# DESIGN OF A UNMANNED AERIAL VEHICLES ASSISTED SEARCH AND RESCUE COLLABORATION ARCHITECTURE FOR EMERGENCY COMMUNICATION SYSTEMS

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**THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY**

**FACULTY OF ENGINEERING**
**UNIVERSITY OF MALAYA**
**KUALA LUMPUR**

**2022**

# UNIVERSITI MALAYA

## ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: ABDU SAIF

Registration/Matric No.:17043514/1

Name of Degree: Doctor Of Philosophy

Title of Thesis: DESIGN OF A UNMANNED AERIAL VEHICLES ASSISTED SEARCH AND RESCUE COLLABORATION ARCHITECTURE FOR EMERGENCY COMMUNICATION SYSTEMS

Field of Study: Wireless Communication

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# DESIGN OF A UNMANNED AERIAL VEHICLES ASSISTED SEARCH AND RESCUE COLLABORATION ARCHITECTURE FOR EMERGENCY COMMUNICATION SYSTEMS

## ABSTRACT

During natural disasters, it is highly likely that the established wireless communication infrastructure. For effective disaster management, it is crucial to replace ground base stations in order to avoid network failure and carry out life-saving activities and recovery operations. The current wireless technologies used for public safety coordination do not provide flexibility, low-latency services, and swift adaptation to the environment during natural disasters. This thesis addresses these issues by studying a theoretical framework for designing and analyzing emergency communication system (ECS) algorithms for post-disaster recovery. UAVs are increasingly valuable to assist ECS and search and rescue (SAR) teams in multiple disaster management operations to increase disaster response effectiveness. However, the UAVs have limited battery lifetime and transmission distance of coverage area and intermittent connectivity on the edge of UAV coverage for the search and rescue operation. Moreover, the interference effect ECS performance while trying to achieve optimal solutions. The ECS design is based on the collaboration of multiple UAVs and SAR teams in order to provide reliable connectivity of wireless coverage service and save people during disasters. The ECS minimizes outage probability and extends the UAV coverage area through clustering and D2D communication based on the proposed selection of the optimal cluster head. Energy harvesting is employed to power communication devices and prolong the wireless communications network lifetime during a disaster to deal with these challenges. An optimal cluster head technique has been proposed to improve energy transfer efficiency and establish sustainable ECS connectivity. Simulation results indicate that the proposed algorithms can significantly reduce the outage probability and energy consumption. The multi-UAV and SAR collaboration have been evaluated based on average capacity, energy efficiency, line-of-sight probability, path loss, throughput performance, coverage probability analysis and outage probability performance. Moreover, the proposed approach has effectively extended the coverage areas and speed up the response to disaster recovery. Furthermore, the proposed EH method maximizes the UAV direct link scenario by around 50% for D2D communication. The optimal cluster head selection algorithm also gives a lower outage probability of approximately 40% compared to nonoptimal cluster selection in UAV to cluster head links and cluster head to cluster member links to improve the network stability. The outage probability of the proposed solution is approximately 10% better than that of related work. This will guarantee the communication link quality between the optimal cluster head and cluster members as D2D communication pairs. It can eliminate the battery power barriers and interference of UAVs and user devices through a combination of EH and PC. The lower computational complexity is evaluated to reduce interference and increase the convergence rate compared with related work.

Keywords: Multi-UAV, SAR Collaboration, Post Disaster, PSN, ECS.

# REKA BENTUK KENDERAAN UDARA TANPA PEMANDU DIBANTU SENI BINA KERJASAMA MENCARI DAN MENYELAMAT UNTUK SISTEM KOMUNIKASI KECEMASAN

## ABSTRAK

Ketika bencana alam, kemungkinan besar infrastruktur komunikasi tanpa wayar yang ditubuhkan oleh rangkaian keselamatan awam gagal. Untuk pengurusan bencana yang berkesan, adalah penting untuk menggantikan stesen pangkalan darat untuk mengelakkan kegagalan rangkaian dan menjalankan aktiviti menyelamatkan nyawa dan operasi pemulihan. Teknologi tanpa wayar semasa yang digunakan untuk koordinasi keselamatan awam tidak memberikan fleksibiliti, perkhidmatan latensi rendah, dan penyesuaian pantas kepada alam sekitar semasa bencana alam. Tesis ini menangani isu-isu ini dengan mengkaji rangka kerja teori untuk mereka bentuk dan menganalisis algoritma Sistem Komunikasi Kecemasan (ECS) untuk pemulihan selepas bencana. UAV semakin bernilai untuk membantu pasukan ECS dan mencari dan menyelamat (SAR) dalam pelbagai operasi pengurusan bencana untuk meningkatkan keberkesanan tindak balas bencana. Walau bagaimanapun, UAV mempunyai hayat bateri yang terhad dan jarak penghantaran kawasan liputan dan sambungan sekejap-sekejap di pinggir liputan UAV untuk operasi mencari dan menyelamat. Selain itu, gangguan itu menjejaskan prestasi ECS semasa cuba mencapai penyelesaian yang optimum. Reka bentuk ECS adalah berdasarkan kerjasama pelbagai UAV dan pasukan SAR untuk menyediakan sambungan perkhidmatan liputan tanpa wayar yang boleh dipercayai dan menyelamatkan orang semasa bencana. ECS meminimumkan kebarangkalian gangguan dan memperluaskan kawasan liputan UAV melalui kluster dan komunikasi D2D berdasarkan cadangan pemilihan ketua kluster optimum. Penuaian tenaga digunakan untuk peranti komunikasi kuasa dan memanjangkan hayat rangkaian komunikasi tanpa wayar semasa bencana untuk menangani cabaran ini. Teknik kepala kluster optimum telah dicadangkan untuk meningkatkan kecekapan pemindahan tenaga dan mewujudkan sambungan ECS yang mampan. Keputusan simulasi menunjukkan bahawa algoritma yang dicadangkan dapat mengurangkan kebarangkalian gangguan dan penggunaan tenaga dengan ketara. Kerjasama multi-UAV dan SAR telah dinilai berdasarkan kapasiti purata, kecekapan tenaga, kebarangkalian garis penglihatan, kehilangan laluan, prestasi kendalian, analisis kebarangkalian liputan dan prestasi kebarangkalian gangguan. Selain itu, pendekatan yang dicadangkan telah meluaskan kawasan liputan dengan berkesan dan mempercepatkan tindak balas untuk pemulihan bencana. Selain itu, kaedah EH yang dicadangkan memaksimumkan senario pautan langsung UAV sekitar 50% untuk komunikasi D2D. Algoritma pemilihan ketua kluster optimum juga memberikan kebarangkalian gangguan yang lebih rendah kira-kira 40% berbanding pemilihan kluster bukan-bukan dalam UAV kepada pautan kepala kluster dan ketua kluster ke pautan ahli kluster untuk meningkatkan kestabilan rangkaian. Kebarangkalian gangguan penyelesaian yang dicadangkan adalah kira-kira 10% lebih baik daripada kerja yang berkaitan. Ini akan menjamin kualiti hubungan komunikasi antara ketua kluster optimum dan ahli kluster sebagai pasangan komunikasi D2D. Ia boleh menghapuskan halangan kuasa bateri dan gangguan UAV dan peranti pengguna melalui gabungan penuaian tenaga dan kawalan kuasa. Kerumitan pengiraan yang lebih rendah dinilai untuk mengurangkan gangguan dan meningkatkan kadar penumpuan berbanding dengan kerja yang berkaitan.

Kata kunci: Multi-UAV, Kerjasama SAR, Pasca Bencana, PSN, ECS.

# ACKNOWLEDGEMENTS

First of all, praise to ALLAH S.W.T, Most Gracious, Most Merciful, for giving me the strength and courage to accomplish this thesis. It has been a tough ride all the way to the end and I am very grateful to him for finally being able to complete it. I would like to express my sincere gratitude to my Supervisor Prof Ir. Dr.Kaharudin Bin Dimyati and Assoc. Prof.Ir. Dr. Kamarul Ariffin Bin Noordin for the continuous support of my Ph.D. study and related research, for their patience, motivation, and immense knowledge. They guided me in all the time of research and writing of this thesis. I could not have imagined having better supervision and mentor for my Ph.D. study. I would also like to acknowledge the part supported by the UK Engineering and Physical Sciences Research Council (EPSRC): Project DARE under grant agreement no. EP/P028764/1, and the University of Malaya, under grant agreement no. IF035A-2017 and IF035-2017 and Ministry of Higher Education Yemen.

Without such generosity, I would not have been able to fully concentrate on my research. Also, I thank my friends in the institution and Lab technicians in the department. A special thanks to my family. Words cannot express how grateful for all the sacrifices you've made on my behalf. Your prayer for me was what sustained me. I would also like to thank my brothers, sisters, and all of my friends who supported me in writing and carry out me strive toward my goal. I would like to express appreciation to my beloved wife who spent. sleepless nights with me and was always my support in the moments when there was no one to answer my queries.

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# LIST OF SYMBOLS AND ABBREVIATIONS

1G : First-Generation.
2G : Second-Generation.
3G : Third-Generation.
3GPP : 3rd Generation Partnership Project.
4G : Fourth-Generation.
5G : Fifth-Generation.
6G : Sixth Generation.
AI : Artificial Intelligence.
ALMA : Augmented Lagrange Multiplier Approach.
APCO : Association of Public Safety Communications Officials.
AtA : Air-to-Air.
AtG : Air-to-Ground.
C4FM : Continuous 4-Level Frequency Modulation.
CMs : Cluster Members.
D2D : Device to Device.
DMO : Direct Operation Mode.
ECS : Emergency Communication System.
EE : Energy Efficiency.
EFR : Emergency First Responders.
EH : Energy Harvesting.
ETSI : European Telecommunications Standards Institute.
GBS : Ground Base Station.
GEO : Geosynchronous Equatorial Orbit.
GIRN : Government Integrated Radio Network.
GSM : Global Systems for Mobile Communications.
ICT : Information and Communication Technologies.
IMT-A : International Mobile Telecommunication Advance.
IoT : Internet of Thing.
ITU : International Telecommunication Union.
KPIs : Key Performance Indicators.
LEACH : Low-Energy Adaptive Clustering Hierarchy.
LEO : Low Earth Orbit.
LMRS : Land Mobile Radio System.
LTE : Long Term Evolution.
LTE-A : Long Term Evolution Advanced.
M2M : Machine-to-Machine.
MANET : Mobile Ad hoc Networks.
MESA : Mobility for Emergency and Safety Applicatns.
NE : Nash Equilibrium.

| | | |
|---|---|---|
| OSI | : | Open Systems Interconnection. |
| PC | : | Power Control. |
| PCP | : | Poisson Cluster Process. |
| PDO | : | Packet Data Optimized. |
| PMC | : | Passive Multi-hop Clustering Mechanism. |
| PPDR | : | Public Protection and Disaster Relief. |
| PS | : | Power Splitting. |
| PSN | : | Public Safety Network. |
| PTWC | : | Pacific Tsunami Warning Center. |
| QoS | : | Quality of Service. |
| S2S | : | SAR to SAR. |
| SAR | : | Search and Rescue. |
| SE | : | Spectral Efficiency. |
| SPR | : | Shortest Path Routing. |
| SWIPT | : | Simultaneous Wireless Information and Power Transfer. |
| TDMA | : | Time Deviation Multiple Access. |
| TETRA | : | Terrestrial Trunked Radio. |
| TIA | : | Telecommunications Industry Association. |
| TS | : | Time switching. |
| TSR | : | Time Slot Ratio. |
| UAV | : | Unmanned Aerial Vehicle. |
| UE | : | User Equipment. |
| UHF | : | Ultrahigh-Frequency. |
| V2V | : | Vehicle-to-Vehicle. |
| VHF | : | Very High Frequency. |
| WCS | : | Wireless Communication System. |
| WEH | : | Wireless Energy Harvesting. |
| WLAN | : | Wireless Local Area Network. |
| WPCNs | : | Wireless Powered Communication Networks. |

# CHAPTER 1: INTRODUCTION

## 1.1 Introduction

Natural Disasters such as earthquakes, hurricanes, tornadoes, and severe snowstorms frequently result in devastation to telecommunication infrastructures. In such circumstances, the cellular infrastructure network services can often be vulnerable and are not able to provide the necessary coverage services (Casoni et al., 2015), i.e., the infrastructure can be damaged, partially unavailable, or significantly overloaded. This hinders the Search and Rescue (SAR) operations between emergency personnel and victims from functioning effectively. It has been reported that since 1995, around four billion people were affected by natural disasters, while more than two million have died (Voigt et al., 2016). Undoubtedly, it is vital to obtain first-hand knowledge in order to estimate the destruction in post-disaster scenarios. A Public Safety Network (PSN) is a communication network typically used by government agencies and emergency services such as police forces, fire brigades, medical emergency services, and SAR operations for responding to disaster incidences. A PSN provides the coverage services needed and allows first responders to communicate with the disaster victims with good reliability and efficient connectivity (Jarwan et al., 2019). It is imperative for the first responder to communicate and respond in a timely manner to an emergency to save lives (Chung & Noh, 2021). One example of a PSN implementation in Malaysia is the Government Integrated Radio Network (GIRN). It started its operation in December 2009. However, the system's capabilities are limited in the treatment of connectivity with cellular infrastructure failure for SAR operations. It is difficult to add new ingredients into the system for reducing network congestion and data collection in disaster management recoveries (Azmani et al., 2017). Hence, the Emergency Communication System (ECS) can quickly deploy fast responding, reliable connectivity, and effective communication during public safety operations that will fulfill the considerations and gaps of GIRN. Thus, there is an essential need for the ECS between first responders and victims for SAR operations in such scenarios to speed up recovery operations, thus reducing the loss of life and properties. ECS refers to communication services during an emergency when the cellular network is damaged, linking the SAR teams inside the disaster area with SAR teams outside the disaster area for information exchange and smooth search and rescue operations (Bhattacharjee et al., 2016). The cellular era began around the 1980s, and since then, it has undergone dramatic changes, increasing its significance to human lives. Figure 1.1. shows the development of all the cellular generations from First-Generation (1G) to the expected Sixth Generation (6G) for a typical cycle of every ten years. In 1G, the system worked under an analog system with a voice calling system. Second-Generation (2G) was then found and developed into digital technology, namely Global Systems for Mobile Communications (GSM), and subsequently followed by Third-Generation (3G) with its triple-play services. The Long Term Evolution Advanced (LTE-A) system developed by 3rd Generation Partnership Project (3GPP) became the Fourth-Generation (4G) and satisfied the requirements set by the International Telecommunication Union (ITU) for the International Mobile Telecommunication Advance (IMT-A) Standard (Ghosh et al., 2010). The Fifth-Generation (5G) technology is expected to have massive broadband properties to support future industrial applications with Artificial Intelligence (AI) and Internet of Thing (IoT), and in 2030 6G is expected to arrive (Sheth et al., 2020); (Nakamura, 2020). The current wireless technologies used for public safety coordination include 4G Long Term Evolution (LTE), Wireless Local Area Network (WLAN), and dedicated public safety systems such as Terrestrial Trunked Radio (TETRA) and Association of Public Safety Communications Officials (APCO) Project 25 (P25) (Baldini et al., 2013); (V. Sharma et al., 2018). However, these technologies may not provide flexibility, low-latency services, and swift adaptation to the environment during natural disasters (Mozaffari et al., 2019). Moreover, a PSN faces many problems such as network congestion, low traffic rates, concerns over interoperability, and lack of globally applicable common spectrum (Gorcin & Arslan, 2008);(Kumbhar et al., 2016). While 5G facilitates seamless integration of wireless communications in every facet of society through its impressive Key Performance Indicators (KPIs) (Wu et al., 2021), natural disasters could still lead to significant service disruptions since 5G KPIs do not focus on post-disaster emergency communication scenarios (Sambo et al., 2019); (K. Zhou et al., 2017). The available systems may not offer the required flexibility and timely responses to environmental disruption. Thus, an Unmanned Aerial Vehicle (UAV) could be the most suitable option to substitute and temporarily replace the damaged terrestrial communication infrastructures (Wu et al., 2021). In this case, UAVs could be employed to ensure that the network is always up and running. The literature shows that researchers are increasingly interested in exploring the advantage of UAVs as a replacement for terrestrial station functions, especially in the aftermath of natural disasters (Simic et al., 2015).

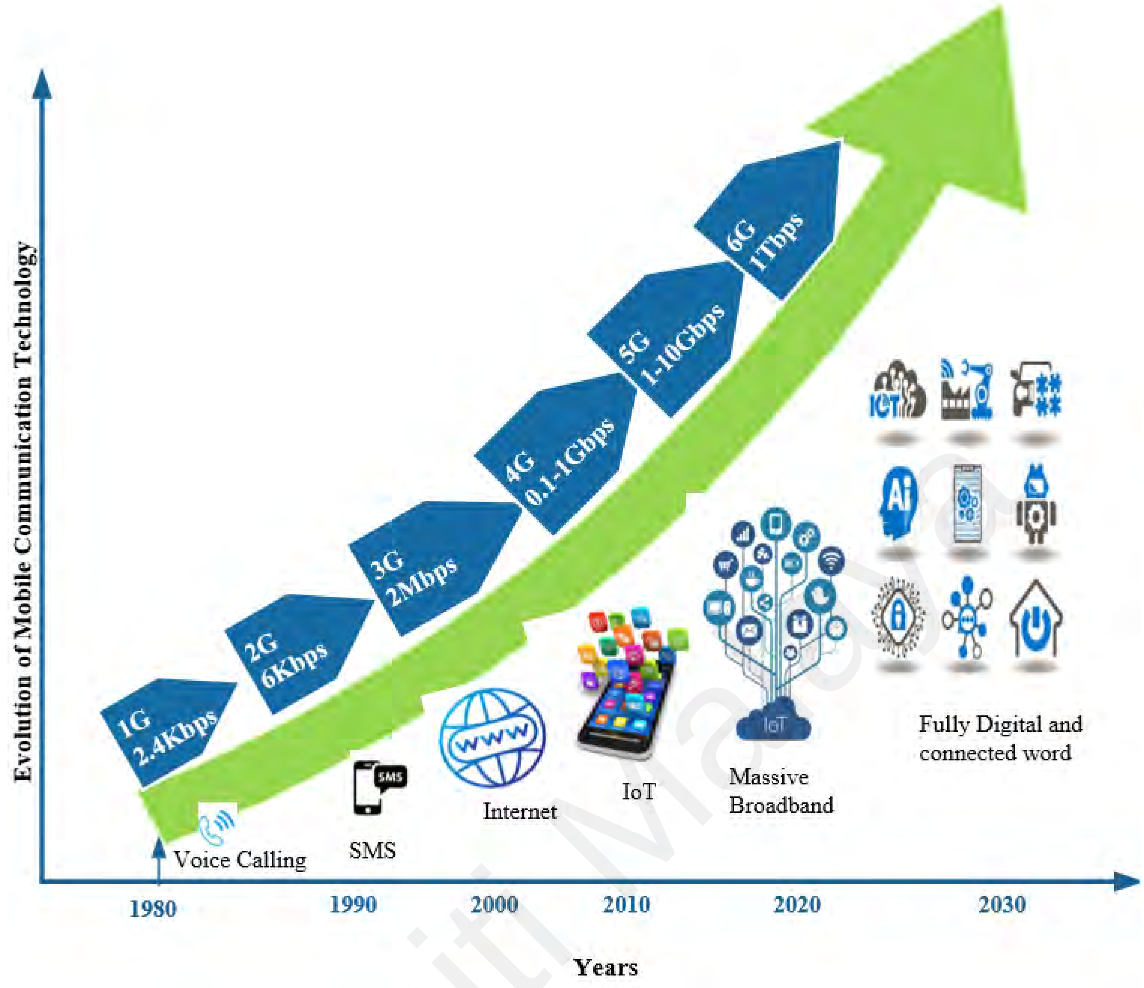

Figure 1.1: Development of Mobile Communication Technologies and Services

## 1.2 UAVs in Public Safety Network

UAVs have acquired remarkable popularity thanks to their variety of applications in numerous domains spanning from surveillance, health, agriculture, and smart cities. UAVs are also increasingly being used to aid SAR teams in disaster management operations, especially to perform various disaster preparedness and recovery tasks. The beauty is that a UAV does not require highly constrained and expensive infrastructure (e.g., cables). They can quickly fly and dynamically change their positions to provide on-demand communications for the search and rescue teams in emergencies (Mozaffari et al., 2019). Numerous surveys summarize these advantages for various circumstances and situations (Pádua et al., 2020); (Syed et al., 2021) ; (Mishra & Natalizio, 2020) . UAVs can

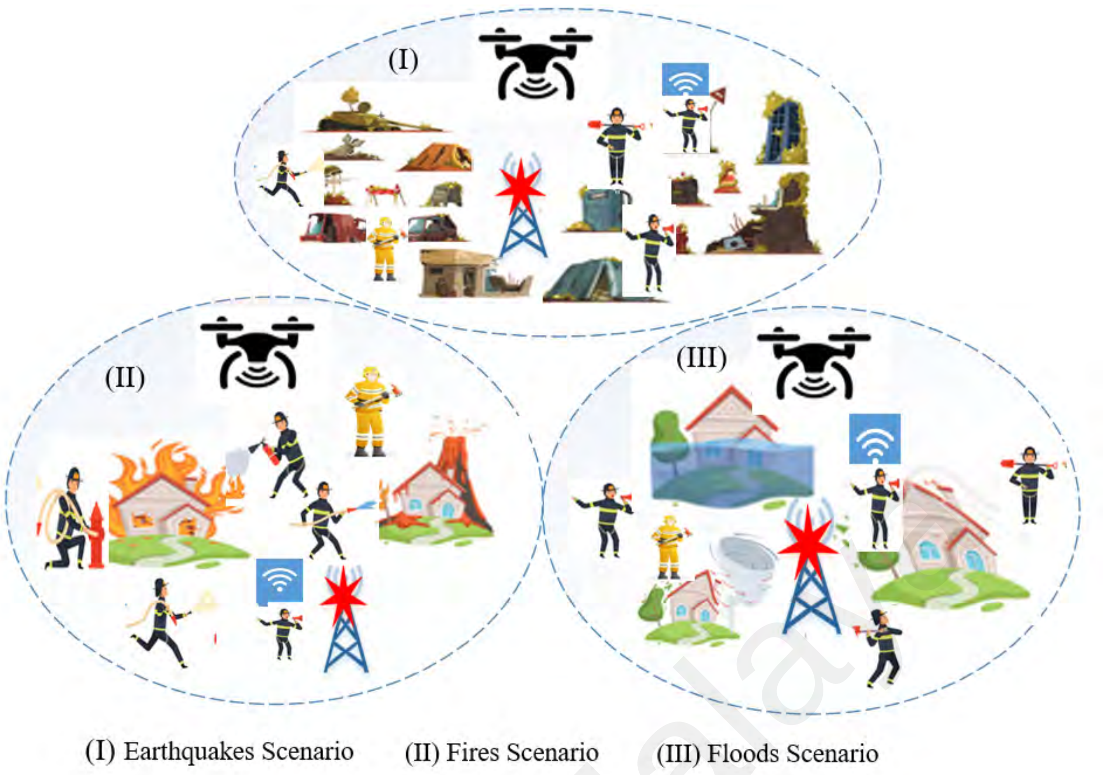

**Figure 1.2: Leveraging UAVs and SARs for Disaster Management.**

be integrated with multi-layered architecture, for example, they can be utilized to enable emergency communications with minimum energy consumption that effectively reach out to victims in remote areas (Shakoor et al., 2019). UAV-enabled wireless networks bring many benefits, such as enhanced coverage area, increased system capacity, low cost, low maintenance, on-demand and swift deployment, high mobility, and high probability of LoS (Y. Liu et al., 2020); (Vincent et al., 2006). UAVs are also known for their reliability, connectivity, and capability to improve the Quality of Service (QoS) of specific heterogeneous networks (Ali et al., 2018); (Q. Zeng et al., 2018a). Thus, UAVs are seen as a promising solution to enhance the public safety network scenarios to support mission-critical applications such as earthquakes, floods, and fires, as shown in Figure 1.2. However, there are limitations to UAVs in a public safety network in terms of processing energy efficiency and battery power lifetime.

### 1.2.1 Energy Harvesting

Energy Harvesting (EH) offers an attractive solution to satisfy the energy requirements for the PSN due to its capability to prolong the network lifetime and hence keep the network running during disasters. Energy harvesting for UAVs and Device to Device (D2D) communication has attracted a great deal of attention, mainly to improve energy efficiency post-disaster. In other words, EH can overcome the battery power limitations of UAVs and user devices, resulting in a long-term solution that extends the network's lifetime. Energy is harvested from radio signals in EH, which converts incoming wireless signals into usable energy sources and delivers the additional power required to serve connected user devices.

One such technique is the Simultaneous Wireless Information and Power Transfer (SWIPT) schemes that can be effectively used to provide cost-effective information and energy access to wireless devices in various 5G wireless network implementations (Rajaram et al., 2019); (Z. Zhou et al., 2017). The multi-UAV relays can assist PSN through wireless power transfer, which is achieved in the conventional Power Splitting (PS) and Time switching (TS) as strategies to enhance energy harvesting between the source and destinations nodes to implement energy harvesting transmission and reduce large-scale fading (Ji et al., 2019). The UAV acting as an energy source provides RF energy for multiple energy harvesting powered D2D pairs with much information to be transmitted. The D2D communication is adopted in secure communications for Wireless Powered Communication Networks (WPCNs) to provide public safety, and disaster relief services (K. Ali et al., 2016); (Chu et al., 2017b). While transmitting power $D2D_{Tx}$ in the coverage area aims to assist received power $D2D_{Rx}$ in the out-of-coverage area to recover the disaster area via an energy harvesting relay (Chu et al., 2017a). Therefore, RF-EH and SWIPT are considered essential techniques to prolong the battery lifetime of D2D communication for an extended coverage area (Le et al., 2017). Besides, D2D communication Power Control (PC) is utilized to improve system capacity. extend the network coverage area and keep the interference under control (Ji et al., 2020).

### 1.2.2 D2D Power Control

The power control strategies are considered viable to enhance wireless network throughput performance based on reducing D2D communication consumption power and eliminating interference with other user devices. Thus, D2D communication is a promising solution to cope with resource limitations in network infrastructure failure, making the network spectrum more efficient and establishing a link between functional areas and user devices in a dysfunctional area. Therefore, D2D communications are enabling national security, and public safety services and provide an alternative communication link between the user devices with cellular networks that are partially or fully damaged due to a natural disaster event (Ali et al., 2018). D2D-based low power transmission and energy-saving features make it a perfect candidate for vital communication backup in a case of a network infrastructure failure or a natural disaster (Ahmad et al., 2018). The source and destination node's power consumption for D2D communication is still challenging for achieving energy efficiency with reliable connectivity. However, interference between the deployed UAV and D2D communication is still a problem that needs attention. Hence, power control was proposed to eliminate the interference between the UAV and D2D links for reliable connectivity with minimal power consumption during disaster recovery. In the D2D power control, each device can independently select and transmit its power to maximize (or minimize) the utility function to establish connectivity with network resources. In addition, the power control algorithm for D2D communications plays an essential role in reducing power consumption while saving energy in emergencies. The utility function is one of the considerations for power control distribution in the space of D2D communication and UAV cellular coverage. Furthermore, UAVs are integrated with multi-hop D2D communication using a clustering technique in a downlink scenario to improve the Spectral Efficiency (SE) and Energy Efficiency (EE) in dysfunctional areas. Thus, the power control of D2D pairs in clusters is used to mitigate interference and minimize outage probability.

## 1.3 Problem Statement

Due to natural disasters such as earthquakes, floods, and fires, terrestrial communication network infrastructure is damaged or collapses. Therefore, first responders and victims cannot obtain wireless coverage access to information exchange for timely warning and smooth evacuation. UAVs represent the critical technology that can help an emergency response, search and rescue, data gathering, and disaster management by establishing emergency communications. However, a UAV comes with a limited battery lifetime and transmission distance of coverage area. These bottlenecks need to be resolved to ensure success in the search and rescue operation. Moreover, there is a limitation in intermittent connectivity on the edge of UAV coverage to link the user devices in the functional area with dysfunctional user areas out of coverage. In summary, there are three problems that require attention in this thesis:

- Due to natural disasters, the terrestrial communication network infrastructure damage must be replaced by ECS for information exchange and smoothing victims' evacuation.
- The UAVs have limited coverage to cover all disaster areas, and the user devices out of their coverage are unable to obtain the coverage services
- The interference and high computational complexity are problems that affect the performance of ECS.

