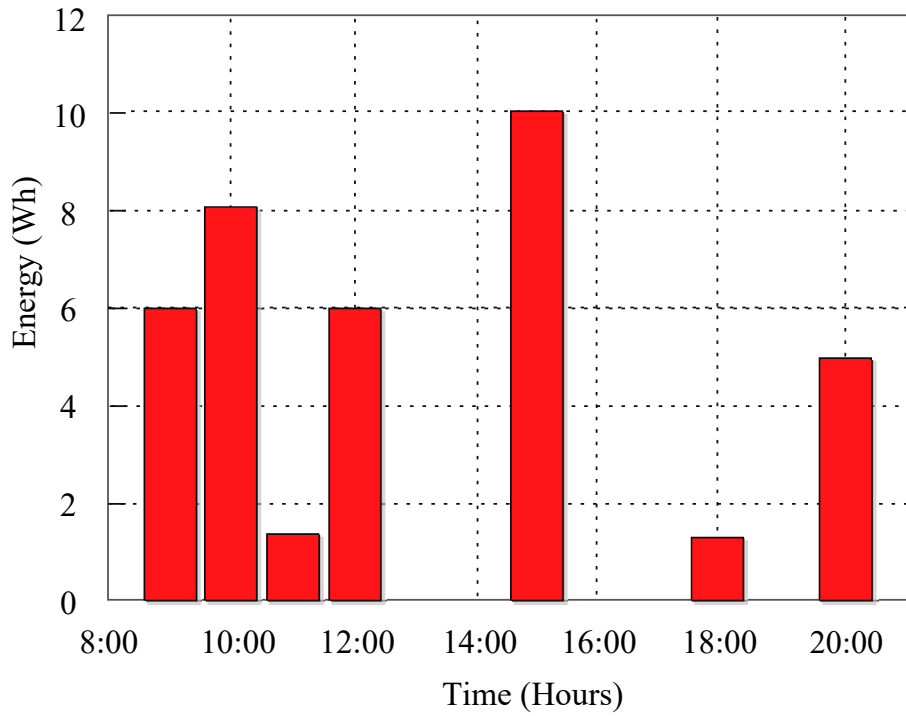


Figure 5.6: Energy drawn from charging points

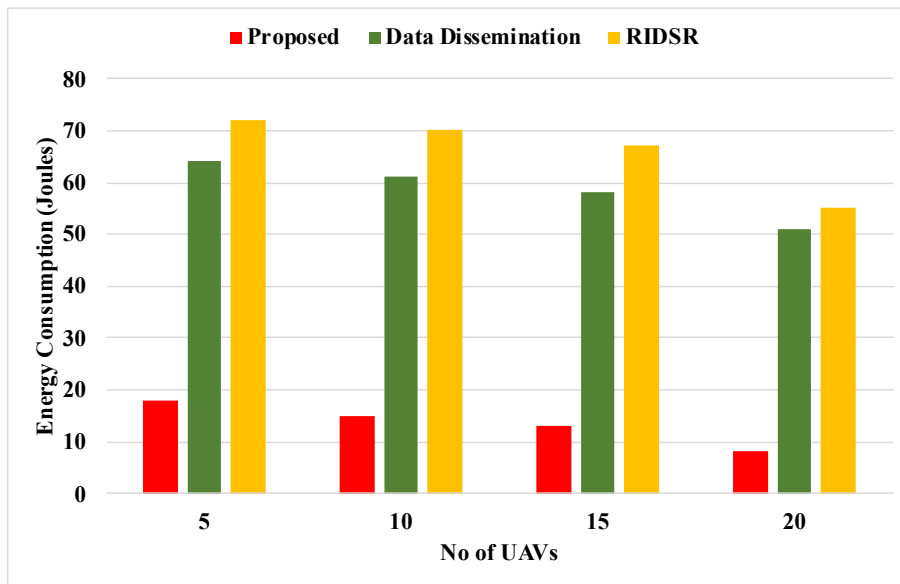


Figure 5.7: Comparison of energy consumption for proposed technique with data dissemination and RIDSRS (energy efficient routing algorithm).

5.9 Summary

This Chapter presents a location aware opportunistic energy charging scheme that helps to extend the lifetime of the operating UAV. For this, an opportunistic charging through solar harvesting using solar plates and wireless charging through charging

points is proposed in the scheme. For this purpose, a realistic deployment of charging points and UAVs in a city is used. Moreover, this case study is used to evaluate the performance of the opportunistic charging scheme. The case study proves the effectiveness of the proposed scheme. This chapter also accomplishes the first objective by developing an efficient location aware energy charging technique for the multi-UAVs network.

5.9.1 Future Work

In future, this work can be implemented using real test bed scenario for understanding the implications with respected to realistic infrastructure characteristics.

Chapter 6

Conclusion and Future Scope

The main contribution of this thesis is to provide location-aware, congestion free, collision free and energy-efficient UAV network. However, the provisioning of these metrics is a challenging task. For the purpose three techniques utilizing the different environments for UAV networks were proposed in this work.

In Chapter 3, the requirement of efficient location-aware Medium Access Control for collision and congestion free transmission for UAV network is consider as a core problem . An efficient media access control strategy is proposed which also considers the energy requirements along with the location of each drone in the network to avoid the bottlenecks (if any) that may tend to fail the entire network. The main observations are:

- The model formalized an efficient solution, which provided sustainable connectivity in drone networks with efficient control as well as the provisioning of applications at high quality of service.
- The scheme utilized the properties of the firefly optimization algorithm and formed an efficient timing slot mechanism that results in the formation of an energy-efficient and location-aware Medium Access Control for unmanned aerial vehicle networks.
- The scheme was numerically tested followed by network simulations by using

end users in transmission mode with the UAVs.