## 1.4 Research Objectives

This thesis aims to design a multi-UAV with the SAR team's communication of ECS to provide wireless coverage service for SAR operations during disasters. The design of an ECS framework is able to provide reliable connectivity, reduce the battery power barriers, and extend the network coverage. To achieve the aim, the following objectives need to be fulfilled:

- To design an ECS framework with multi/single UAV for continuous and reliable connectivity for a disaster scenario.
- To minimize outage probability and extend UAV coverage area through clustering and D2D communication based on the proposed optimal Cluster Head algorithm that satisfies the ECS requirement.
- To evaluate the computational complexity and interference and compare it with other work.

## 1.5 Scope of the Study

This study aims to discover ECS used to prepare against a disaster for search and rescue operations. The ECS is designed based on multi/single UAVs to guarantee connectivity between the functional and dysfunctional areas during the cellular infrastructure network damage. The energy consumption of UAVs will be reduced by utilizing clustering D2D communication, EH, and PC to prolong the network lifetime. Cluster Head is the main distribution point for the cluster members and it is responsible to forward the cellular traffic of its clients (i.e., other users who belong to the same cluster). CHs are selected based on the highest residual energy, the maximum number of neighbour nodes, and the smallest distance from UAVs. Outage probability will be minimized based on the distribution of optimal cluster head nodes on the edge of UAV coverage. The D2D communication can increase the communication range of coverage for extended coverage areas for disaster recovery countermeasures. The performance of ECS to recover the disaster connectivity is through the air-to-air and air-to-ground channels to get efficient connectivity recovery and help victims post-disaster. Therefore, the multi-UAV are collaborating with SAR team communication to reach the number of victims efficiently. In addition, Shortest Path Routing (SPR) will help fast connectivity response for SAR team operation tasks. Multi-UAV performs several missions to save energy and lower the system latency. Therefore, the proposed algorithms are designed to prolong the system lifetime and minimize the system response resulting from network failure. In addition, multi-UAV and SAR collaboration algorithms with SPR can deliver communication and monitor a larger area, and quick response for disaster communication recovery. A single UAV system can only provide limited operational tasks to achieve full active function and cover smaller neighbourhoods with a direct network connection. The selection of optimal CHs will provide the network with more efficient and stable route solutions during post-disaster situations. UAV deployment with the optimal CH to reduce outage probability and energy consumption. The computational complexity will be reduced for a suitable network design to recover from natural disasters and potentially save many lives.

## 1.6 Thesis Outline

This thesis is composed of five chapters. Chapter 1 presents the overview of wireless technologies, UAVs in PSN, energy harvesting, the power control problem statement, research objectives, and the working scope of the thesis. Chapter 2 reviews the state-of-the-art natural disaster effect on wireless networks towards supporting the PSN and its role in disaster communication relief. The chapter starts by reviewing UAVs for an ECS and D2D to extend the coverage area with clustering techniques for enabling technologies and emphasizing the critical requirements for natural disaster communication relief. After that, the performance of different wireless frameworks is compared regarding UAVs, D2D, clustering, and un-clustering in disaster and without disaster situations. Moreover, the methods and techniques used to improve post-disaster communications of the chosen wireless network standard to satisfy the requirements of the ECS to provide wireless service to the large-scale area are explained in detail. Chapter 3 describes the system modelling and algorithms for Multi/Single-UAV to provide the best wireless network standard that satisfies the minimum requirements used to recover disaster communications. The ECS system models are proposed for fast disaster recovery and to help SARs teams rescue victims. In addition, this chapter describes the related main equations used in this system modelling and parameter configuration in the simulation model for every research contribution and system parameters for every stage, and a chapter summary. Chapter 4 focuses on the research on achievable analysis coverage/outage probability, energy efficiency, and energy consumption. The ECS performance through UAVs, D2D and clustering is able to support disaster communications. Moreover, the achievements provide the minimum requirements for efficient communications by comparing the existing wireless network standards with properly selected system parameters for the proposed approaches. This chapter discusses the proposed implementation and validation of the optimal CH algorithm to maximize outage probability. Chapter 5 presents the overall conclusion of the research work and the possibility of the research's impact on future technology. Finally, this chapter mentions the current limitation of the proposed work and gives the direction for further improvement in the future.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Introduction

This chapter demonstrates a brief background of the effect of natural disasters on the network infrastructure and solutions available for exchanging information and smooth evacuation of victims. The failure of the network infrastructure is the inability of user devices to obtain wireless services in the disaster zone. A PSN helps to link the Emergency First Responders (EFR), share information and communicate in various media with reliability and continuous connectivity during emergencies. In addition, the fundamentals of a PSN-based ECS fill a gap in the literature by providing a standard that reviews a comprehensive set of technologies, from the most popular to the most advanced communications technologies applied as mission-critical communications systems in emergencies. Therefore, the part of solutions through a PSN for disaster recovery include balloons, satellites, and mobile care stations. However, such disaster recovery solutions are delayed in providing communication services to disaster areas, which can cause further damage, injury, and loss of life. Thus, the ECS is integrated with the PSN as an alternative system to replace the ground base stations for the response of victims and disaster recovery operations. Therefore, UAVs are integrated with the ECS as a substitute to replace terrestrial communication in disaster occurrence. However, UAVs have limitations for disaster recovery in terms of processing power and distance of coverage areas. An efficient disaster recovery design that reinstates communication systems by UAVs, D2D communications, and clustering techniques is needed. In addition, designing an ECS based on multi-UAV collaborations with SARs for efficient disaster recovery is essential to handling a natural disaster.

## 2.2 Natural Disasters

Natural disasters are sizeable adverse occurrences resulting from the Earth's natural processes, such as tsunamis, earthquakes, floods, volcanic eruptions, avalanches, blizzards, cyclonic storms, hail storms, tornadoes, fires, pandemics/epidemics, landslides, and other natural events. Natural disasters commonly cause significant damage to buildings and infrastructures and depending on the types and severities, there can be considerable loss of life or casualties involved following the occurrence of natural disasters, either due to the disasters themselves or associated consequences (e.g., fire after an earthquake) (Adibi, 2015). During wide-scale natural disasters and unexpected events, the existing terrestrial communication networks can be damaged or destroyed, thus becoming significantly overloaded, as evidenced by Hurricanes Sandy and *Irma* (Lyu et al., 2018). In 2017, hurricanes Harvey, Irma, and Maria in the USA and the earthquake in Central Mexico affected network infrastructure. In other cases, the network infrastructures in Italy, Nepal, and New Zealand were affected by earthquakes. The user devices within the disaster zone were unable to obtain wireless coverage services. Those cases showed the necessity for investigating cellular network weaknesses for handling traffic in these crucial circumstances. For the natural disaster SAR team efforts in such situations, the PSN needs to link the dysfunctional and functional areas to search and rescue the victims. In this scenario, communications between EFR and victims of SAR activities are essential to public safety.

## 2.3 Public Safety Network

PSNs are specialized wireless communication networks to create emergency-resilient communication environments that maintain access to prevent or respond to incidents that harm or endanger persons or property. Moreover, a PSN is necessary for communication between EFR, firefighters, and emergency workers, and perhaps most importantly, they are a legal requirement in many countries around the world. Thus, a PSN is essential for improving the coordination among first responders, aiding the efforts of medical personnel, and enabling the adaptation of crisis management protocols (alerts, evacuation policies) (Sikeridis et al., 2018). Moreover, the concept of the PSN is used to share information and communication resources in a natural disaster to prevent and respond to the endangerment of people's lives. The PSN copes with the absence of terrestrial communications infrastructure during and after the disaster to help rescue and relief teams perform their tasks efficiently. A PSN is an infrequent collaboration focused on developing and using Information and Communication Technologies (ICT) to prevent and respond to the endangerment of people's lives. In addition, a PSN allows EFR to communicate in various media with reliability and continuous connectivity during emergencies for police, fire, and ambulance services to enhance coverage services and efficiency in operating in critical situations (Yarali, 2020). The PSNs should enable flexible connectivity without delay in providing communication services to injured areas to avoid further loss of victim life during safety and rescue operations (Shaikh & Wismüller, 2018). In post-disaster, search and rescue teams need to know the location of the affected people and what resources they need for evacuation help. In this realm, the requirement has been to develop the standard of a highly robust system that can address the specific communication needs of emergency services. Thus, the researchers focus on the automatic analysis of satellite data to provide information products for more effective disaster risk reduction, evaluating the needs for post-disaster response and recovery. However, satellite communications, especially Low Earth Orbit (LEO), have ubiquitous coverage and lower channel loss than Geosynchronous Equatorial Orbit (GEO) due to the cost of launching large-scale constellations and latency through higher distances. Furthermore, the satellite communications system is introduced as a core network for emergency management and disaster recovery that is able to link users in disasters with others outside the disasters (Y.-M. Lee et al., 2010). Thus, the connectivity of future network communication will integrate with terrestrial communications, satellite communications, and airborne communications to streamline emergency responses among the victims in disaster management.

## 2.4 The standard of Public Safety Network

In an emergency instance, reliable communication is vital to enable and support successful emergencies and SAR operations to prepare against disaster countermeasures. A PSN is essential to ensure appropriate actions and proper management can be carried out efficiently among the search and rescue teams. Therefore, a legacy PSN requires modernization to improve EFR safety and compatibility with various disasters for the effectiveness of SAR operational tasks. FirstNet in the United States created a nationwide, high-speed broadband wireless network that can transform the capabilities of public safety technologies by providing broadband, ubiquitous, and mission-critical voice and data support (Kumbhar et al., 2016); (Mozaffari et al., 2019). Nevertheless, effective emergency and natural disaster management depend on efficient mission-critical voice and data communication between EFR and victims. In this section, the standard of PSNs is classified into LMRS networks and broadband networks. The APCO-25 and TETRA suite of standards fall under the LMRS network, while the LTE-based broadband PSC network falls under the broadband network.

### 2.4.1 LMRS Network

Land Mobile Radio System (LMRS) is a narrow band technology used for critical voice communications between EFR and trapped victims. LMRS is a wireless communication system intended for terrestrial user devices comprised of portables and mobiles, such as two-way digital radios or walkie-talkies for military, commercial, and EFR applications. As a result, the main goal of LMRS systems is to provide mission-critical communications and enable integrated voice and data communications for reliable connectivity in disaster emergency response. Therefore, a global trend of 3GPP LTE/NR broadband networks replaces LMRS for more advanced use cases, with fast and reliable voice communications in cellular network failure.

#### 2.4.1.1 APCO-25

APCO and European Terrestrial Trunked Radio (TETRA) are widely used suites of standards for LMRS-based digital radio communications. In the same context, APCO-25, also known as Project 25 (P-25), is widely used by federal, state/province, and local PSNs in North America to communicate with other PSNs and mutual aid response teams in emergencies. Therefore, the anlage/digital (A/D) system revolution since the 1990s is used to implement technological advances by expanding the capabilities of digital radio to communicate with other APCO-25 radio modes. Additionally, deploying APCO-25 compliant systems will allow for a high degree of equipment interoperability and compatibility in three different phases, where advancements have been gradually introduced (Lunness, 2007). In Phase1, radio systems operate in 12.5 kHz analog, digital, or mixed-mode and use the Continuous 4-Level Frequency Modulation (C4FM) technique and a non-linear modulation for digital transmissions. Therefore, Phase1 of P25-compliant systems are backward compatible and interoperable with legacy systems to provide an open interface to the radio frequency (RF) subsystem to facilitate interlinking between different vendor systems. Phase2 improved spectrum utilization and introduced a 2-slot Time Deviation Multiple Access (TDMA) system that provides two voice traffic channels in a 12.5 kHz band allocation and doubles the call capacity. It also lays emphasis on interoperability with legacy equipment, interfacing between repeaters and other subsystems, roaming capacity, and spectral efficiency/channel reuse. Project Mobility for Emergency and Safety Applicatns (MESA) collaborated with the European Telecommunications

Standards Institute (ETSI) and the Telecommunications Industry Association (TIA) to define a unified set of requirements for APCO-25 Phase3. The initial agreement for project MESA was ratified in the year 2000, and planning activities address the need for high-speed data for public-safety use (Lunness, 2007). Meanwhile, project MESA aims to facilitate adequate, efficient, advanced specifications and applications to address public safety broadband communication needed to ensure appropriate actions and proper management can be carried out efficiently among the search and rescue teams.

#### 2.4.1.2 TETRA

TETRA (Trans-European Trunked Radio) is a digital mobile radio standard for voice and data transmission, which is essentially confined to layers 1-3 of the Open Systems Interconnection (OSI) model and intended to operate in existing Very High Frequency (VHF) and Ultrahigh-Frequency (UHF) professional mobile radio frequencies (Kumbhar et al., 2016). On the other hand, TETRA fulfills the same role for European and Asian countries. It has been developed by the ETSI based on Release 1 and Release 2. Release 1 is the original TETRA standard, which was known as the TETRA standard, supports three modes of operation, which are voice plus data, Direct Operation Mode (DMO), and Packet Data Optimized (PDO) (Dunlop et al., 1999). The voice +data is the most used mode, which allows switching between voice and data transmission, and it can be transmitted on the same channel using different slots. The DMO has supported direct voice and data transmission for a transparent or encrypted call between the subscriber units without the base stations, especially when the user devices are in the outside coverage area, (Kumbhar et al., 2016). The PDO standard has been created for occasional data-only to cater to a high volume of data shortly for connectivity. Therefore, the coverage services and voice are necessary for mission-critical communications and need a high volume of data, which can be the beneficiaries of the PDO standard (Kumbhar et al., 2016).

In contrast, Release 2 provided additional functions and improvements to the already existing functionality of TETRA to enhance data services, offering more flexibility and greater data capacity (ETSI, 2007). With an adaptive selection of modulation schemes, RF channel bandwidths, and coding, user bit rates can vary between 10 Kbits/s to 500 Kbits/s. Subsequently, data rate plays a vital role in relaying mission-critical information during an emergency to timely warning for smooth evacuation of victims. For example, monitoring a remote victim in an emergency scenario would require data to support real-time duplex voice/video communication and telemetry of disaster occurrence. Thus, TETRA enhanced data service would play an essential role in such a mission-critical scenario by keeping the applications that need high data rates, such as multimedia and location services. In the other considerations, TETRA improvements also include adaptive multiple rate voice codec, mixed excitation linear predictive enhanced voice codec, and trunked mode operation range extension, which extended the range for air-ground services to 83 kilometres when compared to 58 kilometres in TETRA Release1 (Censi et al., 2012).

### 2.4.2 LTE Broadband Network

LTE technology was standardized by the 3GPP in 2008 and had been evolving. In response to growing commercial market demands, LTE-Advanced was specified as 3GPP Release10. Moreover, 3GPP has developed Release 11 and Release 12, intending to extend the functionality and raise the performance of LTE -Advanced (Nakamura et al., 2013). The LTE Broadband network can meet PSN connectivity and identify possible future developments to enhance its ability to provide the necessary service in cellular network failure. LTE is the most widely deployed broadband communication technology that will allow high data rate applications that are impossible to support with LMRS. In addition, LTE will enable unprecedented broadband service to PSN and bring the benefits of lower costs, consumer-driven economies of scale, and rapid evolution of advanced communication capabilities (Kumbhar & Güvenç, 2015). The main goal of LTE is to increase the capacity and high-speed data over wireless data networks to a performance level close to Shannon's capacity bound (Baldini et al., 2013). Therefore, LTE-based broadband, dedicated solely for public safety use, can deliver much-needed advanced communication and data capabilities. Furthermore, the LTE-mobile broadband standard is utilized in a PSN in large-scale deployment for flexible air interface with low latency in the two critical features for enhanced connectivity. In other words, LTE direct communications are developed from 3GPP based on proximity services (ProSe), including D2D discovery and communication between the functional and dysfunctional areas. Moreover, LTE group communications are developed by 3GPP to meet the demands and requirements such as low-latency communication bearer setup, priority access for group calls, and QoS improvement. Furthermore, LTE has been the targeted platform for Machine-to-Machine (M2M) communications, PSN, and D2D services for maturity and relatively incremental improvements (Kumbhar, 2020). The 5G technology is expected to have fundamental technological components that will transform the capabilities of broadband networks (Andrews et al., 2014). For example, full-fledged efforts from researchers at the University of Surrey's 5G Innovation Centre managed to attain one terabit per second (Tbps) of data speed (Worth, 2015). Therefore, the 5G enables PSN connectivity to support reliable, mission-critical communication that helps ECS speed up connectivity and recovery operations during the disaster. 5G is the global standard for a unified, more capable wireless mobile broadband and is expected to be the infrastructure for emergency services, natural disaster rescue, public safety, and military communications (Arjoune & Faruque, 2020). In addition, the 5G offers several powerful, flexible features to secure reliable communication for improving EFR network coverage, accessibility, and situational awareness. Furthermore, in terrestrial communications, the coverage service connectivity is provided through tower masts to help PSNs establish communication links between the disaster and non-disaster areas for proper secure operations. Hence, effective communication during public safety operations is needed via robust, fast, and capable disaster recovery countermeasures that can be carried out efficiently during the search and rescue team operations.

Table 2.1: **Comparison of Existing PSN Standards**

| PSN Standards | Advantages | Limits |
|---|---|---|
| LMRS Network | ✓Two-way digital radios<br>✓EFR applications<br>✓Fast and reliable voice communications.<br>✓APCO-25 has a fixed data rate of 4.4 Kbits/s for voice communications and 9.6 to 96 Kbits/s for a data-only system.<br>✓A high degree of equipment interoperability.<br>✓Operate in a 12.5 kHz band for analog, digital, or mixed-mode.<br>✓TETRA has a digital mobile radio standard for voice and data transmission.<br>✓supports three modes of operation, which are voice plus data.<br>✓Monitoring a remote victim in an emergency scenario.<br>✓Supporting real-time duplex voice/video | ✓Narrowband technology<br>✓Limited number of users<br>✓Low-speed data for public safety network<br>✓The system does not work with public safety broadband communication<br>✓The system needs more actions<br>✓Proper management can be carried out efficiently among the search and rescue teams.<br>✓Fixed modulation scheme with 2 bits per symbol.<br>✓Fixed Forward Error Correction rate as per DAQ3.4.<br>✓Single input single-output (SISO) Antenna Configuration node with an Omni-directional pattern. |
| LTE Broadband | ✓Meet PSN connectivity<br>✓Identify possible future developments.<br>✓Enhances its ability to provide the necessary service in cellular network failure.<br>✓Widely deployed broadband communication technology.<br>✓A high data rate applications.<br>✓Increases the capacity and high-speed data over wireless data networks.<br>✓Low-latency communication bearer setup.<br>✓Priority access for group calls.<br>✓QoS improvement.<br>✓MIMO has been an integral part of LTE with the goal of improving data throughput and spectral efficiency.<br>✓LTE-Advanced introduced 8$x$8 MIMO in the DL and 4$x$4 in the UL. | ✓Does not depend on cell load but relies on factors such as channel quality indicator (CQI) feedback, transmitted by the UE.<br>✓SINR less than 0 dB indicates poor link quality (UE is located at the cell edge).<br>✓Limited spectrum allocation for LTE-based PSC.<br>✓Limited code block length in LTE, full SNR efficiency is not feasible.<br>✓There are limitations in LTE unlicensed spectrum sharing that needed more further studies |

### 2.4.3 Emergency Communication System (ECS)

An emergency notification system allows to quickly deliver of a message to a group of people to generate emergency alerts that are accessible to different people (Malizia et al., 2009). Emergency services play a vital role in society by providing help to affected people and minimizing damage to public and private assets and the environment during emergencies. In gathering many people in the same place, mobile networks typically become congested or unavailable. Disaster management services require high flexibility in network infrastructure management and rescue group communication due to the collapse of buildings, power systems, and communication infrastructure. An ECS is defined as any system that is organized for the primary purpose of supporting one-way and two-way communication of emergency information between both individuals and groups of individuals. The operations of the ECS include alerts, timely notifications, and directives for evacuation for information exchange that affect response and recovery. Moreover, the ECS is an alternative system with robust, fast, effective communication between EFR and trapped victims during public safety operations. The ECS is essentially required for reliable and flexible disaster mitigation and relief operation to work perfectly everywhere and every time in any circumstances. Space technologies and new integrated ECS are able to mitigate the impact of natural and man-made disasters. Space technology includes space vehicles such as spacecraft, satellites, space stations, orbital launch vehicles deep-space communication, and other technologies that support cellular networks. Therefore, space technologies represent the solution in ECS for disaster management and recoveries, with its free mobility with no obstacles for preparedness, detection, mitigation, and response. The ECS designs new, potentially attractive telecommunication architectures to better manage a disaster scenario (Carreras-Coch et al., 2022). However, the terrestrial communication resources are limited when infrastructure is damaged or there is excessive traffic. The tethered balloons used Los communication, low interference, and long transmission range as ECS when a large-scale natural disaster occurs for collecting information on disaster areas to rescue recovery and survey purposes (Carreras-Coch et al., 2022). Integrating ECS with LTE networks is vital to provide coverage services through broadband communication for link disaster and un-disaster area in the case of terrestrial infrastructures damage in disaster situations (Casoni et al., 2015). Therefore, broadband communications during a disaster or emergency times need to be reliably connected, available, robust, quickly deployable, and accessible from any location. Therefore, the TV and radio broadcasting are pre-disaster warnings, while the rescue mission relies on a primary cellular network. However, these systems have already exposed the deficiency of efficient use of ECS with damage to the cellular network in post-disaster (Tsai et al., 2011). For example, in the Japan disaster, the pre-disaster warnings were used by the Pacific Tsunami Warning Center (PTWC), which issues to notify people (Heidarzadeh & Satake, 2014). In this context, using the ECS can help through a disaster warning, the emergency reporting stage, victims ask for help by reporting emergency conditions through emergency calls, and in the rescue and medical care stage, rescue teams search for victims and treat the injured and try to save lives. However, the challenging issue for disaster is to re-stabilize the situation in a non-communication environment due to infrastructure loss. Thus, re-stabilizing the system will be slow and expensive, so in such cases, short-range mobile devices can be beneficial to construct a multi-hop mobile Mobile Ad hoc Networks (MANET) for quick connectivity to reach the sufferers. These traditional technologies cannot satisfy the critical timing requirements of disaster warning and emergency medical services. Unsurprisingly, alerting through aerial vehicles is the most promising method for disaster warning. The mobile operator networks lack disaster recovery and congestion control mechanisms that allow the system to work even in the failure of crucial backhaul network links (Verin, 2014). In the proposed ECS, disaster warning centers can directly warn normal users through UAVs without the involvement of mobile operators. The emergency medical information of the user is collected via a mobile application to accelerate the medical support time. Therefore, to minimize the effects of a disaster, the mobile applications supporting decision-making through real-time analytics must be fast and accurate. Integrating UAVs into ECS is a promising way to accomplish efficient network recovery with altitude and power control to maximize the system throughput between the UAVs and ground nodes (Hu et al., 2021). It is known that the first hours after a disaster are critical to maximizing the rescue and recovery of victims. UAVs established the ECS through end-to-end communication, localization, navigation, and coordination to inform the people through various communication channels about disasters and their areas of effect. In this sense, the use of multiple small UAVs based upon aerial robots is able to navigate over large areas faster to communicate with first responders to collect data about victims (Perez-Imaz et al., 2016). In addition, Public Protection and Disaster Relief (PPDR) is a wireless communication used during emergency operations to find suitable architectural solutions that meet worst-case emergency scenarios for reliable post-disaster recovery connectivity. To cope with unpredicted emergencies, the ECS structure is integrated with UAVs, multi-robot, and sensor networks to provide the emergency occurring places (Shakoor et al., 2019). The ECS was designed to optimize the altitudes of multi-UAVs to maximize the energy efficiency enabled in an emergency's connectivity response (L. Li et al., 2021). Technologies such as Wi-Fi that operate on an unlicensed frequency spectrum are affected by congestion and are susceptible to external interference that can make the technology unusable. Therefore, the broadband UAV-directional antenna is integrated with Wi-Fi devices to extend the communication range and provides real-time communication capability for disasters (J. Chen et al., 2017). In addition, the UAV-assisted emergency Wi-Fi network is utilized for a reliable, resilient, and quickly deployable ECS to expedite the rescue operations manner by guiding the survivors to the nearest rescue camp location (Panda et al., 2019). Hence, UAV represents the critical technology that can help ECS with disaster management and recoveries for fast response and reliable connectivity in disaster scenarios (Panda et al., 2019). The mini-UAV collaboration has become popular among emergency response teams to deploy ECS to enable effective communications during rescue operations (Arafat & Moh, 2019). Moreover, UAV is integrated with an ECS to assist the terrestrial network for fast response and reliable connectivity in a disaster scenario. However, the ECS has limitations of the cluster-based channel model to minimize the UAV outage probability during the disaster recovery.

## 2.5 UAVs for Emergency Communication System

UAVs are reliable, resilient, and quickly deployable. UAVs can collaborate to perform search and rescue missions. UAVs can guide SAR teams with monitoring tasks during the rescue (Ansari & Cho, 2018). UAVs serving as data relays hold significant promise for delivering on-demand connectivity and providing public safety services or aiding in recovery after communication infrastructure failures caused by natural disasters (Pokorny et al., 2018). A UAV-assisted emergency Wi-Fi network is utilized to expedite rescue operations and synchronization and avoid communication disruption to the relief center for better rescue planning for the monitoring of natural disaster management such as Figure 2.1, (Panda et al., 2019). The advantage of UAVs is that they can fly at different altitudes according to their purposes and needs, provide wireless services to ground nodes, and serve as the best alternatives for reinstating communication systems during disasters (Q. Zeng et al., 2018a). UAVs can be used as mobile base stations to provide overall wireless coverage services while minimizing channel access delays in disaster-stricken areas and guiding the SAR teams (Mayor et al., 2019). One such option is the multi-UAV and SAR communication design, extending the wireless coverage area (Zhao et al., 2019). Furthermore, improving the QoS depends on Los and received signal strength and bandwidth, throughput, and delay performance (Gupta et al., 2020). UAVs integrated with D2D communications need to keep communication lines open and running during faultier communication in natural disasters. Gathering data during a disaster is essential to guide research and rescue teams to perform their complex tasks efficiently (Alsamhi, Ma, et al., 2019). In disaster recovery, UAVs are classified into single-UAV and multi-UAV communications. In single-UAV communication, the link is established with ground user devices. In contrast, multi-UAV communication establishes the link with several UAV nodes that communicate with ground user devices. Therefore, a multi-UAV (cooperative and layered) system can take two patterns, UAV to UAV (U2U) and UAV to the ground station (U2G), to provide the solutions for energy and coverage range issues for rescue and safety to the victims (Arafat & Moh, 2021); (Hayajneh et al., 2018). Furthermore, a UAV flight path is classified into o-path, rectangular-path, zigzag-path, and s-path. Meanwhile, the s-path is used for large-scale paths, whereas the o-path, rectangular path, and zigzag path are used for short flight duration with less energy consumption (Christy et al., 2017). In this context, the flight time is directly related to the UAV energy consumption limitation, enabling longer hovering times to provide the coverage services (Mozaffari et al., 2019). Thus, the UAV can be categorized into a fly at a lower altitude platform (LAP) and a higher altitude platform (HAP) to provide the coverage service (Saad et al., 2020); (Darwish et al., 2021). Subsequently, the UAVs can function at LAP/HAP to provide a Los communication link to user devices and streamline emergency responses (S. H. Alsamhi et al., 2021). Its transmission and distance coverage establish reliable connections at minimal energy expenditure (Mozaffari et al., 2019). These flying platforms eliminate some drawbacks of space technology communication for assisting terrestrial communications, such as cost, delay, deployment time, flexible mobility, operability, fast networking, and cost-effectiveness. Subsequently, UAV deployment in a LAP plays an efficient role in disaster recovery due to ease of deployment and Los at low cost (S. H. Alsamhi et al., 2021); (Gupta et al., 2020). While UAVs suffer from limited battery lifetime caused by standardization and handling disaster-resilient communication, this constraint limits their capabilities to a considerable extent (Nguyen et al., 2018). Thus, UAV energy consumption and battery life become significant constraints in the case of network infrastructure collapse (Gautam & Sharma, 2020). This becomes the primary drawback as UAVs run on battery power which can run out very quickly during coverage services in disaster scenarios. Here, EH can reduce the battery power limitation of the UAV network and provide a sustainable solution to extend the network lifetime. Therefore, backhaul connectivity, security, and energy consumption are some of the constraints of these flying platforms. Tethering represents the critical solution for providing power supply to the UAV. Tethering is used to tie the UAV to the ground, speed up data transfer, supply power to the UAV, and solve the battery lifetime (Q. Li et al., 2020). In other words, Networked Tethered Flying Platforms (NTFPs) are used by practically every flying platform, including the government, military, and industries, to overcome these constraints (Garcia et al., 2019). Furthermore, issues with the Ground Base Station (GBS) and user devices in the limitation of the power source during disaster occurrence. In further consideration, UAVs will be integrated as free-flying platforms in 6G architectures and will be crucial enablers for developing wireless communication systems (Garcia et al., 2019). Therefore, replacing the Ground Base Station (GBS) with a UAV is viable and can be integrated with optimal relay hops to improve wireless coverage services. In this regard, UAVs were used for PSN in the aftermath of the 2011 earthquake and tsunami in Japan to relieve the ECS wireless network services (Merwaday & Guvenc, 2015); (Mozaffari et al., 2019). The UAVs serve as relay-assisted nodes to transfer wireless information and power between the D2D user devices outside the coverage area to the core network. However, UAVs have limitations for the transmission distance and power to recover disaster communication during disaster recovery countermeasures. Thus, an optimal relay is a promising approach to extending coverage based on MH/D2D communication to improve wireless coverage services during disaster events (Y. Zeng et al., 2016). A UAV is considered a relay station for reliable connectivity in ECS (Y. Chen et al., 2017). The UAV provides configuration to centralize beam coverage wireless signals to an optimal relay for reliable connectivity and increased strength of the received signal at the edge nodes. In this context, the increase in signal strength at relay nodes helps link with the nodes outside the coverage area to obtain the coverage services. Furthermore, the UAV can fly and transmit wireless coverage to an optimal relay node selected based on the residual energy and link quality in the edge of UAV coverage. Thus, D2D communication aims to extend the UAV coverage through relay hops in a downlink wireless communication system, where D2D users coexist in an underlying manner.