- The simulation study suggested that the scheme is capable of providing congestion-free, collision-free and energy efficient Medium Access Control with improvements in signalling and conservation of energy.
- The proposed scheme performs better in terms of packet delivery ratio, average throughput and end-to-end delay. It also provides a better channel utilization (more than 90%) in contrast to the existing variants of this category.

In Chapter 4, an SDN-enabled location-aware opportunistic offloading scheme for multi-UAVs ecosystem is designed wherein the data traffic is offloaded to any other available channel in an opportunistic manner to provide channel congestion free communication.

- To fully understand the functionality of the proposed technique, 1) a location-aware offloading, 2) network selection algorithms are formulated.
- The algorithms provide an optimal channel according to the migration request received by the task manager.
- The proposed technique is able to reduce the handover latency, end-to-end delay and provides a high throughput in contrast to the existing state-of-the-art-solutions.

In chapter 5, an SDN-enabled location-aware opportunistic wireless energy charging scheme is proposed for UAVs on the fly in order to replenish the battery of UAVs while performing their tasks.

- A solar harvesting technique is presented wherein UAVs are equipped with photovoltaic solar panels to generate energy on the fly.
- The UAVs can charge their battery from the geo-located charging point using the wireless charging technique in the absence solar energy.

- The controller provides the path planning and shares the coordinates of the charger with the UAVs.
- A simulated deployment of charging points in a city is placed and a case study has been evaluated to prove the effectiveness of the proposed scheme.

6.1 Future Scope

Although the main aim of this thesis work, i.e., to provide location-aware, congestion free, collision avoidance and energy efficiency for UAVs network has been achieved successfully. Some of the suggestions, which can contribute to expand this work as listed as follow:

- The major aim of the work has been focused on the QoS parameters maintenance for UAVs network while serving the ground users. More number of QoS parameters can be consider for further improvement of the developed schemes.
- The security measures can also be include in the developed schemes. This will enhance the reliability of the schemes.
- In the developed schemes, real time deployment with addition in objective functions will provide more versatility to the schemes.
- In wireless energy charging scheme the studied scenario is limited to one UAV, it can be explored for multiple UAVs.

Research is a continuous process. The work presented in this thesis can be utilized for the deployment of UAVs in various consumer-based applications and service across the smart city. For this reason, two location-aware futuristic models, 1) Drone-as-a-Product delivery agent, and 2) Drone-as-a-QoS enhancement agent for Internet services for consumer applications as future research directions have been addressed for research community.

- **Location-aware Drone as a Delivery Agent:** In the futuristic smart cities, most of consumer applications are expected to rely on innovative technologies and techniques for minimizing the human effort and involvement in their business accomplishments. Therefore, major companies and service providers are eyeing towards the delivery of their products, medicines and parcels using drones.
- **Location-aware Drone as a QoS Enhancement Agent for Internet Services:** In this model, the drones are used as QoS enhancement agent for provisioning of Internet services in remote area and disaster affected areas. The drones act as aerial small cells that are connected to the macro base station in order to serve a geographical area. UAVs are used for relaying data and provisioning Internet services in the areas where the consumers face the challenges of congestion, poor signal and low data rate. Using drones as mobile small cells, the Internet consumers are provided a wide coverage with high data rate, which help to reduce the operational and capital expenditure in next generation 5G cellular networks.

References

- [1] FAA, *FAA Publishes First Set of UAS Facility Maps*, 2017, (Accessed on: March 2018). [Online]. Available: <https://www.faa.gov/news/updates/?newsId=87945>
- [2] Z. Kaleem, M. H. Rehmani, E. Ahmed, A. Jamalipour, J. J. Rodrigues, H. Moustafa, and W. Guibene, “Amateur drone surveillance: Applications, architectures, enabling technologies, and public safety issues: Part 1,” *IEEE Communications Magazine*, vol. 56, no. 1, pp. 14–15, January 2018.
- [3] M. Wazid, A. K. Das, N. Kumar, A. V. Vasilakos, and J. J. Rodrigues, “Design and analysis of secure lightweight remote user authentication and key agreement scheme in internet of drones deployment,” *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3572–3584, April 2018.
- [4] Facebook, *The technology behind Aquila*, (Accessed on: March 2018). [Online]. Available: <https://www.facebook.com/notes/mark-zuckerberg/the-technology-behind-aquila/10153916136506634/>
- [5] Google, *Balloon powered Internet for everyone*, (Accessed on: March 2018). [Online]. Available: <https://x.company/loon/>
- [6] S. Hayat, E. Yanmaz, and R. Muzaffar, “Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint,” *IEEE Communications Surveys Tutorials*, vol. 18, no. 4, pp. 2624–2661, 2016.