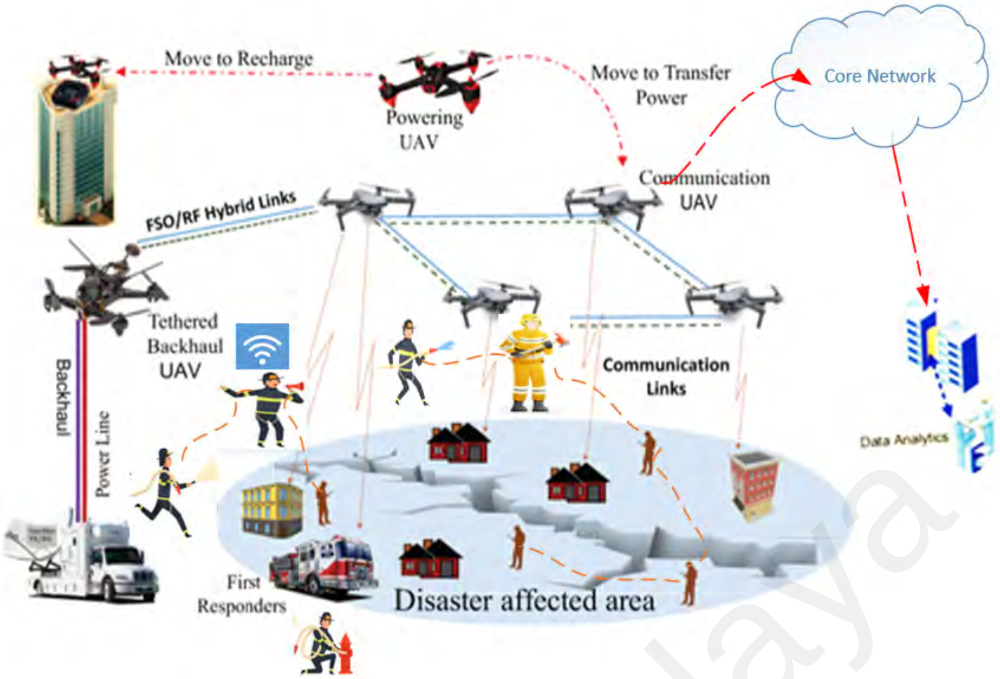

**Figure 2.1: UAVs for Monitoring Natural Disasters**

### 2.5.1 UAV Power Control

The cross-tier interference from space-air-ground heterogeneous networks is solved by a two-stage joint hovering altitude and power control in UAV networks considering(J. Wang et al., 2018). In Wu et al. (2018), the UAV power control act to achieve fair performance for user devices in downlink communication. In addition, the power control is executed in multi-UAV to mitigate the interference to improve the network coverage and network connectivity (Tang et al., 2021). The UAV power control is essential to improve energy efficiency and communication security for relay and remote IoT applications (Fu et al., 2021).

Therefore, the transmit power control and clustering of ground user devices the optimized by UAVs downlink transmission to maximize the minimum average rate and improve post-disaster connectivity. The Design of multi-UAV trajectories with short-distance LoS links can be proactively and dynamically established for ground user devices and alleviate the co-channel interference with undesired UAV singles. In this context, the power control is optimized in each iteration to minimize the interference and consume power. Successive convex optimization technique utilized to solve non-convexity of the UAV power control problem with fixed trajectory(Wu et al., 2018).

## 2.6 D2D to Extend the Coverage Area

D2D communication is one of the new technologies that appear to be a promising component in next-generation communications. In Ali et al. (2018), D2D communication is considered one of the essential components of future information network architecture. It can effectively improve spectral efficiency and alleviate the bottleneck of limited radio resources. In AliHemmati et al. (2016), D2D communications can improve next-generation network performance by transmitting cellular traffic without additional infrastructure. In AliHemmati et al. (2017), the number of devices is expected to radically increase shortly, with an estimated above 50 billion connected devices in the future. This allows Peer-to-Peer (P2P) communication between users, with improved spectral efficiency, energy efficiency, and system throughput. In Kar and Sanyal (2020), D2D offloading reduces the load by asking mobile nodes to download content directly from the storage of neighbouring helpers via short-range links. In D. Feng et al. (2013a), direct D2D links are proposed as a possible enabler for Vehicle-to-Vehicle (V2V) communications. However, the incurred intra-cell interference and the stringent latency and reliability requirements are challenging issues affecting D2D communication. Thus, there is a need to establish and evaluate new channel models that help realize the potential advantages of wireless communication. D2D communication is critical for UAV-supported networks to improve coverage performance and includes multi-hops to improve cellular downlink throughput performance. Furthermore, D2D communication is one of the enabling technologies for 5G, supporting proximity-based service (ProSe) for public safety and commercial use (H. Wang, Ding, et al., 2018). In addition, D2D communications are used under centralized control by the cellular network to increase system capacity and energy/spectrum efficiency and improve the wireless coverage in the PSN. Therefore, most studies in D2D communications have focused on multi-hop relay assisted out-band D2D communications to increase overall performance. In this context, researchers' aims include post-disaster events extending the number of hops in the communication link and reducing the receiving bit error ratio efficiently to improve the wireless coverage service efficiency. In this case, D2D communication has mainly focused on multi-hop relay-assisted out-of-band D2D communication to fulfill those requirements (Amodu et al., 2019). In natural disaster events, providing coverage service to help people is essential when the wireless network is damaged and cannot provide wireless coverage service to user devices (Ali et al., 2018). The relay-assisted D2D network uses an MH/D2D communication system to achievable capacity over Rayleigh fading channels. The optimal selection relay of the D2D system and the effect of the number of relays hops on the system capacity and power efficiency is evaluated in (Ioannou et al., 2021), while UAVs are integrated with D2D communication to overcome the energy consumption constraint in (Christy et al., 2017). In addition, the optimal relay nodes play an essential role in a PSN by helping the UAV communicate long distances and overcome the transmission power limitations (Martínez-Vargas et al., 2019); (D. Liu et al., 2019). Moreover, D2D communication is considered to extend the coverage area in PSN environments for Heterogeneous Networks (HetNets) based on the 3rd Generation Partnership Project (3GPP) through MH/D2D communication (Babun et al., 2015). Thus, when some or all infrastructures are unavailable, Release 12 D2D ProSe supports direct data exchanges between User Equipment (UE) without signal relays via eNBs. In Guan et al. (2016), the D2D pair communication underlay uses the cellular spectrum and interferes with the regular cellular user device. Optimal operation requires joint consideration for the achieved D2D rate and the added interference to cellular user devices. In this context, D2D rate maximization concerns only the simplified scenario where the D2D pair has access to a single channel or resource block. In Khoshkholgh et al. (2014), a framework for decentralized interference coordination based on the pricing mechanism is developed for D2D communication underlying cellular systems to guarantee the quality of service of cellular users' devices and D2D links. In Mumtaz et al. (2014), D2D relaying is considered one of the promising technologies to improve spectral efficiency and extend the coverage of the cellular system with low additional costs. In Apostolos et al. (2016), energy efficiency is a significant performance indicator for D2D communications due to users' limited battery capacity. In Rihan et al. (2019), the role of UAVs and MH/D2D communications is to provide reliable connectivity in disaster situations and establish the communication link with user devices in out-of-coverage scenarios. In C. H. Liu et al. (2020), the author proposed integrating UAVs within multi-antenna and MH/D2D communication to extend the coverage area and overcome the transmission power limitations. Therefore, extending the UAV coverage through relay hops and D2D communication is essential to improve the wireless coverage services, spectrum, and energy efficiency in PSN (Babun et al., 2015); (Shakoor et al., 2019). On the other hand, D2D relay communication is proposed to reduce load and energy consumption and serve as a technology for public safety and disaster relief services. Then, the number of D2D communication was increased to minimize the outage probability in a post-disaster scenario (Mozaffari et al., 2016a). The relays will forward the wireless coverage services to a user device out of the UAV coverage through MH/D2D communications (Y. Zeng et al., 2016); (Zhao et al., 2019).

An optimal relay's performance increases with the coverage area by increasing hops and reliably providing wireless coverage services to remote user devices. In other words, D2D communication can offer extended coverage for the SAR devices out of the UAV coverage area (Deepak et al., 2019). Therefore, multi-hop D2D is necessary to extend the SAR coverage, located out of base station coverage, which is the case for disaster scenarios (Gorcin & Arslan, 2008). Hence, efficient multi-hop D2D communications are inevitable during a disaster and can be achieved by selecting Search and rescue head $SAR_h$ nodes. This solution would be more efficient than deploying additional UAVs or continuously relocating the active UAVs, which involves high energy consumption and complex path planning. Furthermore, integration of D2D communication has mainly emerged to offload the increased data traffic and improve the energy efficiency of ECS.

### 2.6.1 D2D Communication Power Control

The existing research body on wireless communication has established that a D2D power control algorithm is a hot topic for researchers. The recognition of D2D power control plays a critical role in saving energy and minimizing power consumption by eliminating interference (C. Shi et al., 2018). The non-cooperative game and utility function will increase the energy network lifetime connectivity of D2D communication to enable national security and public safety services. In addition, the pricing factor is used to consume the power between D2D communication while extending the coverage based on the cost function and price factors (Malik et al., 2020). Therefore, the D2D power control problem distribution requires an algorithm in which each terminal independently uses its transmission to choose a power level to maximize the utility of the user devices for increased lifetime connectivity. Thus, a utility function has been designed to solve the D2D power control problem and eliminate the cellular user devices' interference to meet the QoS requirements in case of a network infrastructure failure or a natural disaster (Lapiccirella et al., 2009). Therefore, the D2D power control problem is formulated as a utility function modelled by a non-cooperative game in the downlink and the uplink communications. The downlink decodes the SINR, while the uplink decodes the throughput performance (Goudarzi & Asgari, 2018). Thus, the energy-saving and network energy lifetime link between the source and destination of D2D is inevitable for efficient wireless communication connectivity in disaster recovery (Riasudheen et al., 2020). According to Yu et al. (2019), it has been proven that the average utility of user devices of the Stackelberg Equilibrium (SE) is lower than that of Nash Equilibrium (NE) since the jammer can reduce the user device utilities by utilizing the power control advantage to improve the user utility (Yu et al., 2019). A power control proposed for improving the energy efficiency of D2D communication while assisting the PSN to improve coverage services during a disaster will speed up relief and recovery operations (K. Lee & Hong, 2017). The UAV can provide service in some specific scenarios, such as post-disaster network recovery or no-infrastructure terrains. However, the problem of interference management between deployed UAVs and underlying heterogeneous networks, which guarantees the quality of service, is still a challenging task. In Selim et al. (2019), the power control was solved by relaxing the non-convex problem of solving successive low computational complexity linear programs to obtain a sub-optimal solution to the problem and its compromise in terms of sum rate. In Safdar et al. (2016), the interference in the network is minimized through a multi-antenna beamforming mechanism with power control. In contrast, the transmit power is maximized toward the direction of the intended D2D receive nodes and limited in all other directions to guarantee the reliability of both the D2D and cellular connections.

## 2.7 Clustering Techniques

A clustering technique is a control protocol that provides efficient and reliable data dissemination routes. On the other hand, clustering establishes connectivity between and among user devices through direct communication to improve the network's performance for sharing data and radio resources (L. Feng et al., 2018). However, rapid network topology cluster reorganization changes will impact network route stability. An approach of Fuzzy C-Means as a clustering tool has been implemented in a PSN to reduce the power consumption of the network (Ansari & Cho, 2018). However, the researchers are looking for effective ways to solve those issues and provide wireless services to the user devices under the disaster zone (A. R. Ansari & Cho, 2018). Here, all researchers have the common goal of designing a ubiquitous network architecture used to solve connectivity that copes with disasters (Ali et al., 2018). To address energy consumption difficulties in wireless networks, researchers have used various clustering techniques that consider power supply constraints. Improving channel link quality and consequently maximizing downlink coverage services necessitates efficient resource deployment. Clustering links user device routes via direct communication to improve network performance for communicative data sharing in the damaged infrastructures (Khuwaja et al., 2018). Accordingly, several clustering approaches have been adopted in wireless networks to tackle power consumption issues, which have recently shown impressive results. The CH considers the relay function to forward the coverage services into destination nodes located in a poor coverage area (Y. A. Shah et al., 2018). In this work, the clustering techniques are considered and utilized to relieve the network infrastructure damage during and post-disaster events. In addition, the UAV model was developed to address the optimal CH selection with clustering and D2D assisted links which are utilized for sustainable connectivity, reducing power consumption, and enhancing the reliability performance of network system coverage in disaster situations. The clustering technique and D2D communication in UAV networks can sustain communication services when the cellular infrastructure becomes partially or fully dysfunctional. In S. K. Haider et al. (2019) proposed an optimum CH selection strategy to maximize the lifetime of wireless sensor networks. Moreover, clustering techniques improve energy efficiency and extend the coverage in wireless communication networks (Mozaffari et al., 2019). Meanwhile, a clustering approach is used with a group of search and rescue defined as

SAR to SAR (S2S) that allows the $SAR_h$, i.e., the head node for communication with all SARs, to extend the network coverage and improve energy efficiency (Bahbahani & Alsusa, 2017). The multi-hop clustering algorithm was used to extend cluster coverage and act for substantially extended cluster coverage. and substantially improve the user device connectivity in the ad-hoc network. The former technique enables network bandwidth to improve spectrum sharing (Ma et al., 2020) effectively. Integrating clustering techniques and MH/D2D communication with LTE-Advanced (LTE-A) system enables efficient spectrum usage and energy consumption in infrastructure failure (Gandotra & Jha, 2016). It is not possible to construct such wireless networks in the disaster's affected regions due to the unavailability or inadequacy of cellular infrastructures, energy/power supply losses, and limited resources. Therefore, in disaster areas, it is unavoidable that communication is an efficient power-saving method, less energy-consuming devices, and a network to smoothly run relief activities (Prior & Roth, 2013).

In this context, the clustering and a SPR algorithm using D2D communication for fast response rapidly with minimum nodes to handle the fast response and reliable connectivity in disaster situations (Panda et al., 2019). Hence, they present an optimal CH technique in a UAV-assisted post-disaster ECS to improve energy transfer efficiency and establish sustainable connectivity for the ECS. The study developed a UAV deployment model equipped with the optimal CH algorithm and assisted by a clustering technique and D2D links to increase network lifetime and enhance the network's reliability in disaster situations. Therefore, the UAV is integrated with clustering techniques and D2D communication for reliable communication in natural disasters. The study considered the optimal CH approach to minimize the outage probability, improving the network lifetime, reliability, and coverage in disaster. In Liu et al. (2019); Rashid et al. (2020), a multi-hop clustering algorithm was employed to transfer wireless services from a UAV to the CH nodes and forward to

Cluster Members (CMs) to enhance cluster coverage and user device connectivity. The study evaluated the optimal CH approach to reduce the outage probability during and after disaster events. Besides, optimal CH with clustering and D2D communications have been proposed. This work focuses on UAVs for providing coverage services integrated with the clustering approach for user devices based on D2D communication. In the case of infrastructure being damaged due to natural disasters, the CH detects wireless coverage services from UAVs and establishes communication links with other user devices within a disaster zone. The network's energy lifetime increases while the UAV's and D2D's load will be minimized due to communication clustering. This approach increases the coverage of the D2D due to its streamlining of the connectivity and efficiency of post-disaster communication. The clustering mechanism is employed to stabilize and provide efficient network coverage required in post-disaster. In each cluster, there is one CH used to manage the whole cluster. Moreover, the clustering network communications are accomplished by the CH, i.e., inter-cluster and intra-cluster communications. The efficiency of a network is measured by the cluster number formed and D2D communication for power consumption (Y. A. Shah et al., 2018). The clustering aims to minimize the average power consumption of the network and user device equipment.

### 2.7.1 Cluster Head Selection

The CHs are the nodes accountable for gathering data from the CMs and forwarding it to the corresponding UAV. CHs are nodes that detect wireless coverage services transmitted by the UAV and forward them to the CMs via down-links (Nguyen et al., 2018). The CHs allow to minimize the UAV's overload and increase communicative efficiency in a post-disaster scenario. CHs establish communication links with CMs based on the D2D communication pair within the cluster's short-range area. Therefore, this type of network management is very complicated because each CH node signals the traffic load. The cluster life and the total number of clusters in the network are essential parameters (M. F. Khan et al., 2018). In addition, topology maintenance creates additional costs because of the mobility information shared with all nodes in the network by a single node. Therefore, the dynamic CH selection method is crucial. Thus, the user device node having the best specifications and more suitable link with the UAV, i.e., nearer to the UAV path, has to be selected. The CHs are chosen based on inter-user device distance, relative speed, user device attributes, and residual energy (Qi et al., 2018). Therefore, the main objective of the multi-hop moving zone is to form stable clusters achieving high packet delivery, and low latency (M. F. Khan et al., 2018). The CH is considered the first step in establishing communication between the UAV and the CMs. In this regard, the D2D-assisted link within the clustering algorithm allows the distance between CMs and CHs to be a long-range link expanding the cluster coverage. In other words, the CH is mentioned by $SAR_h$, and then SAR head selection is crucial and can be critical in establishing efficient communication links with the network and minimizing the outage probability. The SAR distributed at the optimal location, i.e., nearer the UAV path, could be selected as the $SAR_h$ to $SAR_h$ act and be able to move in the disaster zone to be efficient and serve other SARs out of UAV coverage. In this work, the chosen $SAR_h$, i.e., the optimal $SAR_h$, with more residual energy and more neighbourhood nodes, is based on intra-user device distance, relative speed, and residual energy (Qi et al., 2018). Besides, the $SAR_h$ load should be reduced to ensure effective and stable routes and finally lengthen the lifetime of post-disaster communication (D. Zhang et al., 2018). Moreover, the Passive Multi-hop Clustering Mechanism (PMC) ensures that a priority-based neighbour strategy enhances the clustering stability and improves the user device coverage. In addition, the critical focus neighbourhood mechanism organizes user devices. The user device's node and highest priority neighbour are categorized into one cluster. The most stable user device node in the clustering network turns into the CH node, improves the stability and reliability of the clustering efficiently, and reduces the overhead of the cluster. The cluster merger mechanism enhances the stability and reliability of the cluster network to reduce inter-cluster interference during maintenance (Liu et al., 2019). In Haider et al. (2019), an optimum CH selection strategy is proposed to maximize wireless sensor networks prolonging lifetimes. The CH was selected based on the average residual energy, link quality, and distance of each sensor node from the UAV. However, the UAV's limitation is in the power consumption and sustainable connectivity in providing wireless coverage post-disaster. In this case, there is a need for efficient ways to reduce the energy consumption of the user devices and reduce the communication load of UAVs. In addition, D2D communication and clustering techniques in an emergency wireless network are equally capable of reducing the device energy consumption and increasing the network's ability (Christy et al., 2017). In this context, they investigated the clustering techniques and D2D communication to recover disaster communication efficiently and achieve scalability of the system throughput for multiple ground user devices. The clustering of nodes and nominations of CHs were investigated to reach cluster stability in a wireless network (M. F. Khan et al., 2018). Here, the CH is a node responsible for collecting data from the CMs and forwarding them to the UAVs. However, managing this clustering network is challenging due to the signalling traffic load on each CH (M. F. Khan et al., 2018). The study has considered the optimal CH approach to reduce the outage probability during and after disaster events. In addition, the proposed UAV deployment model was developed to address the issues with clustering and D2D communication that is utilized to harvest energy. The UAVs can control the transmit power of the multi-hop SAR to SAR communications to enable wireless networks' stability (W. Huang et al., 2018). Furthermore, energy harvesting is one approach that can be used to power communication devices and prolong the network lifetime during a disaster phase.

## 2.8 Energy Harvesting

EH is a promising solution to save energy and increase the lifetime of the network energy of communication devices during a disaster. Energy harvesting can provide powering over communication through harvesting techniques to overcome the power supply issue. Wireless Energy Harvesting (WEH) comes from energy radio signals that convert wireless signals into source energy (Ali et al., 2018). Based on SWIPT technology, the user devices can harvest energy from radio frequency wireless signalling to enhance EE (Z. Zhou et al., 2017). TS and PS are two convenient schemes for SWIPT to evaluate the performance of two power harvesting activities. In Yang et al. (2020), a SWIPT method was proposed to harvest energy from the radio frequency signals to improve the EE performance and overcome the limitation of battery capacity (Haider et al., 2019); (Yang et al., 2020). The author in Yang et al. (2020) investigated a UAV-powered energy harvesting wireless communication system that was proposed to transfer energy and improve network connectivity duration during a natural disaster. EH's stable matching algorithm solved the resource allocation problem under spectrum reuse and transmit power constraints.

Hence, the integrated method is used to optimize the energy-harvesting time and power control between function and dysfunction, such as UAVs, CHs, and D2D communications in real-time applications. In Z. Li (2012), relay source nodes are considered external wireless charging from the GBS, where wireless services transfer the signal to destination nodes. However, there are difficulties in using the CHs to transfer the wireless services from the UAV to the CMs that are in the out-of-UAV coverage area with energy consumption and sustainable connectivity during the disaster phases. The common goal in any disaster management research is to design a ubiquitous network architecture that can work constantly and successfully in search and rescue missions. In this context, various solutions have been proposed in the literature. For example, a UAV-powered energy harvesting wireless communication system was proposed in X. Liu et al. (2018) to transfer energy and improve network connectivity during a natural disaster. In emergency communications, energy management is a significant concern for the network infrastructure. Here, UAVs increase wireless coverage and reduce channel access delay. Moreover, UAVs are integrated with an ECS to assist terrestrial networks for fast response and reliable connectivity in disaster scenarios (Panda et al., 2019). Efficient resource distribution is critical to improve the channel link quality and thus maximize the downlink coverage services. The power allocation strategies based on RF energy harvesting were investigated in Liu et al. (2020). A UAV carries a pico-base station used to increase wireless coverage and reduce network congestion or traffic overload. They adopted several clustering approaches in wireless networks to tackle the energy harvesting issues, catering to the power supply limitation. The energy harvesting technique presented in this work could increase the battery life and keep the network running during disasters. Energy harvesting powered D2D communications were investigated to maximize the energy efficiency of D2D communications based on time slot allocation and transmit power control to overcome the constraint on energy performance. Additionally, efficient resource distribution was used to improve the channel link quality based on D2D energy harvesting (D2D-EH) to decrease the communication outage probability in post-disaster situations. In addition, efficient resource distribution is used to improve the channel link quality based on the D2D-EH. Moreover, increasing the sum rate of D2D assisted the link to decreasing outage probability post-disaster. In the later study by Liand Fei and Zhang (2018), the Augmented Lagrange Multiplier Approach (ALMA) was proposed to achieve an optimum solution by optimizing the power allocation problem. However, further issues related to the battery prolong the lifetime and the power consumption of the network energy and user device terminals. In J. Zhang et al. (2020); Nguyen et al. (2018), UAVs with multiple antennas serve as relay nodes to transfer wireless information and power among the D2D user devices located outside the coverage area and the core network. Here, an integrated method (i.e., UAV, CHs, and D2D communications) was used to optimize the energy harvesting time and power control between functional and dysfunctional areas. The EH approach improves the network lifetime, reliability, and coverage in disaster situations. The power allocation strategies based on RF Energy Harvesting were investigated (R. Li et al., 2020). Additionally, efficient resource distribution was used to improve the channel link quality based on D2D energy harvesting (D2D-EH) to decrease the probability of communication outages in post-disaster situations. However, there is difficulty underlying the use of the CHs to transfer wireless signals from the UAV to the CMs nodes during disaster phases. In Selim et al. (2019), power control strategies proposed to guarantee service quality were investigated for D2D pair communications underlying UAV planes in post-disaster recovery. Furthermore, the $SAR_h$ should be equipped with SWIPT techniques to harvest energy from the radio frequency signals and improve energy efficiency (Jayakody et al., 2019);(Z. Zhou et al., 2017). Moreover, the $SAR_h$ can be selected based on the weighted residual energy, the number of neighbours, and the distance between the UAVs and $SAR_m$ (Mozaffari et al., 2016b); (G. Wang et al., 2020). However, backhaul connectivity remains a challenging problem for both UAVs and multi-hop S2S in out-of-coverage areas. This is even more severe in a natural disaster where cellular network infrastructure is partially or fully damaged. This has encouraged researchers to focus on new and robust network deployment strategies for public safety communication (D. Zhang et al., 2018) and indeed is one of the research agendas presented in this work.