- [7] DHL, *Unmanned Aerial Vehicles: Ready for take-off?*, (Accessed on: March 2018). [Online]. Available: http://www.dhl.com/en/about_us/logistics_insights/dhl_trend_research/uav.html#.WugfXGaB01h
- [8] Dominos, *Pizza-by-drone a reality with world-first customer deliveries*, (Accessed on: March 2018). [Online]. Available: <https://www.dominos.com.au/inside-dominos/media/november-2016-pizza-by-drone-a-reality>
- [9] R. Prodan and I. Nacu, "The smart homes—a promising business domain which worth attention of romanian telecom companies," *Cross-Cultural Management Journal*, vol. 15, no. 28, pp. 122–128, January 2013.
- [10] A. K. Tripathy, P. K. Tripathy, N. K. Ray, and S. P. Mohanty, "iTour: The future of smart tourism: An IoT framework for the independent mobility of tourists in smart cities," *IEEE Consumer Electronics Magazine*, vol. 7, no. 3, pp. 32–37, April 2018.
- [11] J. Li, Y. Zhou, and L. Lamont, "Communication architectures and protocols for networking unmanned aerial vehicles," in *Globecom Workshops (GC Wkshps), 2013 IEEE*. IEEE, 2013, pp. 1415–1420.
- [12] O. K. Sahingoz, "Networking models in flying ad-hoc networks (FANETs): Concepts and challenges," *Journal of Intelligent & Robotic Systems*, vol. 74, no. 1-2, p. 513, 2014.
- [13] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in UAV communication networks," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1123–1152, 2016.
- [14] I. Jawhar, N. Mohamed, J. Al-Jaroodi, D. P. Agrawal, and S. Zhang, "Communication and networking of UAV-based systems: Classification and associated architectures," *Journal of Network and Computer Applications*, vol. 84, pp. 93–108, April 2017.

- [15] G. A. Thiele, *Antenna theory and design*. Wiley, 1998.
- [16] S. Kumar, V. S. Raghavan, and J. Deng, “Medium access control protocols for ad hoc wireless networks: A survey,” *Ad Hoc Networks*, vol. 4, no. 3, pp. 326–358, May 2006.
- [17] O. Bazan and M. Jaseemuddin, “A survey on MAC protocols for wireless adhoc networks with beamforming antennas,” *IEEE Communications Surveys & Tutorials*, vol. 14, no. 2, pp. 216–239, April 2012.
- [18] A. Alexiou and M. Haardt, “Smart antenna technologies for future wireless systems: trends and challenges,” *IEEE communications Magazine*, vol. 42, no. 9, pp. 90–97, 2004.
- [19] J. Mietzner, R. Schober, L. Lampe, W. H. Gerstacker, and P. A. Hoeher, “Multiple-antenna techniques for wireless communications—a comprehensive literature survey,” *IEEE communications surveys & tutorials*, vol. 11, no. 2, 2009.
- [20] L. Catarinucci, S. Guglielmi, L. Mainetti, V. Mighali, L. Patrono, M. L. Stefanizzi, and L. Tarricone, “An energy-efficient MAC scheduler based on a switched-beam antenna for wireless sensor networks,” vol. 9, no. 2, pp. 117–127, 2013.
- [21] I. Bekmezci, O. K. Sahingoz, and Ş. Temel, “Flying ad-hoc networks (FANETs): A survey,” *Ad Hoc Networks*, vol. 11, no. 3, pp. 1254–1270, 2013.
- [22] R. A. Monzingo and T. W. Miller, *Introduction to adaptive arrays*. Scitech publishing, 1980.
- [23] A. Spyropoulos and C. S. Raghavendra, “Energy efficient communications in ad hoc networks using directional antennas,” in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 1. IEEE, 2002, pp. 220–228.

- [24] M. Gusev, S. Ristov, R. Prodan, M. Dzanko, and I. Bilic, “Resilient IoT ehealth solutions in case of disasters,” in *2017 9th International Workshop on Resilient Networks Design and Modeling (RNDM)*. IEEE, 2017, pp. 1–7.
- [25] I. Budhiraja, S. Tyagi, S. Tanwar, N. Kumar, and J. J. Rodrigues, “Tactile internet for smart communities in 5G: An insight for NOMA-based solutions,” *IEEE Transactions on Industrial Informatics*, vol. 15, no. 5, pp. 3104–3112, 2019.
- [26] R. I. Ansari, C. Chrysostomou, S. A. Hassan, M. Guizani, S. Mumtaz, J. Rodriguez, and J. J. Rodrigues, “5G D2D networks: Techniques, challenges, and future prospects,” *IEEE Systems Journal*, no. 99, pp. 1–15, 2017.
- [27] S. S. Roy, D. Puthal, S. Sharma, S. P. Mohanty, and A. Y. Zomaya, “Building a sustainable Internet of Things: Energy-efficient routing using low-power sensors will meet the need,” *IEEE Consumer Electronics Magazine*, vol. 7, no. 2, pp. 42–49, 2018.
- [28] G. S. Aujla, R. Chaudhary, N. Kumar, J. J. Rodrigues, and A. Vinel, “Data offloading in 5G-enabled software-defined vehicular networks: A stackelberg-game-based approach,” *IEEE Communications Magazine*, vol. 55, no. 8, pp. 100–108, 2017.
- [29] S. M. Bozorgi, A. S. Rostami, A. A. R. Hosseinabadi, and V. E. Balas, “A new clustering protocol for energy harvesting-wireless sensor networks,” *Computers & Electrical Engineering*, vol. 64, pp. 233–247, 2017.
- [30] J. J. Durillo, V. Nae, and R. Prodan, “Multi-objective energy-efficient workflow scheduling using list-based heuristics,” *Future Generation Computer Systems*, vol. 36, pp. 221–236, 2014.

- [31] V. De Maio, R. Prodan, S. Benedict, and G. Kecskemeti, “Modelling energy consumption of network transfers and virtual machine migration,” *Future Generation Computer Systems*, vol. 56, pp. 388–406, 2016.
- [32] S. R. Anton and D. J. Inman, “Vibration energy harvesting for unmanned aerial vehicles,” in *SPIE’s 15th Annual International Symposium on Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring*, vol. 69, 2008, pp. 69–824.
- [33] J. Johnson, E. Basha, and C. Detweiler, “Charge selection algorithms for maximizing sensor network life with UAV-based limited wireless recharging,” in *Intelligent Sensors, Sensor Networks and Information Processing, 2013 IEEE Eighth International Conference on*. IEEE, 2013, pp. 159–164.
- [34] V. Sharma, I. You, G. Pau, M. Collotta, J. D. Lim, and J. N. Kim, “LoRaWAN-based energy-efficient surveillance by drones for intelligent transportation systems,” *Energies*, vol. 11, no. 3, p. 573, 2018.
- [35] K. P. Sharma and T. P. Sharma, “Distributed connectivity restoration in networks of movable sensor nodes,” *Computers & Electrical Engineering*, vol. 56, pp. 608–629, 2016.
- [36] 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.
- [37] V. Sharma, D. N. K. Jayakody, I. You, R. Kumar, and J. Li, “Secure and efficient context-aware localization of drones in urban scenarios,” *IEEE Communications Magazine*, vol. 56, no. 4, pp. 120–128, 2018.
- [38] P. Tripicchio, M. Satler, G. Dabisias, E. Ruffaldi, and C. A. Avizzano, “Towards smart farming and sustainable agriculture with drones,” in *2015 International Conference on Intelligent Environments*. IEEE, 2015, pp. 140–143.

- [39] S. Çaşka and A. Gayrethi, “An algorithm for collaborative patrolling systems with unmanned air vehicles and unmanned ground vehicles,” in *2015 7th International Conference on Recent Advances in Space Technologies (RAST)*. IEEE, 2015, pp. 659–663.
- [40] T. Giitsidis, E. G. Karakasis, A. Gasteratos, and G. C. Sirakoulis, “Human and fire detection from high altitude UAV images,” in *2015 23rd Euromicro International Conference on Parallel, Distributed, and Network-Based Processing*. IEEE, 2015, pp. 309–315.
- [41] B. Coifman, M. McCord, R. G. Mishalani, and K. Redmill, “Surface transportation surveillance from unmanned aerial vehicles,” in *Proc. of the 83rd Annual Meeting of the Transportation Research Board*, 2004, pp. 1–15.
- [42] P. B. Quater, F. Grimaccia, S. Leva, M. Mussetta, and M. Aghaei, “Light unmanned aerial vehicles (UAVs) for cooperative inspection of PV plants,” *IEEE Journal of Photovoltaics*, vol. 4, no. 4, pp. 1107–1113, 2014.
- [43] D. Hausamann, W. Zirinig, G. Schreier, and P. Strobl, “Monitoring of gas pipelines—a civil UAV application,” *Aircraft Engineering and Aerospace Technology*, vol. 77, no. 5, pp. 352–360, 2005.
- [44] J. Willmann, F. Augugliaro, T. Cadalbert, R. D’Andrea, F. Gramazio, and M. Kohler, “Aerial robotic construction towards a new field of architectural research,” *International journal of architectural computing*, vol. 10, no. 3, pp. 439–459, 2012.
- [45] E. Ackerman, “Amazon promises package delivery by drone: is it for real,” *IEEE Spectrum, Web*, 2013.
- [46] D. Bamburry, “Drones: Designed for product delivery,” *Design Management Review*, vol. 26, no. 1, pp. 40–48, 2015.

- [47] J. Stolaroff, “The need for a life cycle assessment of drone-based commercial package delivery,” Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States), Tech. Rep., 2014.
- [48] S. Brar, R. Rabbat, V. Raithatha, G. Runcie, and A. Yu, “Drones for deliveries,” *Sutardja Center for Entrepreneurship & Technology, University of California, Berkeley, Technical Report*, vol. 8, pp. 1–10, 2015.
- [49] A. Claesson, D. Fredman, L. Svensson, M. Ringh, J. Hollenberg, P. Nordberg, M. Rosenqvist, T. Djarv, S. Österberg, and J. Lennartsson, “Unmanned aerial vehicles (drones) in out-of-hospital-cardiac-arrest,” *Scandinavian journal of trauma, resuscitation and emergency medicine*, vol. 24, no. 1, p. 124, 2016.
- [50] J. Scott and C. Scott, “Drone delivery models for healthcare,” in *Proceedings of the 50th Hawaii international conference on system sciences*, 2017, pp. 1–8.
- [51] P. Zhan, K. Yu, and A. L. Swindlehurst, “Wireless relay communications with unmanned aerial vehicles: Performance and optimization,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. 47, no. 3, pp. 2068–2085, 2011.
- [52] A. Mukherjee, S. Chakraborty, A. T. Azar, S. K. Bhattacharyay, B. Chatterjee, and N. Dey, “Unmanned aerial system for post disaster identification,” in *International Conference on Circuits, Communication, Control and Computing*. IEEE, 2014, pp. 247–252.
- [53] S. I. Han, J. Baek, and Y. Han, “Deployment of multi-layer UAV relay system,” in *2018 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2018, pp. 1–6.
- [54] C. Joo and J. Choi, “Low-delay broadband satellite communications with high-altitude unmanned aerial vehicles,” *Journal of Communications and Networks*, vol. 20, no. 1, pp. 102–108, 2018.