## 2.9 Research Gap

The ECS-enabled fast and efficient disaster recovery has several advantages. However, various technical challenges are encountered based on state-of-the-art research works in

Table 2.2. Future-generation wireless systems, such as the 5G network and beyond, are expected to implement increased energy harvesting and power control solutions to reduce power consumption, prolong lifetime, and eliminate interference management mechanisms to achieve more reliable communication. One method for achieving this goal is to reduce the power consumption and maximize coverage area through the clustering, and D2D communication of the network, EH, and PC rather than reducing the transmission power of the UAVs, prolonging energy lifetime and minimizing outage probability. This method will improve the performance of the ECS network by quickly establishing a temporary connectivity link to support emergency management in the disaster relief mission. Several studies have been conducted recently and provide an excellent basis and foundation to identify the research gaps in ECS. These studies are discussed below. Authors in Alsamhi, Ma, et al. (2019) have investigated full-duplex UAV relaying to improve PSN coverage and connectivity. These authors are enhancing the level of PSN that can improve B5G collaboratively for disaster recovery. However, the authors do not mention the clustering, D2D, and PC for PSN-based ECS to facilitate the rescue teams and victims communicating inside and outside the disaster site. The authors in Ansari and Cho (2018); Syed et al. (2021); Wang et al. (2019); Zhao et al. (2019), proposed to use of Multi-UAV and SARs to extend the coverage area for enhancing the EE based on Fuzzy C-Means clustering for poor connectivity and improving ECS, reducing the power consumption and reliable connectivity during disasters. However, those studies do not mention the optimal CH to minimize outage probability through SAR operation for a suitable network design to recover from natural disasters. The authors in Liand Fei and Zhang (2018); Nawaz et al. (2021); Syed et al. (2021) have been investigating Mobile communications from UAV-HAPs that are being used to develop 5G network and multi-UAV collaboration for improving connectivity, ensuring QoS, and extended coverage area. However, those

authors do not consider EH, and PC to minimize network power consumption and optimal CH algorithm for eliminating the battery power barriers and prolonging the network energy lifetime. The authors in Alsamhi, Ansari, et al. (2019); Liu et al. (2018); Zhang et al. (2019) has proposed integrating UAV within multi-antenna and MH/D2D to extend the coverage via utilizing the relay to keep connectivity running in emergencies. Moreover, the author in Saad et al. (2020) has investigated UAVs at LAP and HAP for improving satellite limitation connectivity. However, this study still challenges the energy constraint for prolonging the energy network and stable connectivity in disaster recovery. The authors in Christy et al. (2017); Haider et al. (2019) Qi et al. (2018) investigated the UAV and optimal CH strategy to maximize lifetimes and reduce power consumption to increase the network's ability for reliable EFR connectivity. However, those studies missed using EH to power user devices through SWIPT and optimal CH capabilities to maintain network functions and minimize outage probability during SARs operations. The authors in Ali et al. (2018); (Garcia et al., 2019); (Liu et al., 2020); Liu et al. (2019); Luo et al. (2020) investigate the Wireless Communication System (WCS) powers the UAV-EH and D2D-EH to improve energy lifetime connectivity, eliminate battery power barriers, and reduce network congestion. This thesis studies ECS based on Multi-UAV, SARs, EH, optimal CH algorithm, and PC to improve connectivity, minimized outage, and energy consumption, and extended coverage area. The idea of content-based optimal CH selection in the edge of UAV coverage is to minimize outage probability and D2D within the optimal CH algorithm in the cluster to extend the coverage area, where EH and PC are attempted to eliminate the barriers of battery power, reduce the interference and reduce power consumption for the system.

Table 2.2: Comparison of the proposed Approach with Related Works

| *Highlight* | Ref | UAV | PSN | ECS | D2D | PC | EH | optimal CH |
|---|---|---|---|---|---|---|---|---|
| Full-duplex UAV relaying to improve PSN coverage and connectivity | alsamhisurvey,et al.(2019) | ✓ | ✓ | ✓ | × | × | × | × |
| Improving the level of PSN that can improve B5G in a collaborative manner | alsamhi.et al.(2021) | ✓ | ✓ | ✓ | × | × | × | × |
| Real-time resource allocation apps for ensuring UAV collaboration | syed.et al.(2021) | ✓ | ✓ | ✓ | ✓ | × | × | × |
| Mobile communications from UAV-HAPs are being used to develop 5G | li2uav.et al.(2018) | ✓ | ✓ | × | ✓ | × | × | × |
| UAV at LAP and HAP for improving satellite limitation connectivity | Saad.et al.(2020) | ✓ | ✓ | ✓ | × | × | × | × |
| Multi-UAV and SARs to extending coverage area for enhancing the EE | Zhao.et al.(2019) | ✓ | ✓ | ✓ | ✓ | × | × | × |
| Designs the down/uplink UAV transceiver with(MH/D2D) during the disaster | Ranjan.et al.(2018) | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Multi-UAV for improving connectivity, Qos and extended coverage area | nawazuav.et al.(2021) | ✓ | ✓ | ✓ | × | × | × | × |
| Relay assisted D2D for disaster recovery and improve EE | Ali.et al.(2018) | × | ✓ | ✓ | ✓ | ✓ | ✓ | × |
| Integrating UAV within multi-antenna and MH/D2D to extend the coverage | Liu.et al.(2018) | ✓ | ✓ | ✓ | ✓ | × | × | × |
| UAV and relay for disaster recovery for reducing load and improving QoS | Zhang.et al.(2019) | ✓ | ✓ | ✓ | ✓ | × | × | × |
| Fuzzy C-Means clustering used in PSN to reduce the power consumption | Ansari.et al.(2018) | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| UAV, CHs and CMs for deficient connectivity and EE improvement | Wang.et al.(2019) | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| WCS powers the UAV-EH to improve connectivity and energy lifetime | Liu.et al.(2019) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × |
| , UAV, ECS for fast response and reliable connectivity during disasters | Syed.et al.(2020) | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| UAV and optimal CH for reducing EE and efficient disaster recovery | qisdn.et al.(2018) | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| UAV and optimum CH used as a strategy to maximize WSN prolonged lifetimes | Haider.et al.(2019) | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| D2D and clustering in an ECS and increase the network's ability | Christy.et al.(2017) | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| UAVs, D2D to keep connectivity running in the case of emergencies | Alsamhi.et al. (2019) | ✓ | ✓ | ✓ | ✓ | × | × | × |
| Use WEH as source energy to improve EE and to prolong the time of connectivity | Ali.et al. (2018) | × | ✓ | ✓ | ✓ | ✓ | ✓ | × |
| EH and D2D to maximize EE to eliminate the battery power barriers | luoenergy.et al.(2020) | × | × | × | ✓ | ✓ | ✓ | ✓ |
| UAV and EH to improve connectivity and the resource allocation problem | Liu.et al.(2019) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × |
| UAV, EH and CH to reduce network congestion's and improve connectivity | Liu.et al.(2020) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × |
| ECS based on Multi-UAV, SARs, EH ,optimal CH algorithm and PC to improve the connectivity minimized outage, energy consumption and extended coverage area | This work | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

# CHAPTER 3: METHODOLOGY

## 3.1 Introduction

This chapter describes the proposed algorithms for the design of ECS schemes to achieve the study's objectives. The iteration of greedy algorithms is considered to find the optimal location of the CHs. The optimal cluster Head is affected by power consumption and interference, hence the EH and PC act to reduce the power consumption of the nodes and eliminate the interference. Therefore, the energy consumption, coverage area, prolonging network lifetime, and network sustainability are still challenges for efficient communication during disasters. Furthermore, the design of the ECS is proposed to overcome those challenges. The multi-UAV and SAR collaboration are integrated with clustering and S2S communication. A single UAV is integrated with D2D communication and clustering to reduce energy consumption, extend coverage area, and maintain network sustainability connectivity. In addition, the optimal cluster Head or $SAR_h$ is used to minimize outage probability and speed up response disaster recovery. Moreover, the EH, PC, and SPR can prolong the network lifetime, eliminate interference, and speed up disaster recovery. Finally, the proposed design was evaluated by comparing related work, computational complexity, and convergence rate with minimal power consumption. Moreover, the structure of the research methodology is presented in this chapter. It was conducted through the following stages:

- The proposed design of the ECS is based on the iterative greedy algorithm with the optimal cluster Head at the location on the edge of UAV coverage to minimize outage probability and extend the coverage area. In addition, the EH used the optimal cluster Head algorithm to reduce power consumption and reduce UAVs' load for prolonging network energy lifetime. The power control is used to eliminate the interference that affects the UAVs' connectivity and optimal cluster Heads nodes. The proposed clustering of SAR for efficient connectivity with multi-UAV to deliver communication services to end SARs over larger disaster areas via multi-hop S2S connectivity to improve QoS and achieve better energy efficiency in future wireless networks. Moreover, the SPR extends the S2S coverage area with fast response and reduces the number of hops.

- The system models design the multi-UAV and SAR collaborations to support communication between the in-coverage and out-of-coverage areas to extend the wireless coverage to hard-to-reach remote disaster areas. The utilized clustering approach results in further energy saving in S2S communication and maintains the network connectivity coverage. Furthermore, selecting optimal altitudes for UAVs is effective in terms of improving coverage probability. The deployment is a suitable network design. The deployment network has a single-UAV model for communicating with the optimal cluster Head selection and D2D links. The design is capable of harvesting energy to increase the network lifetime and potentially save many lives.
- The main advantage of the UAVs channel is a higher LoS propagation better than the terrestrial communication channels. Variation is primarily due to the environmental factors and LOS/NLOS probability of communication link. This acts to reduce transmit power requirements and can translate to higher link reliability in the case of infrastructures networks damages. Therefore, the AtG channel may experience lower diffraction and shadowing losses than near-ground terrestrial communications when only non-LOS (NLOS) pathways are available and the elevation angle to the UAV is sufficiently large. Furthermore, the fixed bandwidth is not affected by the Doppler spread of the frequency components of a signal.

## 3.2 The Proposed System Models

The system models describe the user device distribution that includes SARs in the disaster area and deployed multi/single UAVs to achieve the objectives of the study. Multi-UAV performs several missions to save energy and lower the system latency. The algorithm1 is designed to prolong the system lifetime and minimize the system response resulting from network failure. In addition, Multi-UAVs are able to cover a larger area in order to provide a quick response for disaster communication recovery. A single UAV system can only provide limited operational tasks to achieve full active function and cover smaller areas with a direct and simple network connection. The optimal cluster Heads selection (or $SAR_h$) is located on the edge of the UAV coverage area utilized to extend the coverage area, minimize the outage probability, and maintain sustainable connectivity in the disaster event. UAV deployment with the optimal cluster Head algorithm reduces outage probability and energy consumption. The UAV system model is proven to reduce the computational complexity and a suitable network design to recover from natural disasters potentially saves many lives. The user devices in the disaster area are assumed to be distributed randomly, and they are classified into many clusters based on the criteria to select the $CH$. The clustering schemes can also be divided into numbers of nodes that communicate through multi-hop D2D communications. The ECS describes the system modelling, performance methods, and simulation model of the proposed algorithms to minimize outage probability and save power based on optimal cluster Head, clustering, and D2D communication.

### 3.2.1 Multi-UAV System Model

The assumption is to deploy Multi-UAVs in the disaster area to cover the communication of user devices. Here in this study, a system model which consists of a damaged cellular network has been considered. For the sake of simplicity and without loss of generality, the system with cellular BSs has been assumed in the system model, i.e., $\mathrm{BS}_1$, $\mathrm{BS}_2$ and $\mathrm{BS}_3$, where $\mathrm{BS}_1$ is located in the functional area whereas $\mathrm{BS}_2$ and $\mathrm{BS}_3$ are located in the dysfunctional area as exhibited in Figure 3.1, Therefore, UAVs can collaborate with multi-hop S2S communication to extend coverage area, keep connectivity, and achieve impressive performances in disaster recovery due to the UAV's transmission power limitation and the distance to providing wireless coverage. The multi-UAV and SAR collaboration have been proposed with optimal $SAR_h$ in order to minimize outage probability and extend the coverage area during disaster events. The cluster formation will be reconfigured to minimize the outage probability.

Due to natural disasters, e.g., earthquakes, flooding, etc., SARs in dysfunctional areas are unable to receive wireless coverage and services from GBS. To address this issue, UAVs with an altitude $H_n$ and static locations $(x_n, y_n, H_n)$ are deployed to reinstate the service, and the $k^{th}$ UAV is denoted by $U_k = [x_k, y_k, H_k]^T$. In this study, the UAV coverage area is assumed to be circular, and the SARs are distributed according to a Poisson Cluster Process (PCP) with a spatial density of $\lambda_S$. It is assumed that the UAVs are equipped with a directional antenna to maximize the network coverage performance and will adjust their altitudes based on the antenna bandwidth and density of the buildings, i.e., the number of buildings per square km (Xu & Zeng, 2020). There may exist several SARs that are still out of the UAV coverage range and unable to obtain wireless services due to the limited UAV transmission power and coverage distance. In this case, the SARs at the edge of the UAV coverage area plays a critical role in linking SARs that are out of the UAV coverage area. They will act as a relay to communicate with the UAVs through the multi-hop S2S network to distant SARs. It should be noted here that the SARs which are out of the UAV coverage range will utilize the S2S communication mode to establish connectivity based on their residual energy. The S2S link is established when the SINR between the S2S transceivers is less than the SINR between the UAVs and head SAR. A clustering approach is utilized where the SAR devices (denoted by $SAR_m$) send their information to a cluster head denoted by $SAR_h$ in a full-duplex model (X. Liu et al., 2018). The clustering techniques based on the Low-Energy Adaptive Clustering Hierarchy (LEACH) communication protocol are considered optimal cluster Heads to balance energy consumption and prolong network energy lifetime (Ngangbam et al., 2020).

The SARs in the range of UAV coverage, called active SARs, are able to change their locations to service other SAR users in out-of-coverage areas. Hence, the UAVs can collect messages from the SARs which are located in the range of its coverage and the $SAR_h$ in the edge of the coverage area that is connected to the out-of-range $SAR_m$ devices. The SARs are classified into $N$ clusters where the $l^{th}$ cluster includes $N(l)$ SAR devices. The UAVs provide wireless services to $SAR_h$ devices within its coverage range, and the CHs then forward signals to their neighbour $SAR_m$ that is out of the UAV coverage area. For reliable connectivity in a post-disaster scenario, the UAV is able to assign the $SAR_h$ locations to provide coverage for out-of-the-range $SAR_m$. Besides, the $SAR_h$ can minimize the outage probability due to the shorter propagation distance with $SAR_m$. Meanwhile, the multi-hop S2S communications within the cluster will be established using the S2S routing protocol based on a clustering technique and the SPR to reduce the communication latency.

#### 3.2.1.1 UAVs Downlink Communication

The UAVs deliver messages to $SAR_h$ at the ground nodes in the downlink, and the desired signal at the $i^{th}$ $SAR_h$ node is obtained as follows.

$$\tilde{y}^{[i]} = \mathbf{g}^{[i]}\mathbf{v}^{[i]}\tilde{x}^{[i]} + \sum_{i \in \mathcal{S}_{\mathrm{DN}}, i \neq j} \mathbf{g}^{[i]}\mathbf{v}^{[j]}\tilde{x}^{[j]} + n_0, \tag{3.1}$$

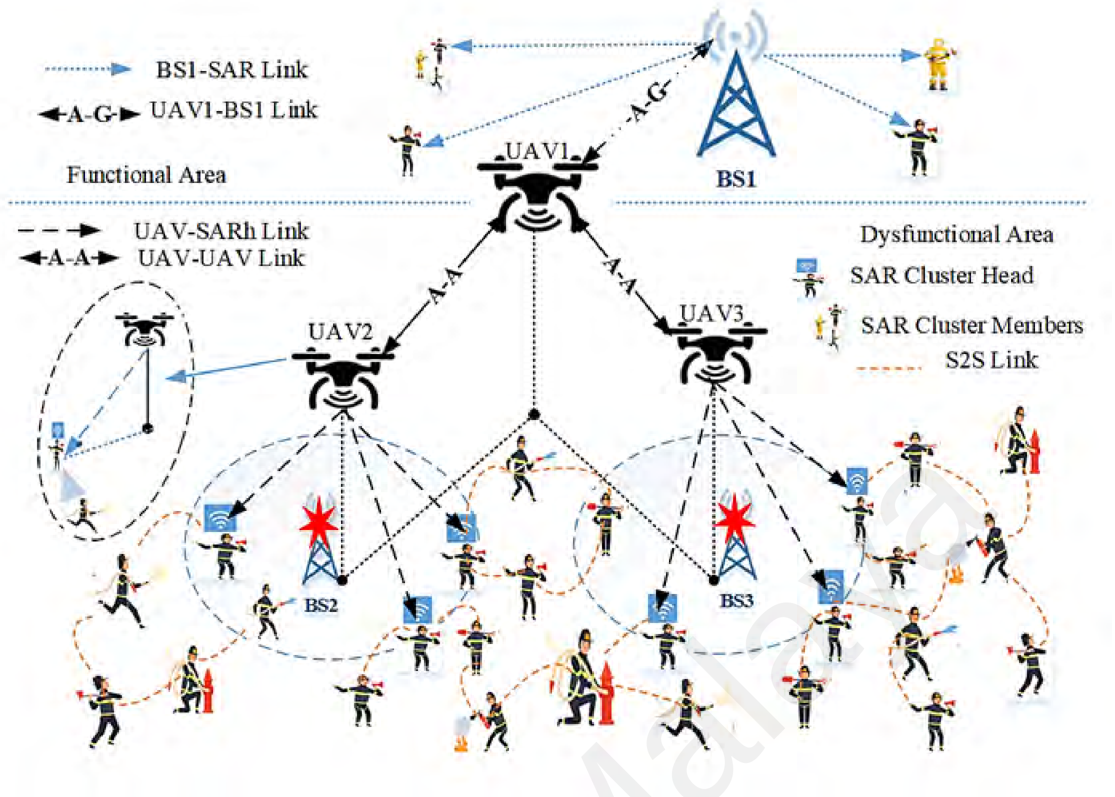

**Figure 3.1: Architecture of the Multi-UAV and Multi-hop S2S Communication.**

where $g^{[i]} = \sqrt{\rho_2 d_{[ki]}^{-\alpha_2}} g_{\mathrm{DL}}^{[i]}$ and $g_{\mathrm{DL}}^{[i]} \in \mathbb{C}^{m \times n}$ is the small-scale fading from the $UAVs$ to the $SAR_h$ receiver node in the downlink. In addition, the $\rho_2$ ,$\alpha_2$ indicate the channel power gain at the reference distance and the path-loss exponent between the UAV and SAR ground nodes, respectively. Similarly, $d_{[ki]}$ denotes the distance from the $k^{th}$ $UAV$ to the $i^{th}$ $SAR_h$ receiver nodes, $v^{[i]} \in \mathbb{C}^{m \times n}$ is the precoding vector of the $SAR_h$ receiver nodes at the UAV and $\sum_{i \in S_{\mathrm{DN}}} \left\| v^{[i]} \right\|^2 \leq \mathrm{p_{sum}}$, where $\mathrm{p_{sum}}$ is the transmit power of UAV. In addition, $\tilde{x}^{[i]}$ is the signal transmit power from the $UAVs$ to the SAR ground nodes. Moreover, the $S_{\mathrm{SD}}$ was considered as the S2S source nodes in the downlink or S2S destination nodes in the uplink that communicate with $UAV_k$.

Subsequently, SINR at the $i^{th}$ $SAR_h$ is obtained as follows.

$$\mathrm{SINR}_{DL}^{[i]} = \frac{\left| \mathbf{g}^{[i]} \mathbf{v}^{[i]} \right|^2}{\sum_{j \in \mathcal{S}_{\mathrm{DN}}, i \neq j} \left| \mathbf{g}^{[i]} \mathbf{v}^{[j]} \right|^2 + \sigma^2}. \tag{3.2}$$

where $S_{\text{DN}}$ is the set that contains $SAR_h$ source nodes in the downlink or the S2S destination nodes in the uplink that communicate with the UAV

#### 3.2.1.2 Downlink Multi-hop Communication

The multi-hop downlink from the UAVs to $SAR_h$ and received signals at $SAR_m$ through $j^{th}$ $S2S_{Rx}$ is obtained as follows.

$$\bar{y}^{[j]} = \bar{h}^{[ij]}\bar{x}^{[j]} + \sum_{i\in\bar{\mathcal{S}}_I} \bar{h}^{[ij]}\bar{x}^{[i]} + \sum_{j\in\mathcal{S}_{\text{DN}}} \bar{\mathbf{g}}^{[j]}\mathbf{v}^{[i]}\tilde{x}^{[i]} + n_o, \tag{3.3}$$

where $\bar{h}^{[ij]}$ is the gain of channel from the $SAR_h$ to $SAR_m$, $h^{[ij]} = \sqrt{\rho_2 d_{[ij]}^{-\alpha_2}} h_{\text{DL}}^{[ij]}$ and $h_{\text{DL}}^{[ij]}$ is the i.i.d. fading of channel between S2S communication in downlink. Therefore, $\bar{g}^{[j]} = \sqrt{\rho_1 d_{[ij]}^{-\alpha_1}} \bar{g}_{\text{DL}}^{[j]}$, where $\bar{g}_{\text{DL}}^{[j]} \in \mathbb{C}^{m\times n}$ is the channel fading vector from the $SAR_h$ to $SAR_m$, and $\bar{x}^{[i]}$ is the transmitted signal by $SAR_h$. Also, $\bar{\mathcal{S}}_I$ is the set of $SAR_h$ transmitters which may cause interference to $j^{th}$ $SAR_m$ receivers within the same cluster. Next, the SINR at the $j^{th}$ $SARm_{Rx}$ can be shown as follows.

$$\text{SINR}_{\text{DL}}^{[j]} = \frac{\hat{P}^{[j]}\bar{g}^{[ij]}}{\sum_{n\in\bar{\mathcal{S}}_I} \hat{P}^{[n]}\bar{g}^{[jn]} + \sum_{i\in\mathcal{S}_{\text{DN}}} \left|\bar{\mathbf{g}}^{[j]}\mathbf{v}^{[i]}\right|^2 + \sigma^2}, \tag{3.4}$$

where $\bar{g}^{[ij]} = \left|\bar{h}^{[ij]}\right|^2$ is the channel gain between the $i^{th}$ $SARh_{Tx}$ and $SARm_{Rx}$ and $P^{\bar{[}j]}$ is the $SAR_m s$ transmit power. In the proposed multi-hop S2S model, the SPR is used to extend the S2S coverage area with fast response and reduce the number of hops. This is because the outage probability in multi-hop S2S communications is vital to sustaining the link between $SAR_h$ and UAVs. Furthermore, UAVs are configured to guarantee uplink and downlink channel efficiency during disasters.

#### 3.2.1.3 UAV Uplink Communication

The messages from a $SAR_m$ which are out of the UAV coverage can be delivered to the UAVs through the $SAR_h$ in the uplink channel. Therefore, the received signal at $k^{th}$ UAVs from the $i^{th}$ $SAR_h$ can be represented as follows (X. Liu et al., 2018).

$$y^{[k]} = \mathbf{u}^{[k]\dagger}\mathbf{h}^{[k]}x^{[k]} + \mathbf{u}^{[k]\dagger} \sum_{i \in \mathcal{S}_{\text{DN}}, i \neq k} \mathbf{h}^{[i]}x^{[i]} + n_0, \tag{3.5}$$

where $u^{[k\dagger]} \in \mathbb{C}^{m \times n}$ are the channel coefficient vectors between the $SAR_h$ transmitting node and UAV receiving node (i.e.,$\mathcal{S}_{\text{DN}}$), and $h^{[k]} \in \mathbb{C}^{m \times n}$ is the decoding vector of the $k^{th}$ destination node at the UAVs in uplink where $\left\|u^{[k]}\right\|^2 = 1$ and $n_0$ is received noise density. Therefore, $x^{[i]}$ is the transmitted signal from $SAR_h$ to the UAVs.

The SINR received at the $UAV_n$ from the $SAR_h$ at the ground nodes is obtained as follows.

$$\text{SINR}_{\text{UAV}}^{[k]} = \frac{P^{[k]} \left|\mathbf{u}^{[k]\dagger}\mathbf{h}^{[k]}\right|^2}{\sum_{i \in \mathcal{S}_{\text{DN}}, i \neq k} P^{[i]} \left|\mathbf{u}^{[k]\dagger}\mathbf{h}^{[i]}\right|^2 + \sigma^2}, \tag{3.6}$$

where $P^{[i]}$ is the transmit power of $SAR_h$ destination nodes. Next, the received signal at $SAR_h$ from the $SAR_m$ in uplink is as follows.

$$\hat{y}^{[i]} = h^{[ji]}\hat{x}^{[j]} + \sum_{j \in \mathcal{S}_I} h^{[ij]}\hat{x}^{[j]} + n_o, \tag{3.7}$$

where $h^{[ji]} = \sqrt{\rho_2 d_{[ji]}^{-a_2}} h_{\text{UL}}^{[ji]}$ and $h_{\text{UL}}^{[ji]}$ denote the small-scale fading coefficients between the $j^{th}$ S2S transmitter and $i^{th}$ S2S receiver which are independent and identically distributed (i.i.d). $d_{[ji]}$ is the distance from the $j^{th}$ $S2S_{Tx}$ to the $i^{th}$ $S2S_{Rx}$. $\rho_2$ denotes the channel gain, and $\alpha_2$ is the path-loss exponent. $\hat{x}^{[j]}$ is the transmitted signal by the $j^{th}$ $S2S_{Tx}$, and $s_I$ is set to include $S2S_{Tx}$ that affects interference to the $i^{th}$ $S2S_{Rx}$ in the same cluster S2S transmitters in uplink. Then the SINR at the $i^{th}$ $S2S_{Rx}$ can be rewritten as follows.

$$\mathrm{SINR}_{\mathrm{UL}}^{[i]} = \frac{\hat{P}^{[i]} g^{[ij]}}{\sum_{n \in \mathcal{S}_I} \hat{P}^{[n]} g^{[in]} + \sigma^2}, \tag{3.8}$$

where $g^{[ji]} = |h^{[ji]}|^2$ is the gain of channel from the $j^{th}$ $S2S_{Tx}$ to the $i^{th}$ $S2S_{Rx}$, and $\hat{p}^{[j]}$ is the transmit power of the $j^{th}$ $S2S_{Tx}$.

#### 3.2.1.4 Line-of-Sight Probability Link

The channel between UAVs and SAR at ground nodes in the downlink is characterized as AtG channel links. The probability of obtaining the LoS link as a function of elevation angle of SAR node, i.e., $\theta_i$, and network environment parameters, i.e., $a$, $b$, is obtained as follows (Nguyen et al., 2018).

$$P_{\mathrm{LoS},[i]} = \frac{1}{1 + a \cdot \exp(-b(\theta_{[i]} - a))}, \tag{3.9}$$

where $a$ and $b$ are parameters associated with the S-curve which is a function of the network environment, i.e., suburban, urban area. The elevation angle $\theta_i$ of the SAR nodes is measured in degrees and is given as follows:

$$\theta_{[i]} = \frac{180}{\pi} \sin^{-1}\left(\frac{h}{\sqrt{x_k^2 + y_k^2 + h_k^2}}\right), \forall k. \tag{3.10}$$

The NLoS probability of the SAR nodes can be obtained as $P_{\mathrm{NLoS},i} = 1 - P_{\mathrm{LoS},i}$. The average channel gain for the links between the UAVs and SAR nodes at the ground is denoted as follows.

$$\bar{h}_{[i]} = P_{\mathrm{LoS},[i]} \left(\sqrt{h_k^2 + x_k^2 + y_k^2}\right)^{-\alpha_{[i]}} + P_{\mathrm{NLoS},[i]} \eta \left(\sqrt{h_k^2 + x_k^2 + y_k^2}\right)^{-\alpha_{[i]}}, \forall k \tag{3.11}$$

where $\alpha_{[i]}$ is the path-loss exponent associated with the AtG link for SAR nodes, and $\eta$ is excessive loss encountered for NLoS links from the UAVs and SAR nodes.

#### 3.2.1.5 Path Loss Analysis

Path loss propagation is a critical factor that affects the wireless channel between the UAVs and SAR through the AtG channel. Hence, the signal path loss is highly affected by environmental parameters such as distance, SAR elevation angles and UAV altitudes. Therefore, path loss can be obtained from the following expression.

$$\mathrm{PL(dB)} = 20\log_{10}\left(\frac{4\pi f_c d_{[ki]}}{c}\right) + \mu_{\mathrm{LoS}} P_{\mathrm{LoS}} + \mu_{\mathrm{NLoS}} P_{\mathrm{NLoS}}, \tag{3.12}$$

where $f_c$ is the carrier frequency, $c$ is the light speed, and $d_{[ki]}$ is the distance between the UAVs and the $SAR_h$ nodes. Then, $\eta_{\mathrm{LoS}}$ and $\eta_{\mathrm{NLoS}}$ are excessive loss due to shadowing and scattering in case of LoS and NLoS links.

#### 3.2.1.6 Throughput Performance

Next, the performance of the cellular network was investigated, for S2S and UAV during and after disaster scenarios. The Air-to-Air (AtA) assumed that channels between the UAVs are free space, and a Rayleigh fading channel is assumed between the S2S transmitters and receivers. Then the fading channel of the S2S communication is modelled as $Cd^{-\alpha}$, where $C$ is the small-scale fading factor which is modelled as a Rayleigh fading process, $d$ denotes the distance from $SAR_h$ to $SAR_m and$ and $\alpha$ is the path loss exponent (Chu et al., 2017a). Other performance improvements in both one-hop and multi-hop S2S communications include higher data rate, energy efficiency, network capacity, and service availability during disaster events (D. Zhang et al., 2018). Therefore, the throughput between the UAVs and

SAR nodes can be obtained as follows:

$$R_{\text{UAVs}}^{[k]} = B \cdot \log_2(1 + \text{SINR}_{\text{UAVs}}^{[k]}). \tag{3.13}$$

Furthermore, the $k^{th}$ CMs will select the optimal cluster Head based on the maximum residual energy, EH, and the number of neighbours that satisfy the SINR threshold and B is a locate bandwidth. Then, the achievable sum rate of all $i^{th}$ optimal cluster Head is given as follows.

$$R_i = \log_2\left(1 + \text{SINR}_{DL}^{[i]}\right) = \quad \log_2\left(1 + \frac{\left|\mathbf{g}^{[i]}\mathbf{v}^{[i]}\right|^2}{\sum_{j\in\mathcal{S}_{\text{DN}}, i\neq j}\left|\mathbf{g}^{[i]}\mathbf{v}^{[j]}\right|^2 + \sigma^2}\right) \tag{3.14}$$

#### 3.2.1.7 Coverage Probability of UAVs

Rician distribution is usually used to model the LoS communication with the dominant path. In contrast, the non-dominant multipaths are severely affected by fading and are modeled by Rayleigh distribution using the shadowing effect on LoS and NLoS links. Therefore, $\phi_{\text{LoS}} \sim N(\eta_{\text{Los}}, \sigma_{\text{LoS}}^2)$ and $\phi_{\text{NLoS}} \sim N(\eta_{\text{NLos}}, \sigma_{\text{NLoS}}^2)$ obey different Gaussian distributions: $\eta_{\text{LoS}}$ and $\eta_{\text{NLos}}$. The coverage probability is generally defined as the probability that the $P_r$ at the receiver exceeds a pre-determined threshold of $p_{min}$ necessary for a successful communication $P_{cov} = \mathbb{P}[P_r \geq p_{\text{min}}]$. Where $P_r$ is the received signal power and $p_{min}$ is the minimum of UAV transmit power. The coverage probability achieved by SAR terminals is obtained as follows:

$$\begin{aligned} P_{cov} = P_{LoS}\, Q\left(\frac{p_{min} + PL_{dB} - p_t - G_{dB} + \eta_{LoS}}{\sigma_{LoS}^2}\right) \\ +(1 - P_{LoS})\, Q\left(\frac{p_{min} + PL_{dB} - p_t - G_{dB} + \eta_{NLoS}}{\sigma_{NLoS}^2}\right), \end{aligned} \tag{3.15}$$

where $PL_{dB}$ represents the path loss, $G_{dB} = 3$ dB represents the antenna gain without losses, $p_t$ is UAV transmit power , $p_{min}$ is the minimum transmit power and Q(·) is a Q-function.

#### 3.2.1.8 Clustering Techniques for SARs

Several clusters are formed based on established direct communication links amongst SARs to provide the most stable and efficient routes for data dissemination for radio resources (Kumar et al., 2020). To achieve cluster stability in a wireless network, optimal clustering of nodes and nominations of $SARhs$ were investigated (A. A. Khan et al., 2018). Here, the $SAR_h$ node is responsible for collecting data from $SAR_m$ and then forwarding the data to relevant UAVs. In addition, clustering techniques and S2S communication are required to improve overall network coverage and energy efficiency, hence extending the communication range, according to to (Christy et al., 2017). It is worth noting that the $SAR_h$ selection is a very important step if the objective is to establish efficient communication links and significantly reduce the outage probability. To achieve this goal, the SARs located close to the UAV path is selected as the $SAR_h$. The chosen $SAR_h$s, i.e., the optimal $SAR_h$s, are those with more residual energy, more neighbourhood nodes, and adequate received signal strength $R_{ss}$ based on the metrics of intra-user device distance, relative speed, and residual energy.

#### 3.2.1.9 SAR Head Selection

The optimal $SAR_h$ location was selected at the edge of UAV coverage to minimize outage probability and extend the coverage area. The Multi-UAV used the same optimal $SAR_h$ with clustering and S2S communication for reliable connectivity in disaster recovery. The significant challenges in UAVs are the failures of connectivity, power consumption, and improving the coverage area in the disaster-injured area due to natural disasters.

Furthermore, the design of ECS algorithms with clustering and S2S communication based on the iterative greedy algorithms is suitable for communication recovery. To achieve high packet delivery with low latency, here there is a need to enable efficient communication between the $SAR_h$ and UAVs dynamically. Therefore, it is essential to select $SAR_h$ with more residual energy and a large number of neighbourhood nodes. Furthermore, $SAR_h$ is determined based on the metrics of inter-SAR distance, relative speed and SAR attributes to efficiently stabilize the extensive cluster coverage (Ali et al., 2018); (Nguyen et al., 2018). In the process of post-disaster clustering, the load on $SAR_h$ should be reduced to provide effective and stable routes to improve the lifetime of post-disaster communication (D. Zhang et al., 2018). Reliable communication among $SAR_h$ during post-disaster by the gateway link should also be optimized. To address this, $SAR_h$ will redistribute the network load and minimize the average power consumption of SAR nodes (Khuwaja et al., 2018); (H. Wang, Chen, et al., 2018).

Therefore, the $SAR_h$ update their locations to achieve higher SNRs. However, this decision is also impacted by the interference from the UAV and SARs near it. Therefore, the optimal $SAR_h$s selection aims at minimizing the transmit power to lower the interference to $SAR_m$ and reduce the energy consumption. The power iteration method is applied in optimal $SAR_h$ to adjust the desired received signals at SARs and minimize the interference of S2S pair communication within the clusters. Furthermore, a Multi-UAV system with advanced cooperative control algorithms has advantages over a single UAV system, especially in time urgent tasks such as detecting nuclear radiation before deploying the salvage. The multi-UAV and SAR collaboration are considered to assist ECS for improve its connectivity in larger disaster areas effectively and efficiently. The UAV-assisted ECS establishes connectivity based on the tasks or the case of disasters. Then the transceiver design of the UAV and the establishment of multi-hop ground D2D communication is studied to extend the wireless coverage of the UAV. In addition, multi-hop UAV relaying is added to realize information exchange between the disaster areas and outside through optimizing the hovering positions of UAVs. Furthermore, deploying a single UAV, however, will only support limited coverage for SARs due to the limited transmission distance.

### 3.2.2 Single UAV System Model

Figure 3.2, illustrates the system model for the proposed UAV-assisted post-disaster communication, where the UAV provides immediate coverage to the disaster area while simultaneously executing wireless power transfer to user devices. The UAV coverage diameter is circular, and the user devices are distributed according to a PCP with a spatial density of $\lambda_{UDs}$. User devices within the UAV coverage range receive wireless services through the LoS link, and selected user devices are located at the edge of the UAV coverage range as CHs to extend the network links between the inside and the outside of the UAV coverage area. The CHs will be the primary distribution nodes for the CMs.In addition, the CMs must have sufficient residual energy to establish D2D communication with the CH.

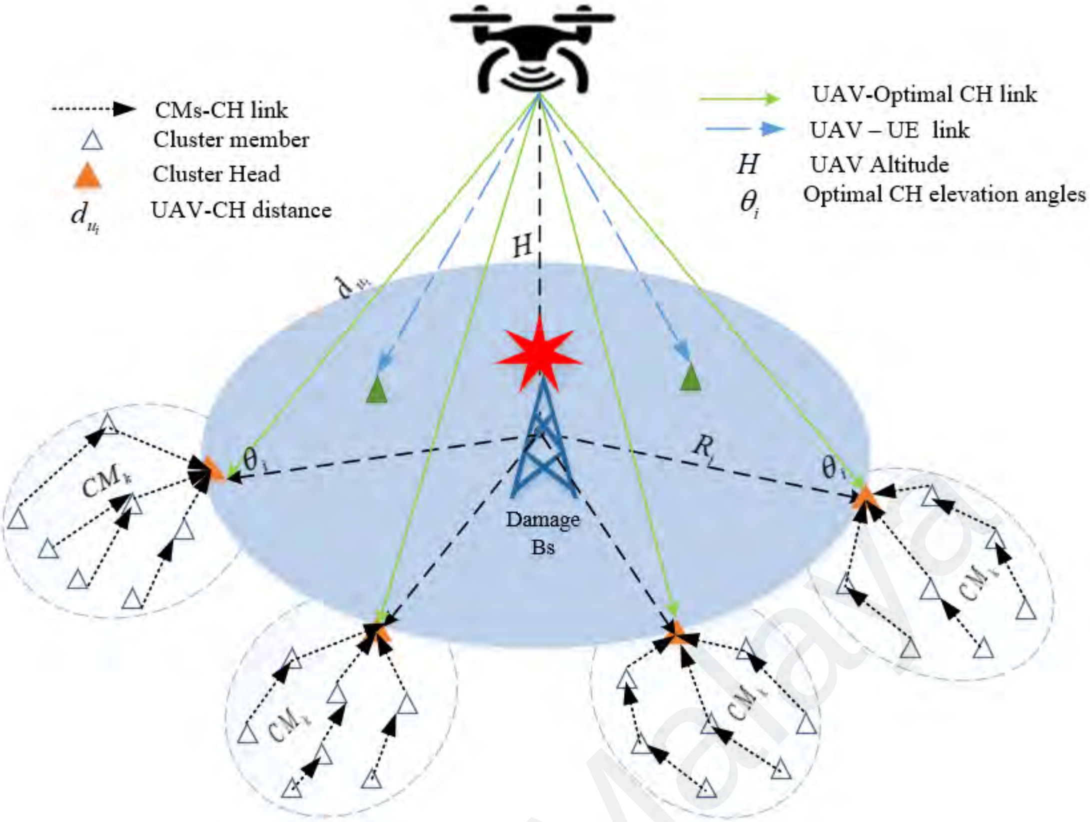

Figure 3.2: The Architecture of the Proposed Single UAV System Model.

### 3.2.2.1 Time Switching Protocol

The time switching protocol has been implemented at the CH to forward the information and power to CMs. The time switching protocol is used to divide messages into packets before sending them. In time switching, the receiver switches between information decoding and wireless EH modes. For a block-based transmission, in time switching protocol, energy is harvested for some percentage of total transmission time $(\alpha T)$, and the remaining time $(1-\alpha)T$ is used for information processing i.e., the energy harvesting receiver turns on for $(\alpha T)$ time and information processing receiver works for $(1-\alpha)T$ time. Therefore a block of information is transmitted from the source to destination nodes via channel propagation. The Time Slot Ratio (TSR) of the transmission is denoted in the transmit nodes as $e_1$, $e_2$ at the channel propagation and $e_3$ at the receiver node, where $e_1 + e_2 + e_3 = 1$. Therefore, the duration of the first time slot $e_1 T$ consists of the wireless coverage energy signals handled in source nodes. Furthermore, the wireless coverage signals are sent to the CHs in the second time slot, $e_2T$, while the CHs send it to the destination CMs in the third time slot, $e_3T$. The total bandwidth is divided into $N$ orthogonal subcarriers, $n \in \{1, 2, \ldots, N\}$, and the network has two wireless coverage links, which are the UAV to CHs and the CH to CMs when the user devices are outside of the UAV coverage area. The nonlinearity in the energy harvesting circuit during the first time slot at the CHs is denoted as follows (Ali et al., 2018);(Lu et al., 2014).

$$E = e_1 T \zeta \sum_{n=1}^{N} p_n^{S,1} \left| h_n^{S-CH} \right|^2 , \tag{3.16}$$

where $p_n^{S,1}$ represents the transmission power from the UAV source in the first time slot over the $n^{th}$ subcarrier for energy transfer, while $\zeta$ denotes the EH efficiency that accounts for the loss in the energy transducer. In contrast, $h_n^{S-CH}$ denotes the channel gain between the UAV source node and the CHs. Therefore, the source node should allocate all available power over the subcarrier with an entire channel gain to optimize the energy harvest at the CH node. The UAV directional antenna is vertically sectorized for 3-D air-ground channel patterns which act to improve energy harvesting(Lyu & Zhang, 2019). Hence, maximizing the channel gain between the UAV and optimal CHs is obtained as the following equation.

$$E = e_1 G, \ \text{ where } \ G = T \zeta P_s \max_n \mid h_n^{S-CH} \mid^2 . \tag{3.17}$$

Here, $P_s$ denotes the maximum UAV transmit power for multiple antennas to enable diversity gains even and increase energy harvesting. Where, $P_s \geq \sum_{n=1}^{N} p_n^{S,1}$ through the UAV source node to the CH node over the $n^{th}$ subcarrier in the first time slot. Therefore, the maximum data rate that can be achieved directly from the CH to CMs is obtained as follows (G. Huang et al., 2015).

$$R = \min\left\{e_2 \sum_{n=1}^{N} \log_2(1 + p_n^{S,2}\gamma_n^{S-CH}), \quad e_3 \sum_{n=1}^{N} \log_2(1 + p_n^{CH}\gamma_n^{CH-CM})\right\}, \tag{3.18}$$

where $p_n^{S,2}$ and $p_n^{CH}$ denote the UAV transmit power in the second time slot and the CHs in the third time slot over the $n^{th}$ subcarrier for information transmission, respectively. Furthermore, $\gamma_n^{S-CH} = \left|h_n^{S-CH}\right|^2 / \sigma_{CH}^2$ and $\gamma_n^{CH-CM} = \left|h_n^{CH-CM}\right|^2 / \sigma_{CM}^2$, where $\sigma_{CH}^2$ and $\sigma_{CM}^2$ denote noise power over each subcarrier at the CH and CMs, respectively. According to (Nasir et al., 2013), the energy obtained in the first time slot should be greater than or equal to the energy consumed to transmit information to the CHs, which is denoted as follows.

$$E \geq e_3 T \sum_{n=1}^{N} p_n^{CH}. \tag{3.19}$$

Note that there are likely many user devices within the UAV coverage range that are possible candidates to perform as CHs. An essential step is then to select the CHs before information and energy can be transferred. The selected CHs are on the edge of the coverage area, and to set up a direct link between CHs-CMs, the signal strength of the SNR value must be higher than a predefined threshold parameter. The UAV coverage is considered to range with the radius of $R_{ha}$ centred at the UAV coverage source, as shown in Figure 3.2. $R_{ha}$ is denoted as follows.

$$R_{ha} = \left(\frac{\zeta p_{UAV}}{EH_{thr}}\right)^{1/\alpha}, \tag{3.20}$$

where $\zeta \in (0,1)$, $p_{UAV}$ is the UAV transmitted power, $EH_{thr}$ is the threshold of the energy harvesting, and $\alpha$ is the path-loss exponent. The Doppler Effect resulting from the relatively higher velocity of UAVs is not taken into consideration in this study.

#### 3.2.2.2 User Device Clustering Based Optimal Cluster Head Selection

Clustering is among the techniques used to provide efficient and stable routes for data dissemination. Clustering establishes links between a group of user devices through direct communication to improve the performance of the network for sharing data and radio resources (Mukherjee & De, 2021). However, rapid changes in network topology, such as in disaster situations, create frequent cluster reorganization, which can seriously impact the network route stability. The clustering of nodes and nominations of CHs were investigated to reach cluster stability in a wireless network (A. A. Khan et al., 2018). Here, the CH is a node that is responsible for collecting data from the CMs and forwarding the data to UAVs. However, managing this clustering network is challenging due to the signalling traffic load on each CH (M. F. Khan et al., 2018).

#### 3.2.2.3 Proposed Optimal Cluster Head Selection

Cluster head selection is crucial and can be critical in order to establish efficient communication links with the network and minimize the outage probability. User devices distributed at the optimal location, i.e., nearer the UAV path, could be selected as the CH. In this study, the chosen CHs, i.e., the optimal cluster Heads selection, are those with more residual energy and more neighbourhood nodes based on the metrics of intra-user device distance, relative speed, and residual energy (Qi et al., 2018). Motivation to use the considered CH selection for purpose of improving computational efficiency and obtaining the diverse optimal solution based on AtG channel and other parameters as the heuristic algorithms optimize CHs location. Therefore, this technique considers a population of candidate solutions which is evolved towards an optimal solution or near-optimal solution. Each candidate solution has a set of chromosomes that are evaluated through an iterative process to obtain the best solution near-optimal.

In addition, the load on the CH should be reduced to ensure effective and stable routes, finally lengthening the lifetime of post-disaster communication (D. Zhang et al., 2018). Therefore, an optimal cluster Head technique to improve the network lifetime is introduced. The CH is chosen based on average residual energy, transmitter-to-receiver link quality, and the distance between the CH and the UAV. Therefore, an optimal cluster head selection approach is utilized to minimize the outage probability during and after disaster events. Then the air-to-ground (AtG) channel model is used for the optimal cluster head to be associated with SAR devices in UAV-assisted communication during disaster recovery. Furthermore, determining the optimal location of the CH is crucial because it reduces the transmission power and effectively increases the coverage probability, and decreases the outage probability.

#### 3.2.2.4 Power Transfer for the Clustering Network

In this section, the mechanism of control signals transmitted by the UAV to CHs and the CH to CMs is presented. The D2D communication is implemented between the CH and CMs to extend the UAV coverage range and improve energy efficiency. The performance of the energy harvesting is evaluated on the clustering within D2D communication links. The UAV transmits the main beam to the optimal cluster Head selection nodes to maximize throughput in the optimal user nodes. CHs can harvest the received energy and forward it to CMs within the cluster through D2D communication. The optimal cluster Head selection will provide more efficient and stable route solutions to the network during post-disaster situations, which is crucial for the search and rescue teams to save lives.

#### 3.2.2.5 Performance Analysis of D2D in Clustering

The time needed to transmit energy with a data packet content of size $S_T$ bits on the $i^{th}$ optimal $CH_i$ and the $j^{th}$ nonoptimal $CH_j$ to the $k^{th}$ cluster member $CM_k$ links that have an achievable rate of $R_{i,k}$ and $R_{j,k}$ bps are given by $S_T/R_{i,k}$ and $S_T/R_{j,k}$, respectively.

The $CM_k$ battery power will be drained by receiving data from nodes $CH_i$ and $CH_j$ by $P_{Rx,i,k}$ and $P_{Rx,j,k}$; then, the $CM_k$ consumes energy to receive the data from $CH_i$ and $CH_j$, which are given by $S_T P_{Rx,i,k}/R_{i,k}$ and $S_T P_{Rx,j,k}/R_{j,k}$, respectively. Similarly, denoting $P_{Tx,i,k}$ and $P_{Tx,j,k}$ as the power drained by the battery of $CH_i$ and $CH_j$ to transmit the data to $CM_k$, respectively, then the consumption of energy by $CH_i$ and $CH_j$ to transmit the content to $CM_k$ is given by $S_T P_{Tx,i,k}/R_{i,k}$ and $S_T P_{Tx,j,k}/R_{j,k}$, respectively (Ali et al., 2018); (Yaacoub & Kubbar, 2012).

It should be noted that $P_{Tx}$ derivations for both $CH_i$ and $CH_j$ are expressed as follows.

$$\mathrm{P_{Tx}} = \begin{cases} P_{Tx_{i,k}} = P_{Tx_{ref,i,k}} + P_{t,i,k} \\ \\ P_{Tx_{j,k}} = P_{Tx_{ref,j,k}} + P_{t,j,k}, \end{cases} \tag{3.21}$$

where $P_{Txref,i,k}$ and $P_{Txref,j,k}$ correspond to the power consumed by the source circuitry nodes of the $i^{th}$ optimal $CH_i$ and the $j^{th}$ nonoptimal $CH_j$ through transmission on the communication link with the $k^{th}$ CM, i.e., $CM_k$, nodes. On the other hand, $P_{t,i,k}$ and $P_{t,j,k}$ correspond to the transmitted power over the air interface on $(CH_i, CH_j)$ to $CM_k$ links.

#### 3.2.2.6 Outage Probability

Clustering techniques and D2D communication have received a great deal of attention because of their ability to enhance network coverage and improve connectivity during disaster scenarios. In this section, the outage probability for user devices is investigated. First, the outage probability for the first-hop link between the UAV and CHs is determined. Second, the outage probability for the second hop between the CH and CMs is determined. The distance between the UAV and CHs is $d_{u,i,j}$, while the distance between CH and an intended CM is $d_{i,j,k}$, where $i, j \in CHs$ and $k \in CMs$.

According to (Ali et al., 2018), the outage probability of D2D communication between

CH and CMs can be expressed as follows.

$$P_{out} = 1 - \exp\left\{-\xi(\theta_d, \alpha)\left(\rho_{UAV}\lambda_{UAV}d_1^2 + \frac{p_{CH}\lambda_{CH}}{N}d_2^2\right)\right\}, \tag{3.22}$$

where $d_1 = d_{u,i,j}$, $d_2 = d_{i,j,k}$, $\alpha$ is the path-loss exponent, and $\theta_d$ is the SINR threshold for the D2D-assisted link.

In addition, $\xi(\theta_d, \alpha)$ is set as follows:

$$\xi(\theta_d, \alpha) = \frac{2\pi^2}{\sin\left(\frac{2\pi}{\alpha}\right)\theta_d^2} \tag{3.23}$$

In the second hop link between CH and CMs in D2D communication, the network outage occurs when one of the two links, i.e., UAV to CHs and CH to CMs, is not successful in achieving the SINR target of $SINR_{\theta_d}$. Therefore, the UAV is located at $(x_u, y_u, z_u)$, the nonoptimal $CH_i$ is located at $(x_j^o, y_j^o)$, while the $k^{th}$ CM is located at $(x_k, y_k)$ out of UAV coverage. Subsequently, the distance in the first hop from the UAV and the $j^{th}$ nonoptimal cluster Head is denoted as $d_{u,j}^2 = (x_u - x_j)^2 + (y_u - y_j)^2 + (z_u - 0)^2$. In the same context, the distance in the next hop from the $j^{th}$ nonoptimal cluster Head and the $k^{th}$ CM is denoted as $d_{j,k}^2 = (x_j - x_k)^2 + (y_j - y_k)^2$. Therefore, the outage probability in (3.22) can be rewritten as follows.

$$P_{out} = 1 - \exp\left\{-\rho_{UAV}\lambda_{UAV}\xi(\theta_d, \alpha)f(x_{u,j,k}, y_{u,j,k})\right\}, \tag{3.24}$$

where

$$f(x_{u,j,k}, y_{u,j,k}) = \|(x_u - x_j)\|^2 + \|(y_u - y_j)\|^2 + \|(z_u - 0)\|^2 + \Lambda\|(x_j - x_k)\|^2 + \Lambda\|(y_j - y_k)\|^2 \tag{3.25}$$

and $\Lambda$ is given as

$$\Lambda = \frac{p_{CH}\lambda_{CH}}{N\rho_{UAV}\lambda_{UAV}}, \tag{3.26}$$

where $p_{CH}$ is the power transmitted by the CHs, $\lambda_{CH}$ is the density of CHs, $\rho_{UAV}$ is the UAV load, and $\lambda_{UAV}$ is the density of UAVs. The partial derivative was taken of $f(x_{u,j,k}, y_{u,j,k})$ in (3.25) with respect to $x_j$ and $y_j$, and by equating them to zero the optimal locations of CHs with minimum energy consumption and outage probability are obtained as follows:

$$x_j^o = \frac{\Lambda x_k + x_u}{1+\Lambda}, \; y_j^o = \frac{\Lambda y_k + y_u}{1+\Lambda}. \tag{3.27}$$

Due to the communication through the optimal cluster Head, the energy consumption and outage probability will be minimized. As a result, the optimal cluster head (CH) nodes are distributed between the UAV nodes and cluster member (CM) nodes at the edge of the UAV coverage area, as shown in Figure 3.1, the CHs to move to their optimal locations and enable communication with the UAV and the $k^{th}$ user device out of their coverage area.

$$d_{j,i}^2 = \left(x_j - \frac{x_u + \Lambda x_k}{1+\Lambda}\right)^2 + \left(y_j - \frac{y_u + \Lambda y_k}{1+\Lambda}\right)^2. \tag{3.28}$$

Similarly, the distance between the optimal cluster Head and the CMs $(x_k, y_k)$ is determined as follows.

$$d_{i,k}^2 = \left(\frac{x_u + \Lambda x_k}{1+\Lambda} - x_k\right)^2 + \left(\frac{y_u + \Lambda y_k}{1+\Lambda} - y_k\right)^2. \tag{3.29}$$

In addition, the distance between the UAV and the optimal cluster Heads selection is determined as follows.

$$d_{u,i}^2 = \left(x_u - \frac{x_u + \Lambda x_k}{1+\Lambda}\right)^2 + \left(y_u - \frac{y_u + \Lambda y_k}{1+\Lambda}\right)^2 + (z_u - 0)^2. \tag{3.30}$$

The CHs are located at the intermediate level between the UAV and CMs. Hence, the optimal location of CHs has been obtained as follows:

$$(x_j^o, y_j^o) = \left( \frac{x_u + \Lambda x_k}{1 + \Lambda}, \frac{y_u + \Lambda y_k}{1 + \Lambda} \right). \tag{3.31}$$

Therefore, the optimal elevation angle of the optimal cluster Head from (3.31) can be achieved as follows:

$$\theta_i^0 = \arctan \left( \frac{\Lambda\, y_k + y_u}{\Lambda\, x_k + x_u} \right). \tag{3.32}$$

Furthermore, the rotation of the CH function among members is selected as the optimal cluster head based on the efficient distribution of the selected CHs in the network to balance the energy consumption and minimize the outage probability. Subsequently, the aim of finding an optimal solution such that the feasible solution will mitigate $P_{out}$ can be formulated as follows:

$$(x_j^o, y_j^o) = \text{argmin}_{\{x_j, y_j\}} P_{out} = \text{argmin}_{\{x_j, y_j\}} f(x_{u,j,k}, y_{u,j,k}).$$

An optimal solution is a feasible solution where the objective function reaches its maximum (or minimum) value. Based on the optimal location of CHs, the outage probability of the link between the UAV and optimal cluster Heads and the optimal cluster Head and CMs in (3.22) can be rewritten as follows.

$$P_{out} = 1 - \mathrm{e}^{\left\{ -\xi(\theta_d, \alpha) \left( \rho_{\text{UAV}} \lambda_{UAV} d_{u,i}^2 + \frac{p_{CH} \lambda_{CH}}{N} d_{i,k}^2 \right) \right\}}, \tag{3.33}$$

where $d_{u,i}^2$ is the distance from the UAV to the optimal cluster Head, while $d_{i,k}^2$ is the distance from the optimal cluster Head to the $k^{th}$ CM.