- [55] S. Zhang, J. Yang, H. Zhang, and L. Song, “Dual trajectory optimization for a cooperative internet of UAVs,” *IEEE Communications Letters*, vol. 23, no. 6, pp. 1093 – 1096, 2019.
- [56] D. L. Gu, H. Ly, X. Hong, M. Gerla, G. Pei, and Y.-Z. Lee, “C-ICAMA, a centralized intelligent channel assigned multiple access for multi-layer ad-hoc wireless networks with UAVs,” in *Wireless Communications and Networking Conference, 2000. WCNC. 2000 IEEE*, vol. 2. IEEE, 2000, pp. 879–884.
- [57] A. I. Alshbatat and L. Dong, “Adaptive MAC protocol for UAV communication networks using directional antennas,” in *IEEE International Conference on Networking, Sensing and Control (ICNSC)*, 2010, pp. 598–603.
- [58] Y. Cai, F. R. Yu, J. Li, Y. Zhou, and L. Lamont, “Medium access control for unmanned aerial vehicle (UAV) ad-hoc networks with full-duplex radios and multipacket reception capability,” *IEEE Transactions on Vehicular Technology*, vol. 62, no. 1, pp. 390–394, 2013.
- [59] J. Li, Y. Zhou, L. Lamont, and M. Déziel, “A token circulation scheme for code assignment and cooperative transmission scheduling in CDMA-based UAV ad hoc networks,” *Wireless networks*, vol. 19, no. 6, pp. 1469–1484, 2013.
- [60] S. Temel and I. Bekmezci, “LODMAC: Location oriented directional MAC protocol for FANETs,” *Computer Networks*, vol. 83, pp. 76–84, 2015.
- [61] A. Jiang, Z. Mi, C. Dong, and H. Wang, “CF-MAC: A collision-free MAC protocol for UAVs Ad-Hoc networks,” in *IEEE Wireless Communications and Networking Conference (WCNC)*, 2016, pp. 1–6.
- [62] W. Wang, C. Dong, H. Wang, and A. Jiang, “Design and implementation of adaptive MAC framework for UAV ad hoc networks,” in *12th IEEE International Conference on Mobile Ad-Hoc and Sensor Networks (MSN)*, 2016, pp. 195–201.

- [63] W. Wang, C. Dong, S. Zhu, and H. Wang, "DFRA: Demodulation-free random access for UAV ad hoc networks," in *IEEE International Conference on Communications, 2017 ICC*. IEEE, 2017, pp. 1–6.
- [64] Z. Zheng, A. K. Sangaiah, and T. Wang, "Adaptive communication protocols in flying ad hoc network," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 136–142, 2018.
- [65] X. Chen, C. Huang, X. Fan, D. Liu, and P. Li, "LDMAC: A propagation delay-aware MAC scheme for long-distance UAV networks," *Computer Networks*, vol. 144, pp. 40–52, 2018.
- [66] G. Wu, C. Dong, A. Li, L. Zhang, and Q. Wu, "FM-MAC: A multi-channel MAC protocol for FANETs with directional antenna," in *2018 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2018, pp. 1–7.
- [67] G. Choudhary, V. Sharma, and I. You, "Sustainable and secure trajectories for the military internet of drones (IoD) through an efficient medium access control (MAC) protocol," *Computers & Electrical Engineering*, vol. 74, pp. 59–73, 2019.
- [68] P. Feng, Y. Bai, J. Huang, W. Wang, Y. Gu, and S. Liu, "CogMOR-MAC: A cognitive multi-channel opportunistic reservation MAC for multi-UAVs ad hoc networks," *Computer Communications*, vol. 136, pp. 30–42, 2019.
- [69] H. Baek and J. Lim, "Time mirroring based CSMA/CA for improving performance of UAV-relay network system," *IEEE Systems Journal*, pp. 1–4, 2019.
- [70] H. Iqbal, J. Ma, K. Stranc, K. Palmer, and P. Benbenek, "A software-defined networking architecture for aerial network optimization," in *NetSoft Conference and Workshops (NetSoft), 2016 IEEE*. IEEE, 2016, pp. 151–155.
- [71] 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 over-

- head and delay,” in *2017 International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE, 2017, pp. 1290–1292.
- [72] Z. Yuan, X. Huang, L. Sun, and J. Jin, “Software defined mobile sensor network for micro UAV swarm,” in *Control and Robotics Engineering (ICCRE), 2016 IEEE International Conference on*. IEEE, 2016, pp. 1–4.
- [73] W. Qi, Q. Song, X. Kong, and L. Guo, “A traffic-differentiated routing algorithm in flying ad hoc sensor networks with SDN cluster controllers,” *Journal of the Franklin Institute*, vol. 356, no. 2, pp. 766–790, 2017.
- [74] A. Ramaprasath, A. Srinivasan, C.-H. Lung, and M. St-Hilaire, “Intelligent wireless ad hoc routing protocol and controller for UAV networks,” in *Ad Hoc Networks*. Springer, 2017, pp. 92–104.
- [75] B. Barritt, T. Kichkaylo, K. Mandke, A. Zalcman, and V. Lin, “Operating a UAV mesh & internet backhaul network using temporospatial SDN,” in *Aerospace Conference, 2017 IEEE*. IEEE, 2017, pp. 1–7.
- [76] K. J. White, E. Denney, M. D. Knudson, A. K. Mamerides, and D. P. Pezaros, “A programmable SDN+ NFV-based architecture for UAV telemetry monitoring,” in *Consumer Communications & Networking Conference (CCNC), 2017 14th IEEE Annual*. IEEE, 2017, pp. 522–527.
- [77] I. Zacarias, J. Schwarzrock, L. P. Gaspar, A. Kohl, R. Q. Fernandes, J. M. Stocchero, and E. P. de Freitas, “Employing sdn to control video streaming applications in military mobile networks,” in *2017 IEEE 16th International Symposium on Network Computing and Applications (NCA)*. IEEE, 2017, pp. 1–4.
- [78] S. Mahmoud, I. Jawhar, N. Mohamed, and J. Wu, “UAV and WSN softwarization and collaboration using cloud computing,” in *2016 3rd Smart Cloud Networks & Systems (SCNS)*. IEEE, 2016, pp. 1–8.