#### 3.2.2.7 Outage Probability of D2D within Clustering

To ensure the decoding correctness in the network receivers, the SNR received by CMs should exceed the threshold value $\gamma_{min}$ (Peng et al., 2013). Therefore, the $k^{th}$ CM establishes link communication with the optimal cluster Head through D2D pair communication. According to the above definitions, when the $i^{th}$ optimal cluster Head transmits wireless signals to CMs, the desired received signals by the $k^{th}$ CM can be expressed as $y_{i,k} = d_{i,k}^{-\alpha}\sqrt{h_{i,k}}\ p_{CH} + \sigma^2$, where $y_{i,k}$ is the received wireless signal from the optimal cluster Head , and $p_{CH}$ is the transmit power for the optimal cluster Head . The instantaneous SINR received by the $k^{th}$ CM is $\gamma_{i,k} = \frac{p_{CH}\ h_{i,k}\ d_{i,k}^{-\alpha}}{\sigma^2 B_0}$, where $h_{i,k}$ denotes the channel gain between the optimal cluster Head and the $k^{th}$ CMs, and $B_0$ is the total bandwidth. Consequently, the outage probability of the link between the optimal cluster Head and the $k^{th}$ CM is expressed as follows.

$$\begin{aligned} P_{out} &= \mathbb{P}\left(\gamma_k < \gamma_{min}\right) = \mathbb{P}\left(h_{i,k} < \frac{\sigma^2 B_0 \gamma_{min}}{p_{CH}\ d_{i,k}^{-\alpha}}\right) = \int_0^{\left(-\frac{\sigma^2 B_0 \gamma_{min}}{p_{CH}\ d_{i,k}^{-\alpha}}\right)} \exp(-x)\ dx \\ &= 1 - \exp\left(-\frac{\sigma^2 B_0 \gamma_{min}}{p_{CH}\ d_{i,k}^{-\alpha}}\right). \end{aligned} \tag{3.34}$$

The outage probability of D2D communication within a cluster will be achieved through the link from the optimal cluster Head to CMs in full-duplex communication mode. Whereas, the maximum data rate that can be achieved with a specified outage probability is denoted as the outage capacity. The outage capacity of D2D communication in the cluster is represented as follows.

$$C_{out,i,k} = (1 - p_{out,i,k}) B_0 \log_2(1 + \gamma_{min}) = e^{\frac{-\sigma^2 B_0 \gamma_{\min}}{p_{CH} d_{i,k}^{-\alpha}}}\ B_0 \log_2(1 + \gamma_{\min}), \tag{3.35}$$

where the outage capacity $C_{out,i,k}$ for D2D communication is based on the bandwidth $B_0$ and distance from the optimal cluster Head to the $k^{th}$ CM. Then, the $k^{th}$ CM receives the multicast signals from the $i^{th}$ optimal cluster Head in the same time slot. The outage capacity of the multicast channel depends on the transmission rate for every $k^{th}$ CM. Therefore,

$$C_{out} = \min\{Cout_1, Cout_2, ...., Cout_k\} \tag{3.36}$$

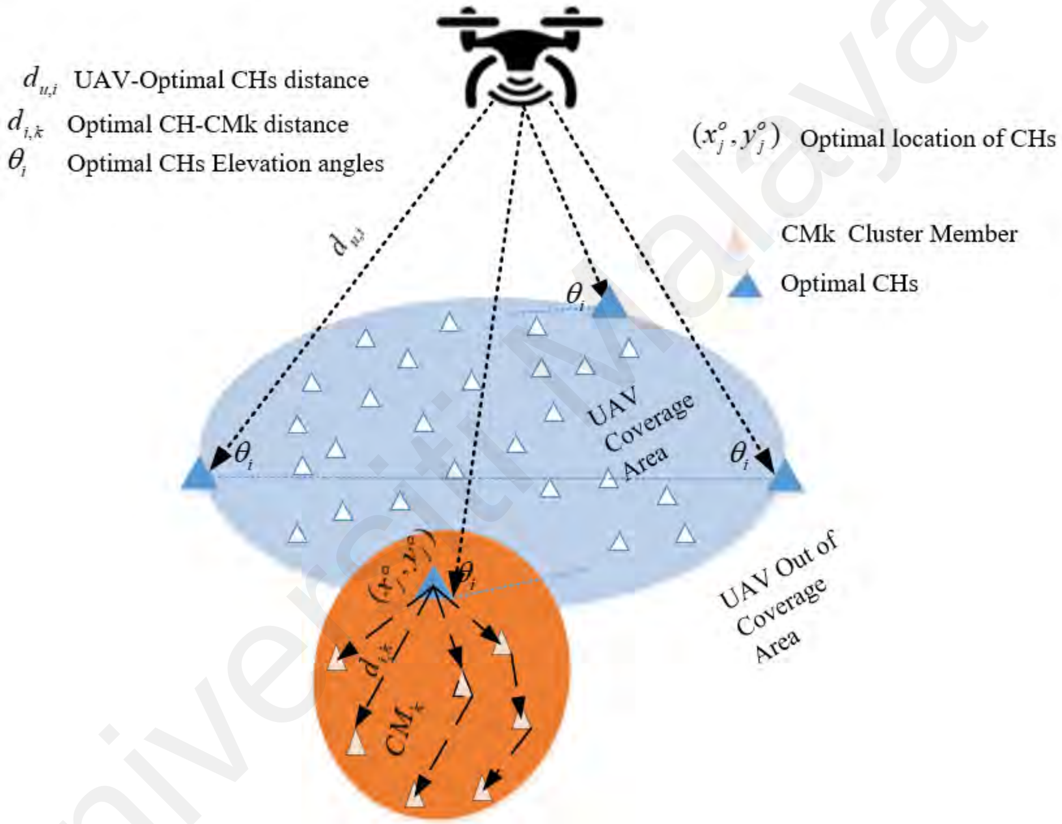

**Figure 3.3: Distribution of UAVs, Optimal Cluster Heads Selection and CMs in the Post-Disaster Scenario.**

According to Figure 3.3, user devices are distributed inside and outside of the UAV coverage area. The user devices within the radio coverage range acquire wireless services from the UAV, while those outsides of the UAV coverage range obtain wireless services from the $i^{th}$ optimal cluster Head. In this study, the UAV is deployed in the disaster area at an altitude of $H_n$ and a static location $(x_u, y_u, z_u)$. The CHs extend the coverage area to provide services to more CMs. The optimal elevation angle of the user devices in the disaster area is denoted as $\theta_i$ for the $i^{th}$ CH. The downlink Air-to-Ground (AtG) channel can be either an LoS link or an NLoS link. Therefore, the probability of LoS and NLoS on the optimal cluster Head served by the UAV are represented in (3.9) (W. Shi et al., 2019). The AtG channel model is exploited for the optimal cluster Heads selection and their associated CMs in UAV-assisted communication during disaster recovery. The channel power gain from the UAV to the optimal cluster Heads selection that are located at $(x_i, y_i)$ under the LoS link is given in (3.11) (Nguyen et al., 2018).

The network link quality, communication performance and path loss are highly affected by LoS and NLoS probabilities and other environmental parameters. Furthermore, the path loss between the UAV and optimal cluster Head selection nodes is obtained in (3.12).

#### 3.2.2.8 Outage Probability of Multi-hop Network

In this study, the outage probabilities have been minimized in both downlink and uplink. Here, some SARs are likely to be located out of coverage of the UAV communication range due to the limited power available on the UAVs, thus they are unable to communicate with the UAVs. These SARs can utilize $SAR_h$s for communication with UAVs as well as multi-hop S2S links to communicate with peer cluster nodes. In the proposed system model, $M$ antennas for each UAV to cover the disaster zone were assumed. Each UAV antenna focuses the beam angle to one $SAR_h$ on the edge of the coverage area to increase the throughput and minimize the outage probability for reliable connectivity in disaster scenarios.

The outage probability is primarily affected by the number of hops and their energy consumption rate. The proposed system model considers equally the efficiency of the $SAR_h$ to establish the links between the $SAR_m$ inside the cluster and to transfer the wireless signals to other $SAR_h$s through the gateway. The successful $S2S_{Tx}$ on downlink and uplink for each hop is denoted as $\Psi_{\rm UL}$ and $\Psi_{\rm DL}$, respectively, and the average transmit power assigned to each S2S nodes is $\hat{P}$. According to X. Liu et al. (2018), the average probability of S2S successful transmission in the uplink and downlink is denoted as follows.

$$\bar{p}_{\rm UL}(\gamma_{UL} > \varepsilon) = \exp\left(-\lambda_S \pi \bar{r}^2_{\rm UL}\ B(\varepsilon, \alpha)\right) = \Psi_{\rm UL}, \tag{3.37}$$

$$\bar{\mathcal{P}}_{\rm DL}\left(\gamma_{DL} > \varepsilon\right) = \quad \exp\left\{-\left[\lambda_S + \lambda_{\rm UAV}\left(\frac{P_{\rm sum}}{\hat{P}}\right)^{\frac{2}{\alpha}}\right] B\left(\varepsilon, \alpha\right)\pi \bar{r}^2_{\rm DL}\right\} = \Psi_{\rm DL}, \tag{3.38}$$

where $B(\varepsilon, \alpha) = \varepsilon^{\frac{2}{\alpha}} \int_{(1/\varepsilon)^{\frac{2}{\alpha}}}^{\infty} \frac{1}{1+u^{\frac{2}{\alpha}}} du.$

Also, $\bar{r}_{\rm UL}$ and $\bar{r}_{\rm DL}$ are the average distances between the $SAR_h$ and $SAR_m$ based on $\Psi_{\rm UL}$ and $\Psi_{\rm DL}$. Then, the formula can be rewritten as $\bar{r}_{\rm UL}$ and $\bar{r}_{\rm DL}$ as follows.

$$\bar{r}_{\rm UL} = \sqrt{\frac{\ln(1/\Psi_{\rm UL})}{\lambda_S \pi B(\varepsilon, \alpha)}},\ and\ \ \bar{r}_{\rm DL} = \sqrt{\frac{\ln(1/\Psi_{\rm DL)}}{(\lambda_S + \lambda_{{\rm UAV}\left(\frac{P_{\rm sum}}{\hat{P}}\right)}\pi \bar{r}^2_{\rm DL}\ B(\varepsilon, \alpha)]}}\ , \tag{3.39}$$

where $\lambda_S$ is S2S density, $\lambda_{\rm UAV}$ is the density of UAVs which can be calculated as $\frac{1}{(\pi H_k \tan\theta)^2}$, $P_{\rm sum}$ is the transmit power for each UAV, $\hat{P}$ is the average power transmitted for each S2S nodes, and $\varepsilon$ is the specific threshold for the received SINR. According to (3.38) and (3.39), the average number of hops can be obtained as follows.

$$J_{\rm UL} = \left\lceil \frac{\mathcal{R}}{\bar{r}_{\rm UL}} \right\rceil = \left\lceil \frac{\mathcal{R}\sqrt{\lambda_S \pi B\left(\varepsilon, \alpha\right)}}{\sqrt{\ln\left(1/\Psi_{\rm UL}\right)}} \right\rceil,\ and\ J_{\rm DL} = \left\lceil \frac{\mathcal{R}}{\bar{r}_{\rm DL}} \right\rceil = \left\lceil \frac{\mathcal{R}\sqrt{\left[\lambda_S + \lambda_{\rm UAV}\left(\frac{P_{\rm sum}}{\hat{P}}\right)^{\frac{2}{\alpha}}\right] B\left(\varepsilon, \alpha\right)}}{\sqrt{\ln\left(1/\Psi_{\rm DL}\right)}} \right\rceil, \tag{3.40}$$

where $\mathcal{R}$ refers to the distance between the multi-hop S2S source and destination, and $\lceil . \rceil$ is the ceiling function. Based on the average outage probability of the $k^{th}$ S2S link in the $l^{th}$ cluster in (3.37) and (3.38), the uplink and downlink average outage probability of multi-hop S2S in the $l^{th}$ cluster can be expressed as a function of success probability for each hop as follows.

$$\begin{aligned}\mathcal{P}^{\mathrm{UL}}_{\mathrm{S2}S,\mathrm{out}} =& 1 - \prod_{m=1}^{J_{\mathrm{UL}}} \left[1 - \hat{\mathcal{E}}^{[m]}_{\mathrm{UL}}\right] = 1 - \prod_{m=1}^{J_{\mathrm{UL}}} \int_{0}^{\bar{r}_{\mathrm{UL}}} \mathcal{P}\left(\gamma_m > \varepsilon_l\right) f_r\left(\hat{r}\right) d\hat{r} \\ =& 1 - \prod_{m=1}^{J_{\mathrm{UL}}} \Psi_{\mathrm{UL}} \left(1 - \exp\left(-\frac{\left(N^{[l]} - 1\right) \ln(1/\Psi_{\mathrm{UL}})}{B_l\left(\varepsilon_l, \alpha\right)}\right)\right),\end{aligned} \tag{3.41}$$

and

$$\begin{aligned}\mathcal{P}^{\mathrm{DL}}_{\mathrm{S2}S,\mathrm{out}} =& 1 - \prod_{m=1}^{J_{\mathrm{DL}}} \left[1 - \hat{\mathcal{E}}^{[m]}_{\mathrm{DL}}\right] = 1 - \prod_{m=1}^{J_{\mathrm{DL}}} \int_{0}^{\bar{r}_{\mathrm{DL}}} \mathcal{P}\left(\gamma_m > \varepsilon_l\right) f_r\left(\hat{r}\right) d\hat{r} \\ =& 1 - \prod_{m=1}^{J_{\mathrm{DL}}} \Psi_{\mathrm{DL}} \left(1 - \exp\left(-\frac{\left(N^{[l]} - 1\right) \ln\left(1/\Psi_{\mathrm{DL}}\right)}{\left[1 + \frac{\lambda_{\mathrm{UAV}}}{\lambda_S^{[l]}} \left(\frac{P_{\mathrm{sum}}}{\hat{P}[m]}\right)^{\frac{2}{\alpha}}\right] B_l\left(\varepsilon_l, \alpha\right)}\right)\right),\end{aligned} \tag{3.42}$$

where $m$ is a set of hops in DL and UL, and $\hat{\mathcal{E}}^{[m]}_{\mathrm{UL}}$ and $\hat{\mathcal{E}}^{[m]}_{\mathrm{DL}}$ are the outage probability expectations of the $k^{th}$ S2S link whose average distances are $r_{\bar{UL}}$ and $r_{\bar{DL}}$, respectively.

#### 3.2.2.9 Energy Consumption for Optimal Cluster Heads selection

The communication links occur from the optimal $CH_i$ to $CM_k$ through a number of clusters $C_l$. Subsequently, the total energy consumed $E_{C_l}$ is expressed as follows:

$$E_{C_l} = S_T \sum_{\substack{i \neq k, \\ i=1,2,\ldots,|C_l|, \\ k \in C_l}} \left(\frac{\Gamma_l P_{Tx_i,k} + P_{Rx,i,k}}{R_{i,k}} + \frac{P_{Rx,i}}{R_i}\right). \tag{3.43}$$

The consumed energy is used by the $i^{th}$ CH, i.e., the optimal $CH_i$ to receive data from the UAV in the first-term links and in D2D communication in the second-term links. The distinguishing variable $\Gamma_l$ is applied from unicasting to multicasting. Moreover, each user device has specific data to transmit in the unicasting uplink. The CMs have residual energy to establish the link with CH, which is able to deliver collected signals to the UAV in the uplink and improve the energy transfer efficiency with shorter-distance connectivity. The same data are forwarded to CMs in the downlink for each coalition, and consequently, unicasting or multicasting on long-range and short-range connections is adopted. In the case of D2D communication from the $CH_i$ to $CM_k$ with short-range unicasting, $\Gamma_l = 1$. Meanwhile, in the case of short-range multicasting, ($\Gamma_l = 1/|C_l| - 1$) compensates for the effect of transmission that occurs only once. In the single cluster, the harvested energy calculated in (3.16) must not be lower than the energy consumption in (3.19). Therefore, those equations can be rewritten as follows.

$$E \geq E_{C_l} \Rightarrow e_1 T \zeta \sum_{n=1}^{N} p_n^{S,1} \mid h_n^{S-CH} \mid^2 \geq E_{C_l} \sum_{n=1}^{N} p_n^{S,1} \mid h_n^{S-CH} \mid^2 \geq \frac{E_{C_l}}{e_1 T \zeta} \tag{3.44}$$

Assuming that each subcarrier has equal power, i.e., $p_1^{S,1} = p_2^{S,1} = p_N^{S,1}$, then the following formula is obtained.

$$p^{S,1} \geq \frac{E_{C_l}}{e_1 T \zeta \sum_{n=1}^{N} \mid h_n^{S-CH} \mid^2}, \tag{3.45}$$

where $p^{S,1}$ is a single subcarrier power as a function of the user devices. Hence, the transmission energy harvested at the CHs is greater than or equal to the energy consumed for the wireless transfer signal between the CH and CMs. Therefore, in the multiple cluster case, the CHs transfer energy to the next cluster through the cluster gateway in a serial multihop manner.

#### 3.2.2.10 Energy Harvesting

The cause of unreliable communication networks during catastrophic circumstances originates from the failure of the network's GBS power supply. Therefore, replacing the GBS with a UAV is a viable option, but the primary drawback is that UAVs run on battery power that can run out very quickly. The same situation occurs with user devices. Consequently, prolonging battery life is critical for post-disaster communications. At the same time, tethered UAV deployment is one potential solution for the power supply problem in disaster scenarios (S. Alsamhi et al., 2019);(Kishk et al., 2020). Furthermore, problems could occur with its ground base station power source. Therefore, EH techniques have been investigated for post-disaster communications. Here, EH can eliminate the battery power barriers of UAVs and user devices and provide a sustainable solution to extend the network lifetime. In EH, energy is harvested from radio signals that convert the wireless signals received into a usable energy source (Ali et al., 2018); (J. Zhang et al., 2020). The harvested energy can increase the flight time of the UAV and provide the extra power needed to serve its connected user devices. Note that the energy harvesting performance for the UAV link in our proposed approach is affected by altitudes, large-scale path loss, user distances, network bandwidth, and so on. The CH uses SWIPT technology to harvest energy from radio frequency wireless signalling to enhance EE (Z. Zhou et al., 2017). CHs are wirelessly powered by harvesting a portion of the received signal power from the UAV based on the time switching protocol and SWIPT. As a relay, CH assumes the role of transmitting the obtained information signal and energy harvesting to the associated user devices (S. T. Shah et al., 2016).

#### 3.2.2.11 UAV Energy Efficiency

The overall instant transmission vector of the UAVs for energy efficiency $EE^{k}_{UAVs}$ is composed of the elements from any link between the UAVs and $SAR_h$ or the $SAR_h$ to the

$SAR_m$ nodes.

$$\mathrm{EE}_{\mathrm{UAVs}}^{[k]} = \frac{R_{\mathrm{UAVs}}^{k}}{P_{tx} h_m}, \tag{3.46}$$

where $h_m$ denotes the number of hops from the UAVs to S2S communications, and $P_{tx}$ is the maximum transmission power of the UAVs in the downlink and SAR in an uplink. An important factor that spectral efficiency needs to evaluate is the spectral efficiency of the UAVs and the SINR for the SAR nodes. The spectral efficiency for the UAVs is measured in bps/Hz and is obtained as follows.

$$\mathrm{SE}_{\mathrm{UAVs}}^{[k]} = \frac{R_{\mathrm{UAVs}}^{[k]}}{B}, \tag{3.47}$$

where $R_{\mathrm{UAVs}}^{k}$ represents the data rate between the UAVs and the SAR nodes, where $B$ is the allocated bandwidth.

#### 3.2.2.12 Optimal cluster Head Power Control Analysis

In the case of CHs that change their locations to the optimal location, the user devices are affected by interference based on the new optimal location. Thus, the cluster formation will be reconfigured to minimize the outage probability. Therefore, the optimal cluster Heads are incorporated to minimize the transmit power to reduce the interference for user devices and minimize the power consumption. The power iteration is applied in optimal cluster Heads to adjust the desired received signals at CMs and eliminate the interference of D2D pair communication. Then, there are $m = 1, 2, \ldots, M$ interfering D2D pair communications. Therefore, the power to transmit vector for D2D pair communication is denoted as $[p_1, p_2, \ldots, p_m, \ldots, p_M]^T$. The SINRs for the UAV to optimal cluster Heads and the optimal cluster Head to CMs are further analyzed to minimize energy consumption and reduce interference. According to (Selim et al., 2019), the SINR at the UAV link with the $j^{th}$ nonoptimal cluster Head and the $i^{th}$ optimal cluster Head can be defined as follows:

$$\gamma_j = \frac{p_j h_j}{\sum_{m=1}^{M} p_m h_{m,j} + \sigma^2}, \quad \gamma_i = \frac{p_i h_i}{\sum_{m=1}^{M} p_m h_{m,i} + p_j h_j + \sigma^2}, \tag{3.48}$$

Finally, the SINR at the receiver of the $k^{th}$ CM as D2D pair communication is given by:

$$\gamma_k = \frac{p_k h_{k,m}}{\sum_{\substack{m=1 \\ m \neq k}}^{M} p_k h_{m,k} + (p_j + p_i) h_{m,j,i} + \sigma^2}, \quad \forall m \in \mathcal{M}, \tag{3.49}$$

## 3.3 D2D Communication Power Control Proposed

D2D communication is one of the enabling technologies for 5G networks that support proximity-based service (ProSe) for wireless network communications. The proposed power control algorithm eliminates the interference between the D2D links for reliable connectivity with minimal power consumption. The power control in D2D is modelled as a non-cooperative game. Each device is allowed to independently select and transmit its power to maximize (or minimize) user utility. The new algorithm is derived from a newly developed utility function, the cost coefficient, and the pricing function. The aim is to guide user devices to converge with the Nash equilibrium by establishing connectivity with network resources. In addition, the proposed algorithm with pricing factors is used for power consumption and reduces the overall interference of D2D communication.

### 3.3.1 The Utility Function

In wireless data networks, the user maximizes its own utility function by choosing the action from the strategy set, such as the choice of its transmit power, and transmission rate. Thus, the choice of the utility function is very important when game theory is employed to solve the problem of power control and resource allocation in wireless data networks. The utility function defines as the number of information bits that are successfully transmitted per joule of energy consumed. Where each device is allowed to independently select and transmit its power to maximize (or minimize) user utility. The proposed utility function of D2D communication is a strategy to enhance power consumption for various values of cost coefficient. The power control problem is formulated as a utility function modelled by a non-cooperative game in the downlink and the uplink communications. Thus, the Nash equilibrium has become a vital technique to prove a unique solution in the non-cooperative game for power control. The non-cooperative power has been chosen based on the equilibrium points' selection mechanism. Hence, the iterative utility functions are able to generate the optimal splitting ratio of the maximized user utility within a feasible set of user devices. There are various proposals regarding the design of the utility function of user devices. However, the game theory constraint in developing user device utility based on physical output and unsatisfied game outcome (Yousef Ali, 2017). Therefore, the user devices that include cellular user and D2D communications with $N$ players and transmission power as the strategy for each player (user devices) are considered. The user devices utility function then allocates each conceivable outcome to a particular player metric number. The higher or lower attribute of a number shows whether the outcome is preferable. The non-cooperative game formulated describes the algorithm for power control to develop a new user device utility iteration function to improve the game outcome. Consequently, the derived power control from the user devices utility function will prove the existence and convergence of Nash equilibrium in the algorithm (Khodmi et al., 2019). This is an act of satisfaction with the convergence to occur as soon as possible and develop the new algorithm for power control. Besides, the iterative power algorithm is used to solve the Nash equilibrium convergence points. it is assume that the utility function of $i^{th}$ user device is $U_i\left(p_i * d\right), \gamma_i^d\left(p_i * d\right)$. In this context, each user's transmission power represents each player's strategy to have achieved Nash equilibrium and improve the utility function unilaterally. Consequently, $i^{th}$ user devices $\in N - player$ is satisfied as: $U_i(p_i^{*d}, \gamma_i^d(p_i^{(} * d)) \leq U_i(p_i^d, \gamma_i^d(p_1^{*d}, p_2^{*d}, \ldots\ldots, p_{i-1}^{*d}, p_{i+1}^{*d}, \ldots\ldots., p_i^{*d})) \quad \forall\ p_i^d$ The proposed algorithm aims to adjust the user device's power transmission that satisfies the SINR threshold and reduces the power of user devices. Furthermore, a utility function is presumed to be convex-shaped and assumes non-negative values to ensure the existence of a non-negative minimum. The proposed utility function of D2D communication is a strategy to enhance power consumption for various values of cost coefficient $(\alpha)$. Thus, the proposed utility function is expressed as:

$$U_i = \left( \frac{\mathit{\Gamma}_i^d}{\alpha \mathit{\Gamma}_i^d + 1} \, \gamma_i^d \right)^2 \tag{3.50}$$

where $\alpha$ is the cost coefficient, and $\Gamma_i^d$ is SINR for an $i^{th}$ user device. The general formula for SINR is:

$$\frac{\gamma_i^d}{p_i^d} = \frac{h_i^d}{I_i^d} \Rightarrow \gamma_i^d = \frac{p_i^d h_i^d}{I_i^d} \tag{3.51}$$

where $I_i^d$ is the interference of the effect to $i$ user devices. The proposed power control algorithm aims to maximize the utility function derived by all the data system devices. The D2D (Tx/Rx) will adjust its power transmitter $(p_i^d)$ to maximize its utility function $U_i(p_i^d)$ for each $i^{th}$ user device. Hence, the maximum utility function will occur at a power level of the derivative of $U_i(p_i^d)$ with respect to $p_i^d$ , i.e. $\frac{\partial U_i}{\partial p_i^d} = 0$. Thus, from the equations (3.51) and (3.52), the utility function can be rewritten as:

$$U_i = \left( \frac{\mathit{\Gamma}_i^d}{\alpha \mathit{\Gamma}_i^d + 1} - \frac{p_i^d h_i^d}{I_i^d} \right)^2 \tag{3.52}$$

Based on a suitable utility function proposed strategy, energy efficiency, and SIR balancing, the utility function has to be either quasi-concave or quasi-convex. Therefore, the utility function should be quasi-concave and an optimal point is selected to be somewhere within the practical parameter range, such as minimum and maximum power, and it depends on other users' behaviour. Hence, the partial derivatives are taken of the utility function in equation (3.52) concerning power, $p_i^d$, and equated to zero, the power control iteration can be obtained to achieve the minimum energy consumption as follows:

$$\frac{\partial U_i}{\partial p_i^d} = \frac{-2\left(\frac{\Gamma_i^d}{a\Gamma_i^d+1} - \frac{p_i^d h_i^d}{I_i^d}\right)}{I_i^d} \tag{3.53}$$

Hence, the necessary condition for $i^{th}$ user devices to maximize their utility to satisfy the SINR target is achieved. The optimal (minimum) value of the D2D utility function occurs when the user device's SINR is equal to the target threshold value. The applicable method to guarantee the QoS of $D2D_s$ is balancing the power control method in which all $D2D_s$ achieve the same target SINR. The aim is to prioritize the QoS of the $D2D_s$ by ensuring that all $D2D_s$ meet the SINR target. However, to attain a higher SNR that is more significant in the target value, the D2Ds require little power in their transmission. Hence, it preserves their battery energy and network energy lifetime while minimizing cross-tier interference. This achieves the reduction in power consumption and the required SINR of D2D communication while mitigating the total interference in the D2D network through the power control game, for its payoff utility function. Thus, the transmit power of $i^{th}$ user device at $(k+1)^{th}$ can be obtained as follows.

$$p_i^{k+1} = \left(\frac{\Gamma_i^d}{a\Gamma_i^d + 1}\right)\frac{p_i^k}{\gamma_i^k} \tag{3.54}$$

Equation (3.55) is further simplified as $\frac{\partial U_i}{\partial p_i^d} = 0$ and $p_i^d > 0$, where the $p^{(k+1)}$ is the transmission power of the $i^{th}$ D2D link at the $k^{th}$ time instant. Subsequently, each D2D link measures its current target SINR ($\Gamma_i^k$) and tries to achieve its target in the next step.

### 3.3.2 Utility Function with a Pricing Factor

The power pricing function aims to assist D2Ds by using lower transmission power based on the non-cooperative game. When using a high-power transmission, the high cost of devices employs this strategy. Thus, the pricing can be sufficient to reduce the nearest D2D$_{s,}$ which uses low power transmission to establish the device link. In this context, each user device adjusts its power transmission to maximize its utility price in a distributed manner. As an estimate of NE, the results balance all user devices' communication power to create a balance between the power transmission of user devices. Furthermore, it is assumed that the pricing function can affect the utility function in (3.56). In that case, the derivative must be found to obtain the iteration power control algorithm with the pricing term factor. The algorithm includes the pricing function for power transmission propagation. Then, the user devices adjust the power level to maximize the net utility (utility pricing). From (3.50), the negative pricing function $-c_i p_i^d$ is added to the utility function, and it can be formulated as follows:

$$U_i = \left( \frac{\mathit{\Gamma}_i{}^d}{\alpha \mathit{\Gamma}_i{}^d + 1} - \frac{p_i^d h_i}{I_i^d} \right)^2 - c_i p_i^d \tag{3.55}$$

where $c_i$ is the pricing factor. Hence, when the partial derivatives of equation (3.61) for power are taken, the power control with pricing can be obtained to achieve strategies of optimum value. Then, the new power control iteration with the pricing factor can be rewritten as follows:

$$p_i^{k+1} = \left( \frac{(ac\mathit{\Gamma}_i^d + 2\mathit{\Gamma}_i^d \frac{\gamma_i^k}{p_i^k} + c)}{2(a\mathit{\Gamma}_i^d + 1)} \right) \left( \frac{p_i^k}{\gamma_i^k} \right)^2 \tag{3.56}$$

$$p^{k+1} = \frac{h_i^k p_i^k \mathit{\Gamma}_i^d}{\gamma_i^k (\alpha \mathit{\Gamma}_i^d + 1)} - \frac{c_i^d}{2} \tag{3.57}$$

where $p^{(k+1)}$ is the transmit power of the $i^{th}$ user devices at the $(k+1)^{th}$ time step, and $\gamma_i^k$ is the SINR of the $i^{th}$ user devices at the $k^{th}$ a time step. The utility function with pricing acts to reduce the power consumption among $D2D_s$ in the proposed power control algorithm. The following advantages are highlighted as follows:

1. Increases the lifetime of the batteries of $D2D_s$ devices.
2. Reduces overall interference that can harm cellular users and $D2D_s$ users for both in-band and out-band networks.
3. Guarantees the QoS of the D2D communication.
4. Lowers interference of $D2D_s$ ad-hoc network resulting in higher acceptance rate in the admission control of the devices.

The challenge of the user device in uplink power control is the limited power transmission capability distance due to the interference the near/far effects. In this regard, the pricing factor's role and the utility function to find the power iteration are brought forward. Furthermore, all user devices will meet their SINR constraints with a lower power level achieved by the game approach to uplink D2D communication. However, an efficient pricing technique would be required to handle the cross-tier interference. The iteration method used in the proposed power control algorithm is the fixed-point iterative method with slower convergence. On the other hand, some researchers proposed that to maximize benefits, the pricing factor should be added to the utility to benefit selfishly, and it must be semi-concave. The ideal point will be chosen in the range of experimental parameters, such as maximum and minimum power, depending on other user devices' behavior (Yu et al., 2019).

### 3.3.3 Computational Complexity Analysis for Algorithm 1

In this section, the computational complexity of the proposed algorithm1 has been determined based on the iteration loop being applied to all SAR nodes in the disaster region. The first loop has been designed to locate the optimal $SAR_h$ based on residual energy, the number of neighbourhoods and $R_{ss}$. The computational complexity for this analysis is $O(t * N_{SAR_h})$ where $t$ represents the number of iterations for each $SAR_h$ rotation nodes. In the second and third loops, $SAR_h$ will deliver the coverage signals to destinations based on SPR and edge weights. The computational complexity for that analysis is found to be $O(t * N^2_{SAR_m})$. Here, the UAV is configured to control the transmit power by sending maximum to transmit power over $n$th subcarriers to an optimal $SAR_h$ and minimum transmit power to active SARs in its coverage range to reduce interference that affects the optimal $SAR_h$ nodes. Therefore, when $N$ user devices distributed were assumed distributed in the system model that includes the $(SAR_h, SAR_m)$, then the total computational complexity for the proposed method solution is on the order of $O(t * N^2)$. For algorithm1, it is necessary to achieve the shortest path routing of multi-hop S2S communication. The design of ECS as Public Safety of disaster recovery that is demonstrated in algorithm 1 has the following steps:

- The $SAR_h$ has the ability to detect its neighbouring $SAR_m$ and establish the connectivity.
- The $SAR_m$ receives the signals and acts as a relay to send them to other $SAR_m$ until the data packet is relay closest to the destination $SAR_m$ in the range of out-of-coverage UAVs.
- This process will continue until the destination $SAR_m$ is reached for coverage services.

**Algorithm 1:** Clustering and $SAR_h$ Selection

```
$t_{max}$: Maximum number of iterations
$P_{max}$: Maximum transmit power of UAVs
$j \in SAR_m$: Out-of-coverage $SAR_m$ nodes
$\varepsilon_{th}$: SINR threshold
$N$: Number of SAR nodes
$S$: Sending nodes
$R$: Receiving nodes
$N$: Total number of user devices
Output: Optimal $SAR_h$ and deliver signals to multi-hop communication
for $t = 1 : t_{max}$ do
    A cluster is formed with its proximity devices based on PCP distribution
    for $k = 1 : N$ do
        UAVs select optimal $SAR_h$ based on residual energy, number of neighbor nodes, and Max $R_{ss}$ Based
          on (3.1)
    end
    for $i = 1 : N$ do
        Calculate $SINR_{DL}^{[i]}$ Based on (3.2)
        if $SINR_{DL}^{[i]} \geq \varepsilon_{th}$ then
            Find maximum $R_{DL}^{[i]}$ for $SAR_h$ Based on (3.14)
        end
        for $j = 1 : N$ do
            if $S(i, k) == inf$ then
                continue
            end
            if $S(i, j) > S(i, k) + S(k, j)$ then

            end
            If $R(i, j) == -1, R(i, k) = k \;\; R(i, j) = R(i, k)$
            $S(i, j) = S(i, k) + S(k, j)$
            Then $SAR_h$ will deliver the signals to the destinations based on SPR and edge weights
            Find the max $R_{ss}$ and $SINR_{\mathrm{DL}}^{[j]}$ in $SAR_m$ Based on (3.3) and (3.4) for Multi-hop communication
        end
    end
end
```

### 3.3.4 Computational Complexity Analysis for Algorithm 2

In this section, the computational complexity of the proposed algorithm is determined and compared with the results in (Selim et al., 2019). In this algorithm, the iteration loop applies to all user devices, including nonoptimal cluster Heads selection, optimal cluster Heads selection, and the $k^{th}$ CMs in lines 8 to 23. The first loop (lines 8 to 13) has been designed to locate the optimal cluster Head based on line (18). The algorithm will find the distance between the UAV and optimal cluster Head and optimal cluster Head to CMs and calculate $EH_i$ at the optimal cluster Head selection nodes based on (1). In each round, the computational complexity is dominated by matrix inversion and multiplication operations according to (3.16) and (3.31). The computational complexity for those analyses is $O(t * N_{(CH_j)})$ where $t$ represents the number of iterations for each CH rotation nodes. In the second loop (lines 14 to 18), the CM will choose its optimal cluster Head. Additionally, CMs can decide to communicate with the optimal cluster Head based on the residual energy, maximum EH and neighbour nodes. In this case, D2D pair communications and outage capacity inside the cluster are calculated based on (24) and (25). The computational complexity for those analyses is found to be $O(t * N_{CM_k})$. The third loop (lines 19 to 22) is intended to minimize the optimal cluster Head power consumption based on the following power control condition: $p_n^{CH} \leqslant \frac{e_1}{Ne_3}\zeta \sum_{n=1}^{N} p_n^{S,1} \left|h_n^{S-CH}\right|^2$. Here, the UAV is configured to control the transmit power by sending the maximum to transmit power over $n$ subcarriers to an optimal cluster Head and the minimum transmit power to UEs in its coverage range to reduce interference that affects the optimal cluster Head nodes. In addition, the optimal cluster Head applies control strategies to forward transmit power with its associated CMs through D2D pair communication to minimize interference and power consumption. Here, the computational complexity based on the power control iteration is $O(t * N_{(CH_i)})$. Therefore, the computational complexity of the algorithm is

$O(t*N_{(CH_j)})+O(t*N_{(CM_k)})+O(t*N_{(CH_i)}))$. Therefore, the $N$ user devices distributed in the system model include $(CH_j, CH_i, CM_k)$, and then the total computational complexity for the proposed method's solution is on the order of $O(3*t*N)$. Furthermore, the complexity of the proposed scheme is mainly determined by the complexity of solving the linear program at each iteration of the search where the linear program is solvable in polynomial time (Megiddo, 1984). The number of iterations is limited to $t = t_{max}$ to guarantee the convergence of the proposed algorithm. The complexity of the related work presented in (Selim et al., 2019) is on the order of $O(LM^c)$. Thus, low complexity is the ultimate benefit of the proposed algorithm used in the emergency communication system for disaster management.The design of ECS as Public Safety of disaster recovery that is demonstrated in algorithm 2 has the following steps:

- Step1: Deploy UAV to provide coverage services for disaster-injured areas.
- Step2: For the distributions, user devices in the range of UAV coverage are chosen as the optimal cluster Head to minimize outage probability and energy consumption.
- Step3: Calculate the EH for optimal nodes to improve connectivity response and prolong the network energy lifetime.
- Step4: Power control is applied to the optimal cluster Head to eliminate interference and save power.
- Step5: The $k^{th}$ $CM_s$ can be able to choose optimal cluster Heads selection for efficient connectivity, extend the coverage area, enhance system capacity and reduce energy consumption.
- Step6: The system is evaluated to calculate the computational complexity of the algorithm.

**Algorithm 2:** Hybrid Optimal Cluster Head Selection, EH and PC for Single UAV Model

```
$t_{max}$ : Maximum number of iterations
$P_{max}$ : Maximum transmission power of the UAV
$CH_j$ : Nonoptimal $CH_j$ nodes
$CH_i$ : Optimal $CH_i$ nodes
$CM_K$ : Out-of-coverage $CM_k$ nodes
$d_{u,i}$ : Distance from the UAV to the optimal $CH_i$
$d_{i,k}$ : Distance from the optimal $CH_i$ to $CM_k$
for $t = 1$ to $t_{max}$ do
    A cluster is formed with its proximity devices based on PCP distribution
    for $i = 1$ to $CH_j$ do
        Find optimal $CH_i$ location $(x_j^o, y_j^o)$ according to (3.31)
        Calculate $EH_i$ based on (3.16)
    end
    for $k = 1$ to $CM_k$ do
        $k^{th}$ CM chooses optimal $CH_i$ based on maximum residual energy, EH and number of the
          neighbourhood
        Calculate $p_{out,k}$ of D2D according to (3.34)
        Calculate $C_{out,k}$ of D2D according to (3.35)
    end
    for $j = 1$ to $CH_i$ do
        The power satisfies $p_j^{CH} \leqslant \frac{e_1}{Ne_3}\zeta \sum_{j=1}^{N} p_j^{S,1} \left|h_j^{S-CH}\right|^2$
        to minimize energy consumption
    end
end
```

## 3.4 Simulation Setup

Extensive simulations have been conducted with MATLAB simulator to evaluate the performance of the proposed algorithms scheme, which is compared with related works and its extended version using the different scenarios of Multi/single UAV, algorithms. For more clarification, Table (3.1) is represent the list of notations.

**Table 3.1: List of Notations**

| Notation | Description | Notation | Description |
|---|---|---|---|
| B | Bandwidth | $f_c$ | Carrier frequency |
| $\sigma^2$ | Noise variance | $n_0$ | received noise density |
| $H_k$ | UAV altitude | $SAR_h$ | SAR cluster head |
| $SAR_m$ | SAR cluster member | $SAR_\theta$ | SAR elevation angle |
| $\alpha$ | Cost Coefficient | $\eta$ | excessive-loss |
| $d_{[ki]}$ | UAV to SAR distance | $\lambda_S$ | SAR density |
| $d_{[ij]}$ | SAR to SAR distance | $\lambda_{UAV}$ | UAV density |
| $N$ | Number of user devices | $\alpha_2$ | path-loss exponent |
| $\mathrm{p}_{\mathrm{sum}}$ | UAV transmit power | $C$ | small-scale fading factor |
| $P^{[i]}$ | $SAR_h$ transmit power | $\mathrm{Q}(\cdot)$ | Q-function |
| $c$ | Light speed | $d$ | $SAR_h$ to $SAR_m$ distance |
| $P_r$ | Received signal power | $p_{\min}$ | Minimum received power |
| $\Psi_{\mathrm{UL}}$ | $S2S_{Tx}$ on uplink | $\Psi_{\mathrm{DL}}$ | $S2S_{Tx}$ on downlink |
| $\varepsilon$ | Specific threshold | $h_m$ | Number of hops |
| $P_{tx}$ | Maximum $UAV_{Tx}$ | $N(l)$ | Number of SAR clusters |
| $\gamma$ | SINR | $\lceil . \rceil$ | Ceiling function |
| $\eta_{\mathrm{LoS}}$ | LoS excessive-loss | $\eta_{\mathrm{NLoS}}$ | NLoS excessive-loss |

### 3.4.1 Multi-UAV, Proposed Algorithms1, Simulation Parameters, Set Up Analysis

The simulation parameters for the multi-UAV system are as shown in Table 3.2 as it will be the same propagation channel conditions as extracted for Multi-UAV communication with SARs AtG channel. The operating carrier frequencies are set at (1.8, 2.6, and 3.5) GHz with a channel bandwidth of 5 MHz. The Rayleigh fading model has been utilized to create heavily built-up ionospheric urban and suburban environments. The number of SARs is 150, and the UAV altitude is in the range of (20-200) m. The range of distance between the S2S communication is (10-70) m. The total network performance was investigated in a MATLAB simulation for the designed ECS for disaster recovery. Several simulations were performed to investigate the performance such as LoS, path loss, throughput, coverage probability, outage probability, energy efficiency, and spectrum efficiency for the varied propagation conditions. In the process of post-disaster clustering, the load on $SAR_h$ should be reduced to provide effective and stable routes to improve the lifetime of post-disaster communication (D. Zhang et al., 2018). Reliable communication among $SAR_h$ during post-disaster by the gateway link should also be optimized. To address this, $SAR_h$ will redistribute the network load and minimize the average power consumption of SAR nodes (Khuwaja et al., 2018); (H. Wang, Chen, et al., 2018).

**Table 3.2: Simulation Parameters for Multi-UAV System Model**

| | |
|---|---|
| Bandwidth | $B = 5$ MHz |
| Noise Density | $\sigma^2 = -174$ dBm/Hz |
| Carrier Frequency | $f = [1.8, 2.6, 3.5]$ GHz |
| Urban | $a = 9.61$, $b = 0.16$, $\eta_{\mathrm{LoS}} = 1$<br>$\eta_{\mathrm{NLoS}} = 20$ |
| Suburban | $a = 4.88$, $b = 0.43$, $\eta_{\mathrm{LoS}} = 1$<br>$\mu_{\mathrm{NLoS}} = 21$ |
| Number of SAR | $N = 150$ |
| UAV Altitude | $H = 20$ m to 200 m |
| Number of BSs | 3 |
| Number of UAVs | 3 |
| S2S Minimum Distance | 10 m |
| S2S Maximum Distance | 70 m |
| Base Station TX Power | 30 dBm |
| S2S TX Power | 15 dBm |
| UAV TX Power | 20 dBm |
| Energy outage threshold | 40 dB |
| SAR Elevation Angle | 0 to 90° |

### 3.4.2 Single-UAV, Proposed Algorithms2, Simulation parameters, Set Up Analysis

The simulation parameters for a single UAV system as shown in Table 3.3. It will have the same propagation channel conditions as extracted for a single UAV collaborating with the user device AtG channel and optimal cluster Head with D2D in the GtG channel. The operating carrier frequencies are set at 3.5 GHz with a channel bandwidth of 5 MHz. The UAV's maximum transmission power is 5 W, the transmission block time is 3 sec, and the vertical distances between the UAVs and the distance from the UAV to active user devices in the range of UAV coverage is 500 m. The Rayleigh fading model has been utilized in urban environments with an excessive loss for LoS and NLos. The number of CH is 6 with spatial density set in Table 3.3, and the UAV altitude is in the range of 100–250 m. The EH at the optimal cluster Heads selection measure is based on the EH efficiency range (0.1- 0.9).

**Table 3.3: Simulation Parameters for Single UAV System Model**

| **Parameters** | **Values** |
|---|---|
| Bandwidth | $B_0$ = 5 MHz |
| Number of clusters | 6 |
| UAV maximum transmit power | $p_u^{max}$ = 5 W |
| Transmission block time | $T$ = 1 s to 3 s |
| UAV-user devices vertical distance | $d$ = 500 m |
| Time slot ratios | $\{e_1, e_2, e_3\} = (0 - 1)$ |
| CH spatial density | $\lambda_{CH} = \{1^{-8}, 2^{-8}, 3^{-8}\}$ |
| Threshold (SNR) | $\gamma_{min}$ = 30 dB |
| D2D transmission distance | $R_d$ = 1 m to 50 m |
| Noise power spectral density | $\sigma^2 = -174$ dBm/Hz |
| Carrier frequency | $f_c$ = 3.5 GHz |
| Path-loss exponent (PLE) | $\alpha$=2-4 |
| EH efficiency | $\zeta$ = 0.1-0.9 |
| $\alpha_{D2D}$ | 3 |
| Excess-loss encountered | $\eta = 0.5$ |
| UAV altitude range | $H$ = 100 m to 250 m |
| Urban environment | $a = 9.6$, $b = 0.16$ $\eta_{LoS} = 1$, $\eta_{NLoS} = 20$ |

## 3.5 Summary

In this chapter, a system model has been proposed for a UAV-assisted emergency communication network that is stable and reliable to manage disaster scenarios. The multi/single UAV models have the capability of selecting user devices that should be performing as the optimal cluster Head and at the same time extending the wireless coverage. The energy harvesting techniques have been investigated with the intent of prolonging the network lifetime. Finally, the power consumption of the optimal cluster Head and reliable connectivity for the UAV and D2D communication range were analyzed. The system model is expected to perform with better outage probability and efficiency for sustainable operations during disasters.

# CHAPTER 4: RESULTS AND DISCUSSION

## 4.1 Introduction

In this chapter, the simulation results are presented extensively to demonstrate the performance of the proposed schemes. In the multi-UAV system model, the SARs are randomly distributed in each scenario under UAV coverage communications and S2S in the out-of-UAV coverage area. The performance of the system model is demonstrated in Los, Path Loss, throughput, coverage probability, and outage probability. In the single UAV model, the performance is shown in the energy harvesting, D2D-power control, outage probability, and SE for optimal and nonoptimal CH.

## 4.2 Multi-UAV and SAR System Model Performance

Ensuring communication infrastructures are always alive during disaster mitigation, and recovery is paramount. In this case, a UAV will be the ideal substitute for the malfunctioning ground base station due to disaster. Hence the multi-UAV and SAR collaboration model improves connectivity in larger disaster areas effectively and efficiently. The multi-UAV and SAR collaboration model demonstrates improved connectivity performance and supports ECS for efficient and reliable disaster recovery to extend the wireless coverage to hard-to-reach and remote disaster areas. The utilized clustering approach results in further energy saving in S2S communication and maintaining the network connectivity coverage extension. The Elevation angle impacts the Los, PL and throughput in the case of an urban and suburban area. The advantage AtG channel is a higher LoS propagation better than the terrestrial communication channels. This acts to reduce transmit power requirements and can translate to higher link reliability in the case of failure networks. Therefore, the AtG channel may experience lower diffraction and shadowing losses than near-ground terrestrial communications when only non-LOS (NLOS) pathways are available, and the elevation angle to the UAV is sufficiently large. The first approach is to develop deterministic models using environmental parameters while considering the UAV altitude and elevation angle from the ground integrated with the environmental parameters to develop deterministic models. Such models are useful to study the fading effects in the channel, and the propagation conditions and hence can provide coverage analysis for optimal UAV position. Furthermore, the 3D UAV coverage solutions can increase the system throughput overall and accommodate more users. In addition, The UAV coverage services are more suitable for scenarios in which the number of users is high and they are distributed in three dimensions with different elevation angles concerning their serving base station. Due to the high altitude of UAV-carried flying base stations, ground users can be easily distinguishable at different altitudes and elevation angles measured concerning the UAV.

### 4.2.1 Line-of-Sight Probability

In Figure 4.1, the channel was examined to ensure its availability for suburban and urban areas. LoS parameters such as $a$, $b$, $\theta_i$ in (3.9) and obstacles will affect the channel particularly due to signal reflections, densities of buildings and radio characteristics. The result shows that as the LoS probability increases, the SAR elevation angles simultaneously increase for the same coverage level in both suburban and urban environments. It can also be seen that the maximum probability of LoS is achieved at the elevation angle of 20° in suburban areas and 50° in urban areas. The aim of the study is focused on the urban area due to more density and corded of the people live, and they need to save during the disaster. Therefore, the radio channel properties in the urban scenario differ from those in the suburban and open areas due to many scattering paths from office buildings, especially when the UAV flies at a low altitude. In these circumstances, UAVs will be able to increase the gain and fly over a region and operate optimally within the SAR receiver's

LoS range. Furthermore, Rician fading occurs when one path typically receives signals in the suburban open area strongly with no obstacles and is not congested with traffic signals or some strong reflection signals.

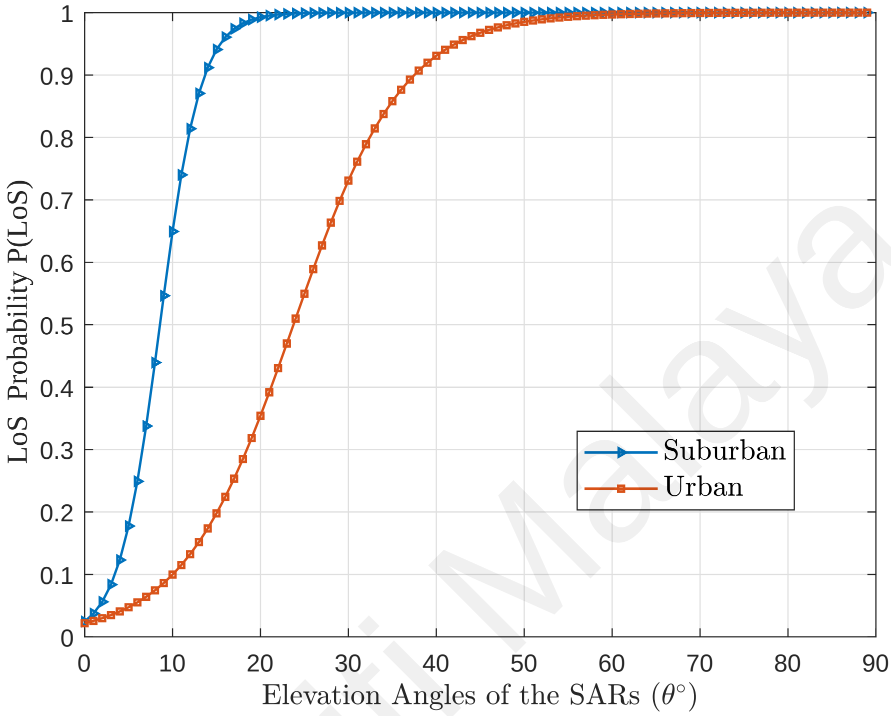

**Figure 4.1: LoS Probability versus SAR Elevation Angle.**

The main reason for this behaviour is that, at higher UAV altitudes, the UAV moves above tall buildings, and it can observe signals that are scattered from a larger number of surrounding buildings. Therefore, at higher UAV altitudes, the signals scattered from the buildings do not arrive at the UAV, hence reducing the Received signal strength (RSS) of multipath for different UAV heights considering the different environments, such as urban and suburban. This different behaviour of the multipath channel suggests that environmental factors and UAV height can significantly impact the channel behaviour and hence the receiver design. As the UAV's altitudes get higher, the smaller circle's size will increase. Also, the UAV coverage area will be increased, and the gap area will be decreased. The increasing UAV altitudes also affect UAV flight time, and the energy consumption of the UAVs in large circles leaves a gap at the centre of the circle but reduces the gap at the edge of the area. In addition, the increase in UAV altitudes reduces the number of small circles created for each path.

In Figure 4.2, the NLoS probability performance is considered based on NLoS parameters in (3.9) where $P_{NLos} = 1 - P_{Los}$ . It can be observed that NLoS probability for the urban areas performed better than the suburban areas when the UAV altitudes increased. This is attributed to the dense distribution of the building and multipath signals towards the destination nodes for the urban areas, whereas the suburban areas showed inadequate NLoS communications due to strong SINR received.

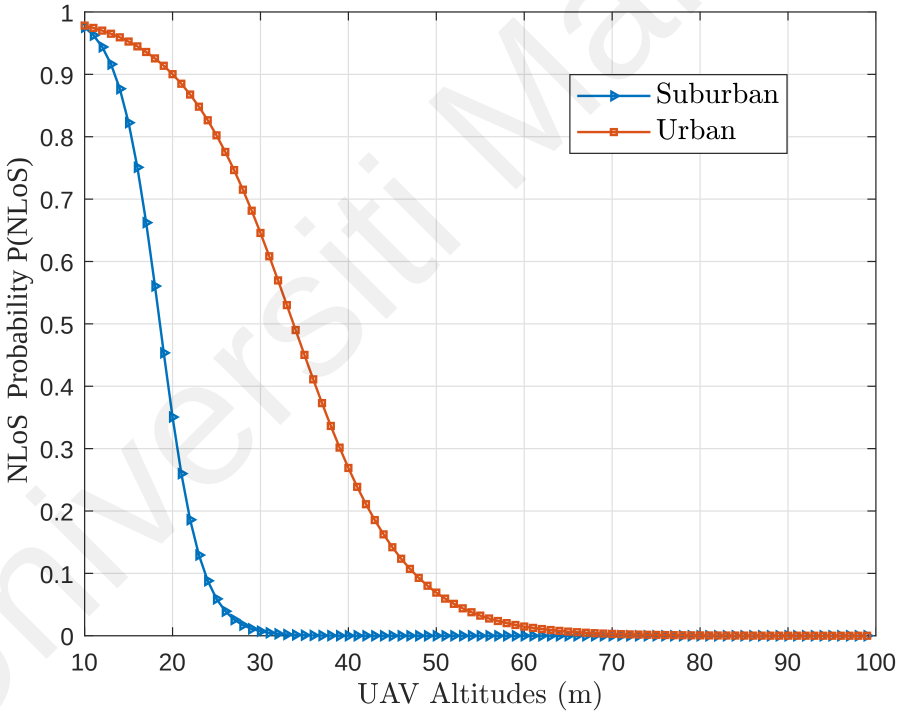

Figure 4.2: NLoS Probability versus UAV Altitude.

### 4.2.2 Path Loss

Path loss propagation is a critical factor that affects the wireless channel between the UAVs and SARs through the AtG channel. Hence, the network link quality, communication performance, and path loss are highly influenced by LoS and NLoS probabilities and other environmental parameters such as distance, SAR elevation angles, and UAV altitudes.

Path loss propagation is another factor that requires careful treatment. It can be seen from Figure 4.3 that path loss increases from 50 dB to 59 dB when the SAR elevation angles vary from 0° to 15° for the urban areas, which is mainly attributed to denser building densities in urban areas. Suburban, however, experiences a lower path loss from 44 dB to 50 dB when the elevation angle of the SAR is increased from 15° to 90° due to a single city model. In addition, the impact of increasing NLoS transmission power is low to don't affect user devices' propagation channel.

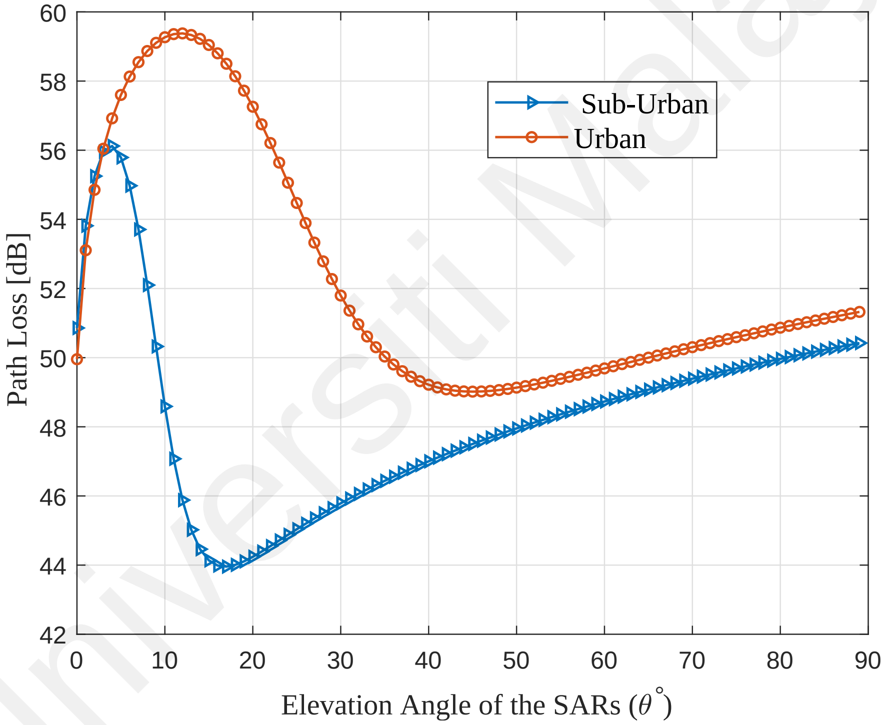

**Figure 4.3: Path Loss versus SAR Elevation Angle**

Figure 4.4, shows the result of path loss when the UAV altitude, $H$, is increased. Note that the UAV altitude has a dual effect on SAR distances and elevation angle on the AtG channels due to the loss of signals through the transmission distance from the UAV. On the other hand, when $H$ is increased, the elevation angle from the UAV to SAR needs to be increased versus the distance to cover the same number of SARs. Therefore, when the LoS probability is increased due to the increase in altitude $H$, the propagation gain has a negative impact. Here, the UAV altitude has different impacts on the path loss for various propagation environments. For example, the maximum path loss in urban areas is measured to be 60 dB for altitudes higher than 80 m due to the higher LoS communication at higher UAV altitudes. However, the path loss is measured to be 57.5 dB in the suburban areas due to the NLoS link that deteriorates the received SINR.