- [79] R. Kirichek, A. Vladyko, A. Paramonov, and A. Koucheryavy, “Software-defined architecture for flying ubiquitous sensor networking,” in *2017 19th International Conference on Advanced Communication Technology (ICACT)*. IEEE, 2017, pp. 158–162.
- [80] 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.
- [81] G. Secinti, P. B. Darian, B. Canberk, and K. R. Chowdhury, “SDNs in the sky: robust end-to-end connectivity for aerial vehicular networks,” *IEEE Communications Magazine*, vol. 56, no. 1, pp. 16–21, 2018.
- [82] V. Sharma, F. Song, I. You, and H.-C. Chao, “Efficient management and fast handovers in software defined wireless networks using UAVs,” *IEEE Network*, vol. 31, no. 6, pp. 78–85, 2017.
- [83] R. I. Bor-Yaliniz, A. El-Keyi, and H. Yanikomeroglu, “Efficient 3-D placement of an aerial base station in next generation cellular networks,” in *2016 IEEE international conference on communications (ICC)*. IEEE, 2016, pp. 1–5.
- [84] 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.
- [85] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, “Efficient deployment of multiple unmanned aerial vehicles for optimal wireless coverage,” *IEEE Communications Letters*, vol. 20, no. 8, pp. 1647–1650, 2016.
- [86] F. Cheng, S. Zhang, Z. Li, Y. Chen, N. Zhao, F. R. Yu, and V. C. 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.

- [87] S. Rohde and C. Wietfeld, "Interference aware positioning of aerial relays for cell overload and outage compensation," in *2012 IEEE vehicular technology conference (VTC Fall)*. IEEE, 2012, pp. 1–5.
- [88] J. Lyu, Y. Zeng, and R. Zhang, "UAV-aided cellular offloading: A potential solution to hot-spot issue in 5G," *Arxiv: <https://arxiv.org/abs/1705.09024>*, 2017.
- [89] R. Zhang, J. Lyu, and Y. Zeng, "Uav-aided offloading for cellular hotspot," *IEEE Transactions on Wireless Communications*, vol. 17, no. 6, pp. 3988–4001, 2018.
- [90] M. A. Messous, H. Sedjelmaci, N. Houari, and S.-M. Senouci, "Computation offloading game for an UAV network in mobile edge computing," in *2017 IEEE International Conference on Communications (ICC)*. IEEE, 2017, pp. 1–6.
- [91] A. A. Ateya, A. Muthanna, R. Kirichek, M. Hammoudeh, and A. Koucheryavy, "Energy-and latency-aware hybrid offloading algorithm for UAVs," *IEEE Access*, vol. 7, no. 2, pp. 587–600, 2019.
- [92] N. Zhao, F. R. Yu, L. Fan, Y. Chen, J. Tang, A. Nallanathan, and V. C. Leung, "Caching unmanned aerial vehicle-enabled small-cell networks: Employing energy-efficient methods that store and retrieve popular content," *IEEE Vehicular Technology Magazine*, vol. 14, no. 1, pp. 71–79, 2019.
- [93] M. Simic, C. Bil, and V. Vojisavljevic, "Investigation in wireless power transmission for UAV charging," *Procedia Computer Science*, vol. 60, pp. 1846–1855, 2015.
- [94] T. Campi, S. Cruciani, M. Feliziani, and F. Maradei, "High efficiency and lightweight wireless charging system for drone batteries," in *2017 AEIT International Annual Conference*. IEEE, 2017, pp. 1–6.

- [95] A. Junaid, A. Konoiko, Y. Zweiri, M. Sahinkaya, and L. Seneviratne, “Autonomous wireless self-charging for multi-rotor unmanned aerial vehicles,” *Energies*, vol. 10, no. 6, p. 803, 2017.
- [96] C. Yang, Y. He, H. Qu, J. Wu, Z. Hou, Z. Lin, and C. Cai, “Analysis, design and implement of asymmetric coupled wireless power transfer systems for unmanned aerial vehicles,” *AIP Advances*, vol. 9, no. 2, p. 025206, 2019.
- [97] T. Long, M. Ozger, O. Cetinkaya, and O. B. Akan, “Energy neutral internet of drones,” *IEEE Communications Magazine*, vol. 56, no. 1, pp. 22–28, 2018.
- [98] S. Jashnani, T. Nada, M. Ishfaq, A. Khamker, and P. Shaholia, “Sizing and preliminary hardware testing of solar powered UAV,” *The Egyptian Journal of Remote Sensing and Space Science*, vol. 16, no. 2, pp. 189–198, 2013.
- [99] S. Morton, R. D’Sa, and N. Papanikolopoulos, “Solar powered UAV: Design and experiments,” in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015, pp. 2460–2466.
- [100] K. J. Duncan, “Laser based power transmission: Component selection and laser hazard analysis,” in *2016 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*. IEEE, 2016, pp. 100–103.
- [101] Q. Chen, D. Zhang, D. Zhu, Q. Shi, J. Gu, and Y. Ai, “Design and experiment for realization of laser wireless power transmission for small unmanned aerial vehicles,” in *AOPC 2015: Advances in Laser Technology and Applications*, vol. 9. International Society for Optics and Photonics, 2015, pp. 71–96.
- [102] A. C. V. Gummalla and J. O. Limb, “Wireless medium access control protocols,” *IEEE Communications Surveys & Tutorials*, vol. 3, no. 2, pp. 2–15, 2000.

- [103] R. Jurdak, C. V. Lopes, and P. Baldi, “A survey, classification and comparative analysis of medium access control protocols for ad hoc networks,” *IEEE Communications Surveys & Tutorials*, vol. 6, no. 1, 2004.
- [104] I. . W. Group, “Part11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications,” *ANSI/IEEE Std. 802.11*, 1999.
- [105] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, “MACAW: a media access protocol for wireless LAN’s,” *ACM SIGCOMM Computer Communication Review*, vol. 24, no. 4, pp. 212–225, 1994.
- [106] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya, “Using directional antennas for medium access control in ad hoc networks,” in *Proceedings of the 8th annual international conference on Mobile computing and networking*. ACM, 2002, pp. 59–70.
- [107] A. Nasipuri, S. Ye, J. You, and R. E. Hiromoto, “A MAC protocol for mobile ad hoc networks using directional antennas,” in *Wireless Communications and Networking Conference, IEEE*, vol. 3. IEEE, 2000, pp. 1214–1219.
- [108] Y.-B. Ko, V. Shankarkumar, and N. H. Vaidya, “Medium access control protocols using directional antennas in ad hoc networks,” in *in Proceedings of IEEE INFOCOM 2000, Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 1. IEEE, 2000, pp. 13–21.
- [109] R. R. Choudhury and N. Vaidya, “Mac-layer capture: A problem in wireless mesh networks using beamforming antennas,” in *4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*,. IEEE, 2007, pp. 401–410.
- [110] Y. Li and A. M. Safwat, “DMAC-DACA: Enabling efficient medium access for wireless ad hoc networks with directional antennas,” in *1st International Symposium on Wireless Pervasive Computing*,. IEEE, 2006, pp. 5–15.

- [111] R. R. Choudhury and N. H. Vaidya, “Deafness: A MAC problem in ad hoc networks when using directional antennas,” in *Proceedings of the 12th IEEE international conference on Network protocols, ICNP 2004*. IEEE, 2004, pp. 283–292.
- [112] Z. Huang, C.-C. Shen, C. Srisathapornphat, and C. Jaikaeo, “A busy-tone based directional MAC protocol for ad hoc networks,” in *in Proceedings MIL-COM 2002.*, vol. 2. IEEE, 2002, pp. 1233–1238.
- [113] J. Wang, H. Zhai, P. Li, Y. Fang, and D. Wu, “Directional medium access control for ad hoc networks,” *Wireless Networks*, vol. 15, no. 8, p. 1059, 2009.
- [114] N. S. Fahmy and T. D. Todd, “A selective CSMA protocol with cooperative nulling for ad hoc networks with smart antennas,” in *Wireless Communications and Networking Conference, 2004, WCNC.*, vol. 1. IEEE, 2004, pp. 387–392.
- [115] J. Mundarath, P. Ramanathan, and B. D. Van Veen, “NULLHOC: a MAC protocol for adaptive antenna array based wireless ad hoc networks in multipath environments,” in *Global Telecommunications Conference, 2004. GLOBE-COM’04. IEEE*, vol. 5. IEEE, 2004, pp. 2765–2769.
- [116] M. Takai, J. Martin, R. Bagrodia, and A. Ren, “Directional virtual carrier sensing for directional antennas in mobile ad hoc networks,” in *Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking & computing*. ACM, 2002, pp. 183–193.
- [117] K. Chin, “Spotmac: A pencil-beam MAC for wireless mesh networks,” in *Proceedings of 16th International Conference on Computer Communications and Networks, 2007. ICCCN*. IEEE, 2007, pp. 81–88.
- [118] S. Bandyopadhyay, K. Hasuike, S. Horisawa, and S. Tawara, “An adaptive MAC protocol for wireless ad hoc community network (WACNet) using elec-

- tronically steerable passive array radiator antenna,” in *Global Telecommunications Conference, 2001. GLOBECOM'01.*, vol. 5. IEEE, 2001, pp. 2896–2900.
- [119] H. Singh and S. Singh, “Smart-802.11 b MAC protocol for use with smart antennas,” in *2004 IEEE International Conference on Communications.*, vol. 6. IEEE, 2004, pp. 3684–3688.
- [120] Y. Li, M. Li, W. Shu, and M.-Y. Wu, “FFT-DMAC: A tone based MAC protocol with directional antennas,” in *Global Telecommunications Conference, GLOBECOM'07.* IEEE, 2007, pp. 3661–3665.
- [121] Y. Takatsuka, M. Takata, M. Bandai, and T. Watanabe, “A MAC protocol for directional hidden terminal and minor lobe problems,” in *Wireless Telecommunications Symposium, WTS 2008.* IEEE, 2008, pp. 210–219.
- [122] H. Singh and S. Singh, “A MAC protocol based on adaptive beamforming for ad hoc networks,” in *14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications, PIMRC 2003.*, vol. 2. IEEE, 2003, pp. 1346–1350.
- [123] Z. Zhang, “Pure directional transmission and reception algorithms in wireless ad hoc networks with directional antennas,” in *IEEE International Conference on Communications, ICC 2005.*, vol. 5. IEEE, 2005, pp. 3386–3390.
- [124] X.-S. Yang, “Firefly algorithms for multimodal optimization,” in *International symposium on stochastic algorithms.* Springer, 2009, pp. 169–178.
- [125] D.-T. Ho, J. Park, and S. Shimamoto, “Performance evaluation of the PFSC based MAC protocol for WSN employing UAV in rician fading,” in *IEEE Wireless Communications and Networking Conference (WCNC)*, 2011, pp. 55–60.
- [126] A. Shalimov, D. Zuikov, D. Zimarina, V. Pashkov, and R. Smeliansky, “Advanced study of SDN/OpenFlow controllers,” in *Proceedings of the 9th central*

- 8 eastern european software engineering conference in russia.* ACM, 2013, p. 1.
- [127] G. S. Aujla, N. Kumar, A. Y. Zomaya, and R. Ranjan, “Optimal decision making for big data processing at edge-cloud environment: An SDN perspective,” *IEEE Transactions on Industrial Informatics*, vol. 14, no. 2, pp. 778–789, Feb 2018.
- [128] G. S. Aujla, N. Kumar, S. Garg, K. Kaur, R. Rajan, and S. Garg, “Renewable energy-based multi-indexed job classification and container management scheme for sustainability of cloud data centers,” *IEEE Transactions on Industrial Informatics*, vol. 15, no. 5, pp. 2947–2957, 2018.
- [129] G. S. Aujla, R. Chaudhary, N. Kumar, R. Kumar, and J. J. P. C. Rodrigues, “An ensembled scheme for QoS-aware traffic flow management in software defined networks,” in *2018 IEEE International Conference on Communications (ICC)*, May 2018, pp. 1–7.
- [130] G. S. Aujla, R. Chaudhary, K. Kaur, S. Garg, N. Kumar, and R. Ranjan, “SAFE: Sdn-assisted framework for edge-cloud interplay in secure healthcare ecosystem,” *IEEE Transactions on Industrial Informatics*, vol. 15, no. 1, pp. 469–480, 2018.
- [131] R. Chaudhary, G. S. Aujla, N. Kumar, and J. J. P. C. Rodrigues, “Optimized big data management across multi-cloud data centers: Software-defined-network-based analysis,” *IEEE Communications Magazine*, vol. 56, no. 2, pp. 118–126, Feb 2018.
- [132] R. Chaudhary, G. S. Aujla, S. Garg, N. Kumar, and J. J. P. C. Rodrigues, “SDN-enabled multi-attribute-based secure communication for smart grid in IIoT environment,” *IEEE Transactions on Industrial Informatics*, vol. 14, no. 6, pp. 2629–2640, June 2018.

- [133] A. Jindal, G. S. Aujla, N. Kumar, and S. Misra, “Sustainable smart energy cyber-physical system: Can electric vehicles suffice its needs?” in *2018 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2018, pp. 1–6.
- [134] H. Ghazzai, M. B. Ghorbel, A. Kadri, M. J. Hossain, and H. Menouar, “Energy-efficient management of unmanned aerial vehicles for underlay cognitive radio systems,” *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 4, pp. 434–443, 2017.
- [135] O. Younis and S. Fahmy, “HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks,” *IEEE Transactions on mobile computing*, vol. 3, no. 4, pp. 366–379, 2004.
- [136] G. S. Aujla and N. Kumar, “SDN-based energy management scheme for sustainability of data centers: An analysis on renewable energy sources and electric vehicles participation,” *Journal of Parallel and Distributed Computing*, vol. 117, pp. 228–245, 2018.
- [137] G. S. Aujla, M. Singh, N. Kumar, and A. Zomaya, “Stackelberg game for energy-aware resource allocation to sustain data centers using RES,” *IEEE Transactions on Cloud Computing*, 2018, doi: 10.1109/TCC.2017.2715817.
- [138] X. Yang, G. Han, L. Liu, A. Qian, and W. Zhang, “IGRC: An improved grid-based joint routing and charging algorithm for wireless rechargeable sensor networks,” *Future Generation Computer Systems*, vol. 92, pp. 837–845, 2019.

LIST OF PUBLICATIONS

Journal Publications (SCI/SCIE):

1. Sahil Vashisht and Sushma Jain, “An Energy-Efficient and Location-Aware Medium Access Control for Quality of Service enhancement in Unmanned Aerial Vehicular networks”, *Computers and Electrical Engineering*, Vol. 75, Feb 2019, pp. 201-217. - **IF: 2.663**
2. Sahil Vashisht and Sushma Jain, “Software-defined network-enabled opportunistic offloading and charging scheme in multi-unmanned aerial vehicle ecosystem,” *International Journal of Communication and Systems*. Jan 2019, Vol. 32, no. 8, pp. 1-28. - **IF: 1.3**
3. Sahil Vashisht and Sushma Jain, “Location-Aware Network of Drones for Consumer Applications” *IEEE Consumer Electronic Magazine*, vol. 8, no. 3, pp. 68-73, April 2019. - **IF: 4.016**
4. Sahil Vashisht, Sushma Jain and Gagangeet Singh Aujla “MAC protocols for unmanned aerial vehicle ecosystems: Review and challenges” *Computer Communications*, vol.160, pp. 443-463, June 2020. - **IF: 2.816**

Conference Publications (outside India):

1. Sahil Vashisht, Sushma Jain and Ravinder Mann, “Software Defined UAV-based Location Aware Deployment Scheme for Optimal Wireless Coverage.” In Proc. of *IEEE PICom 2019*, 5-8 August 2019, Fukuoka, Japan.