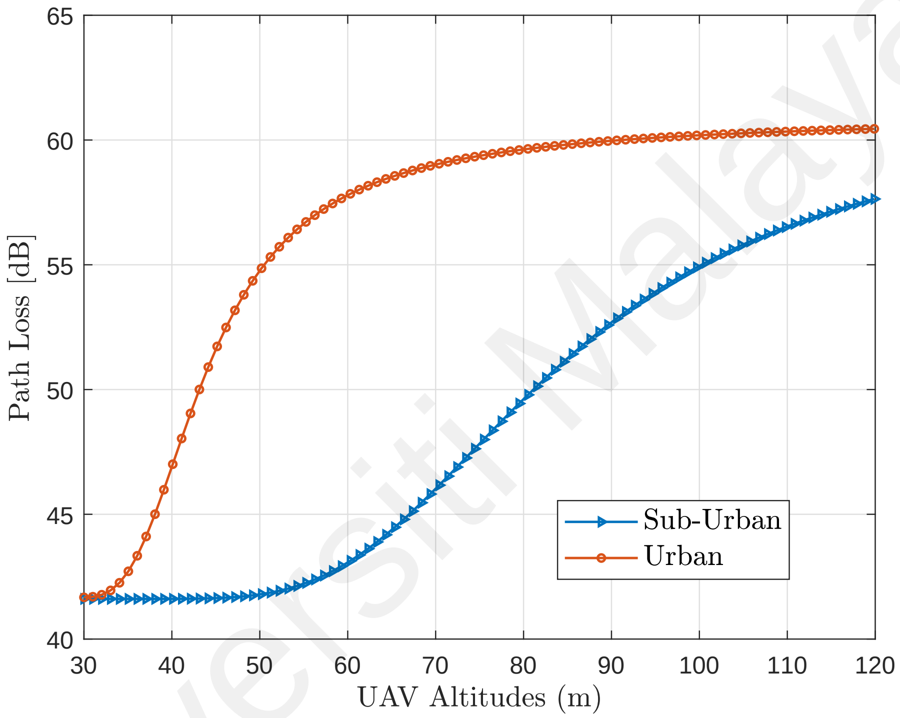

**Figure 4.4: Path Loss versus UAV Altitude**

The distance between the UAVs and SARs affects the performance of the covered services provided by UAVs.

As shown in Figure 4.5, UAV altitudes have no effect on the probability of LoS and only impact the NLoS link due to large-scale path loss in suburban areas. However, in urban areas, the path loss is likely to be affected by altitudes because of the fact that the transmit power should be increased with distance.

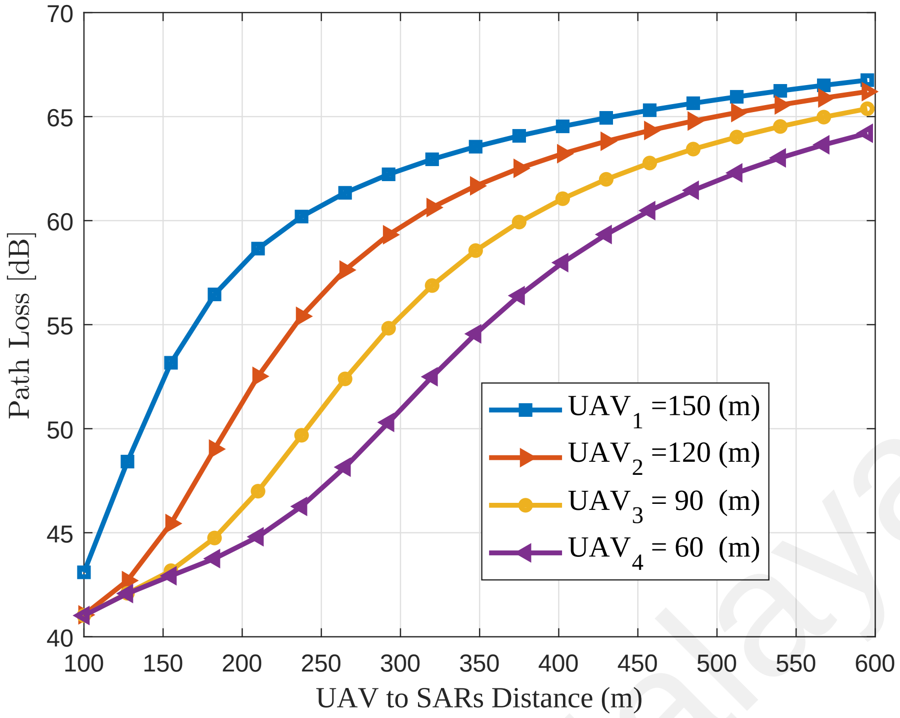

**Figure 4.5: Path Loss versus UAV–SAR Distance for Various UAV Altitudes.**

### 4.2.3 Throughput Performance

The throughput is defined as data successfully delivered to the destinations via a communication link between the UAV and user devices. Figure 4.6 demonstrates the result of throughput versus UAV to SARs distance. The throughput is maximum when the distance is 100 m for suburban areas and 150 m for urban areas. Since then, the throughput decreases until the distance is around 200 m for suburban areas and 350 m for urban areas, where the throughput increases again. The decrease is mainly attributed to LoS interference from the UAV to the SARs. Therefore, it is possible to conclude that optimal throughput can be obtained when the UAV is at 150 m from the SAR for urban areas whereas, for suburban areas, it is at 100 m.

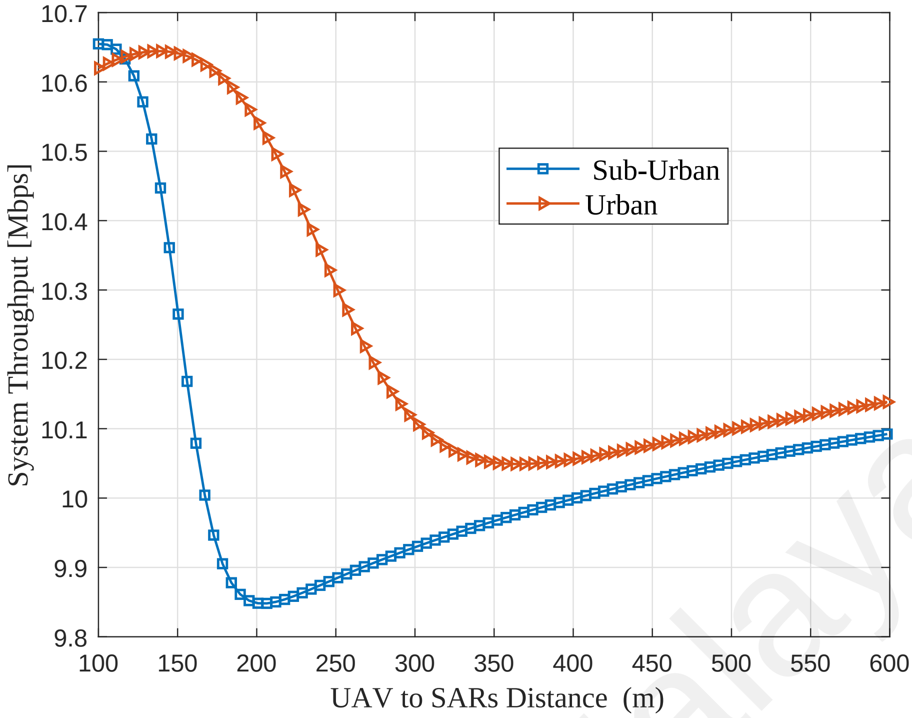

**Figure 4.6: Throughput versus UAV-SAR Distance.**

Figure 4.7 represents the analysis of system throughput as a function of the elevation angle. It can be observed from the figure that the system throughput was maximized for all propagation environments, i.e., as the elevation angles changes from 0° to 7° for suburban areas, 0° to 15° for urban areas. This is due to the large-scale path loss via the distance of SAR that affects the elevation angle. On the other hand, the suburban area gives the most negligible system throughput due to the increased NLoS for high building densities.

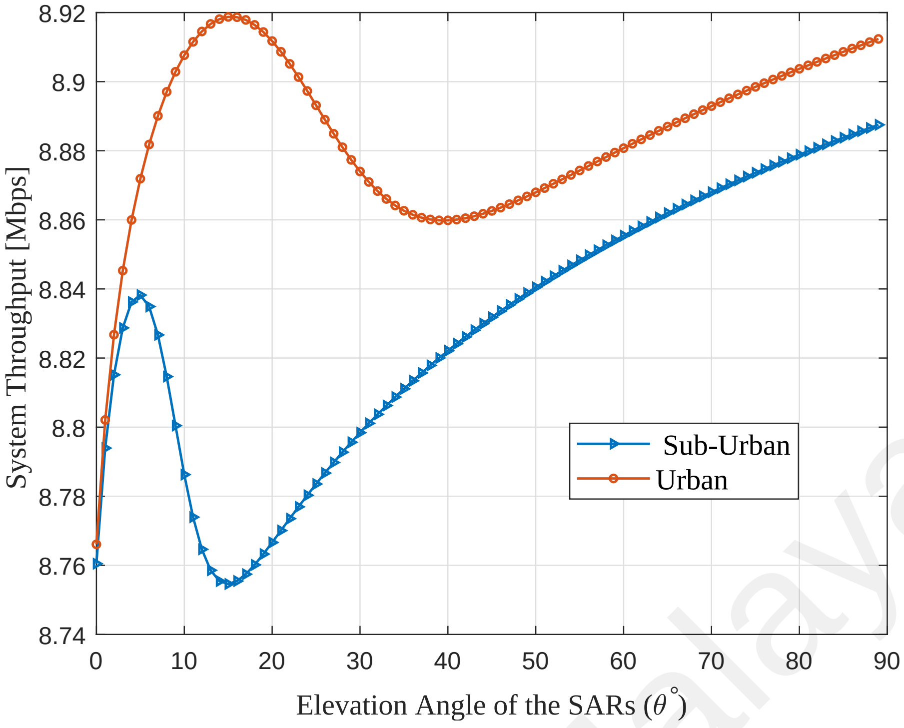

**Figure 4.7: Throughput versus SAR Elevation Angle.**

Figure 4.8 demonstrates the effect of UAV altitudes on the system throughput in urban areas and suburban environments. The result reveals that a suburban area environment produces higher throughput than the environment of an urban area. This is due to the suburban areas having a higher probability of LoS communication than the urban areas. Suburban areas generally have lower building density, whereas urban areas have high building density, impacting the received SNR. The system throughput is linearly increasing for each altitude due to the fixed bandwidth utilization and low interference increment on the received SINR.

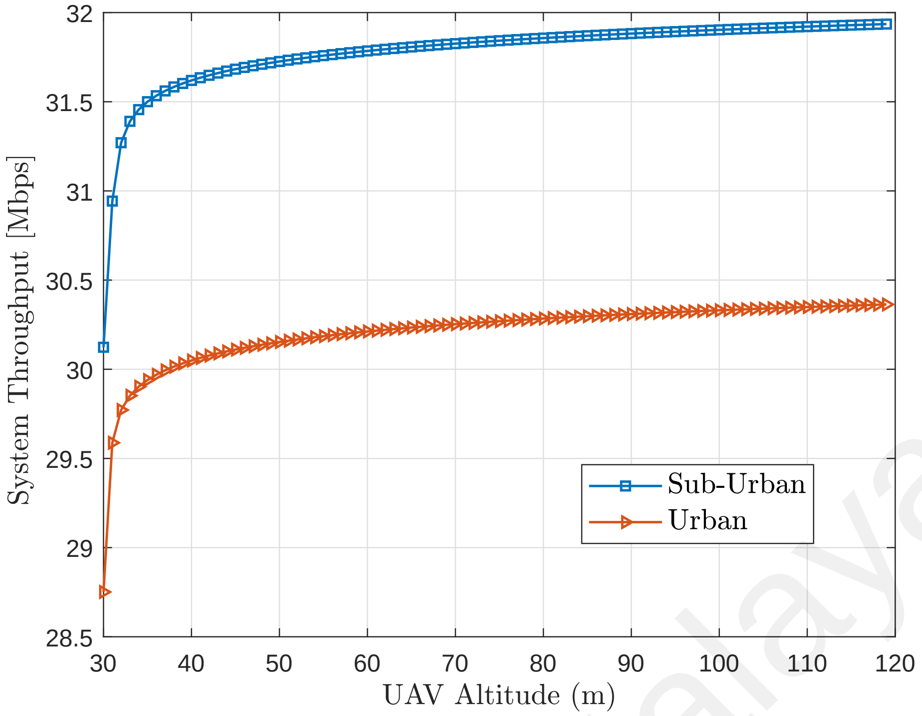

**Figure 4.8: Throughput versus UAV Altitude.**

### 4.2.4 Analysis of Coverage Probability

The coverage probability is defined as the probability that the SINR of the downlink signal from the serving UAV to the user is above a threshold. UAV-assisted SAR device coverage probability performance improves the quality of service. It is typically derived from altitude, SAR elevation angles, and path loss scale.

Figure 4.9 shows the performance of the coverage probability versus the energy outage threshold in suburban areas and urban environments. The normalized coverage probability decreases with the increasing energy outage thresholds due to the effect of LoS and NLoS radio propagation on the received signal. For example, in suburban areas, the coverage probability decreases from 1 to 0 when the energy outage threshold increases from 0 dB to 25 dB due to the improved LoS. On the other hand, the coverage probability decreases from 1 to 0 in the urban areas as the energy outage threshold increases from 0 dB to 30 dB. This is due to the increased NLoS barriers that influence the received signal strength due to high building densities in urban areas.

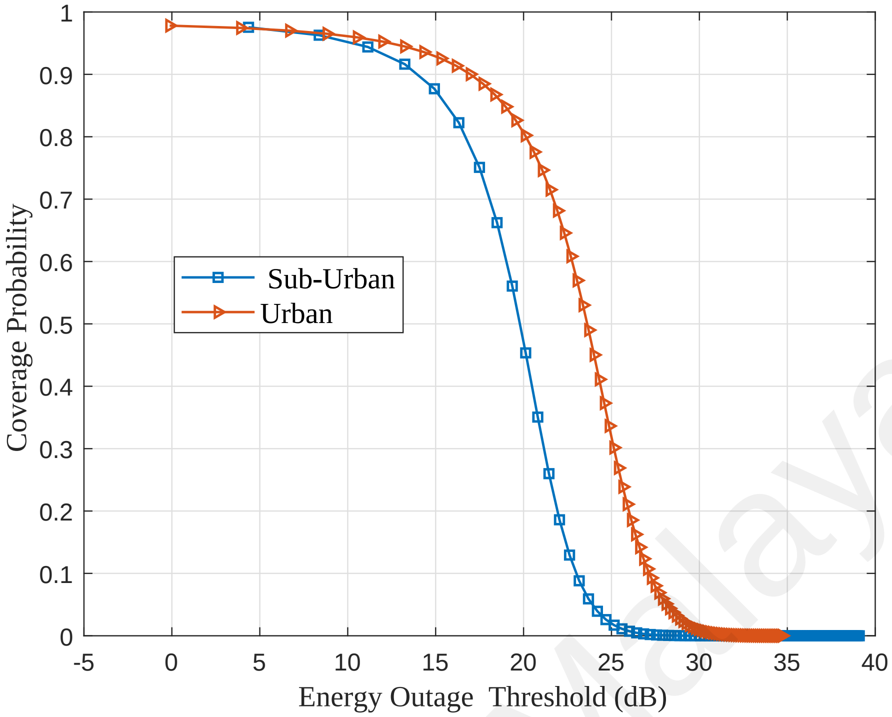

**Figure 4.9: Coverage Probability versus Energy Outage Threshold**

Figure 4.10 shows the coverage probability performance versus SAR elevation angle at each UAV altitude. It can be observed that the normalized coverage probability decreases with increasing SAR elevation angle due to LoS and NLoS radio propagation on the received signal. The trend continues due to reduced communication distance and increased elevation angle between the UAV and SARs until it reaches an elevation angle of around 25° at $UAV_1 = 100m$, 35° at $UAV_2 = 150m$, and 45° at $UAV_3 = 200m$. Since then, the coverage probability started to increase as the SAR elevation angle increased due to the improved LoS close to the UAVs via the distance of SARs that affect the elevation angles.

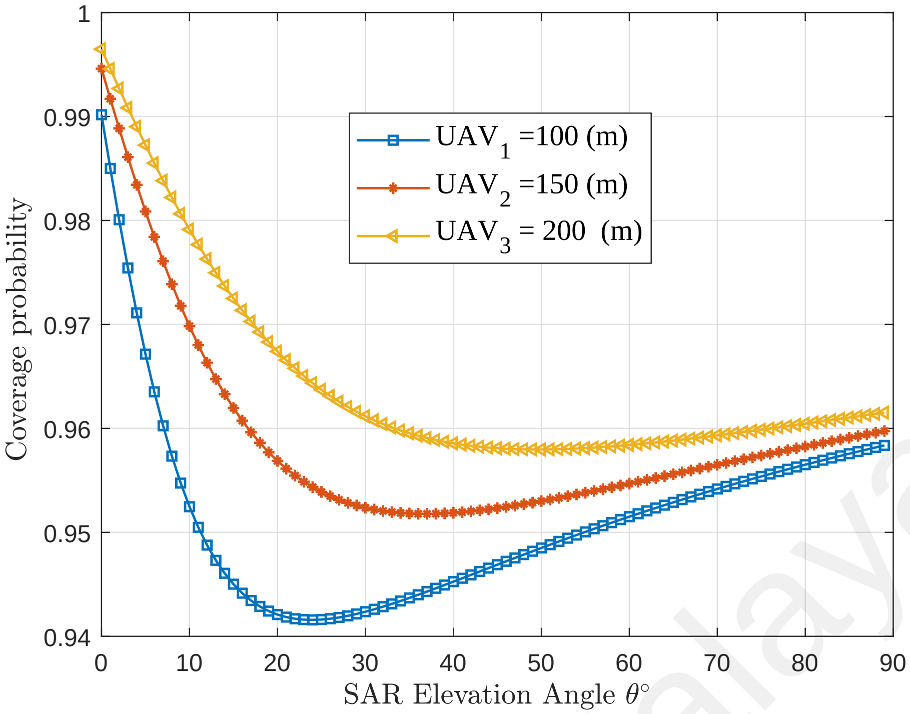

**Figure 4.10: Coverage Probability versus SAR Elevation Angle**

### 4.2.5 Outage Probability

Outage probability is defined as the minimum SNR less than the required threshold to ensure decoding correctness in the network receivers. However, the ECS has limitations when minimizing the UAV outage probability during disaster recovery with the cluster-based channel model. Figure 4.11 shows the result of outage probability versus energy outage threshold for the disaster and without-disaster events. It can be observed that the outage probability increases faster in disaster areas than without disaster. That is, the outage probability increases from 0 to 1 when the energy outage threshold is increased from 0 dB to 25 dB for the disaster scenario, whereas in the case without disaster, the outage probability increases from 0 to 1 when the energy outage threshold is increased from 0 dB to 40 dB. This is attributed to the limitation of transmission power in the disaster area. Thus, it can be deduced that the transmission power of the source plays a significant role in minimizing the outage probability and maximizing the throughput.

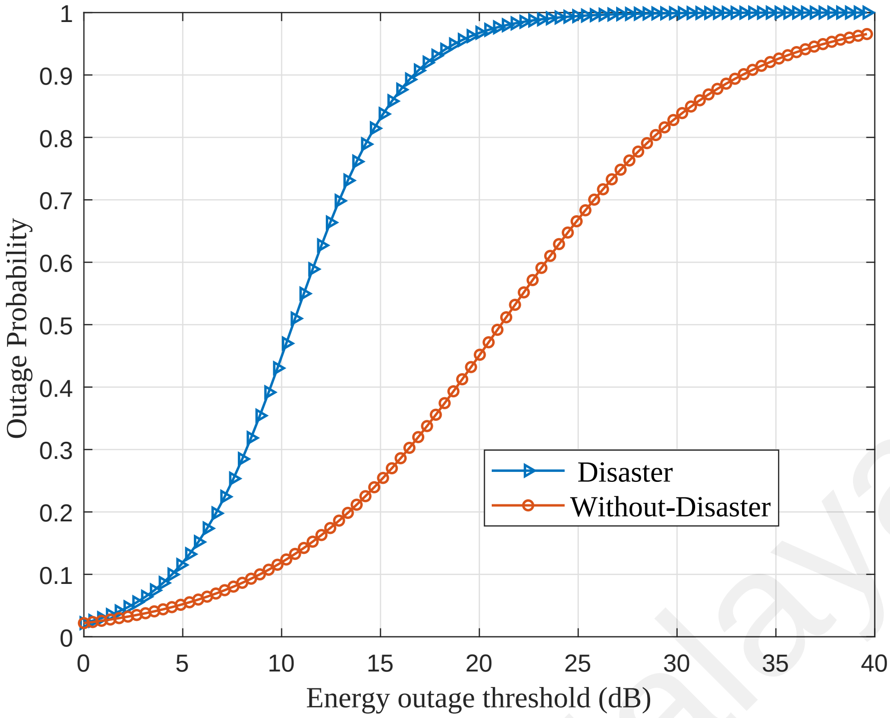

**Figure 4.11: Outage Probability versus Energy Outage in Disaster and without Disaster**

Next, the analysis of different post-disaster scenarios is performed for the link between UAV and S2S communications in the theoretical and simulation results, as illustrated in Figure 4.12. The results show that the outage probability of the UAV increases from 0.1 to 0.97 for simulation and 0.1 to 0.8 for theoretical when the energy outage threshold increases from 25 dB to 57 dB, while S2S rises from 0.03 to 0.95 for simulation and 0.1 to 0.95 for theoretical when energy outage thresholds rise from 19 to 51 dB. Hence, UAVs gain stronger LoS propagation between the source and the destination despite having adequate coverage compared to S2S. This indicates that a UAV is a suitable replacement for the dysfunctional ground base station. Moreover, in the high outage threshold f condition, the noise is very small compared to the desired signal power, so the SINR is mainly on the ratio between the signal power and interference. The relative separation between the serving and interfering UAVs would degrade with an increase in the UAV height, so the SINR decreases the coverage. Meanwhile, the interference is negligible in the low SNR condition, and the increase of the height will lead to more path loss, which worsens the signal power and hence the SINR and coverage.

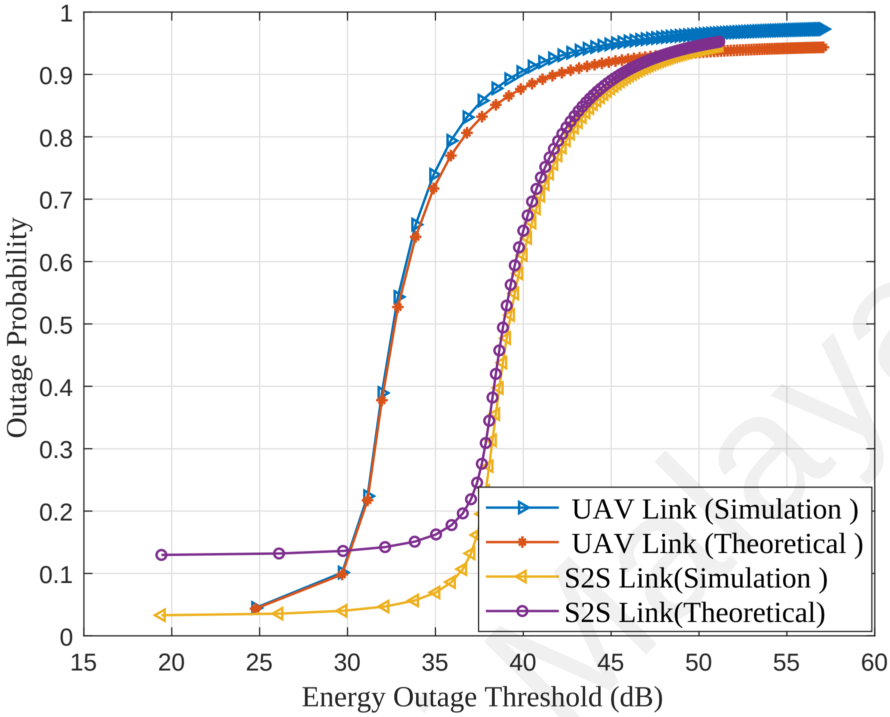

**Figure 4.12: Outage Probability versus Energy Outage Threshold for UAV and S2S**

### 4.2.6 Energy Efficiency

Energy efficiency is defined as the ratio of system throughput to the total power consumption, measured in bits/joule. Energy efficiency ensures continuous communication between the UAVs and SARs and prolongs the network lifetime. Therefore, both the UAV and the S2S energy efficiency will be analyzed. It can be seen from Figure 4.13 that the energy efficiency decreases as the SAR distance increases. It should also be mentioned that the energy efficiency for each scenario becomes close together as the SAR transmission distance increases. This indicates that as the SAR distance increases, the interference effect becomes insignificant. Similar to the case of UAV altitudes, this trend can be alleviated by having more transmission power as the distance increases. Note that energy efficiency is primarily reduced by co-channel interference. However, having a directional antenna improves the efficiency metrics.

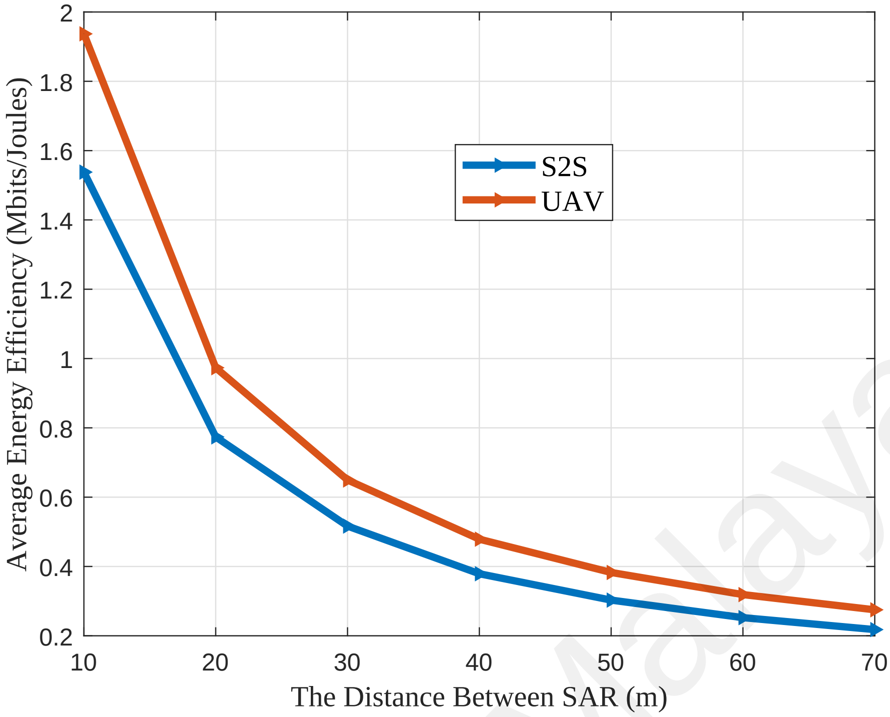

**Figure 4.13: Average Energy Efficiency versus SAR Distance at $f_c$ = 3.5 GHz**

Power saving is one of the major constraints to disaster recovery. Figure 4.14 shows the power efficiency performance for multi-hop S2S communication to reach the people affected by disasters. Multi-hop S2S power efficiency is defined as the ratio of throughput and transmits power for $SAR_h$ to $SAR_m$. Hence, increasing S2S hops can effectively improve energy efficiency. Furthermore, the multi-hop S2S communication can save power and improve connectivity to provide coverage services for the SARs that are out of UAV coverage in disaster situations.

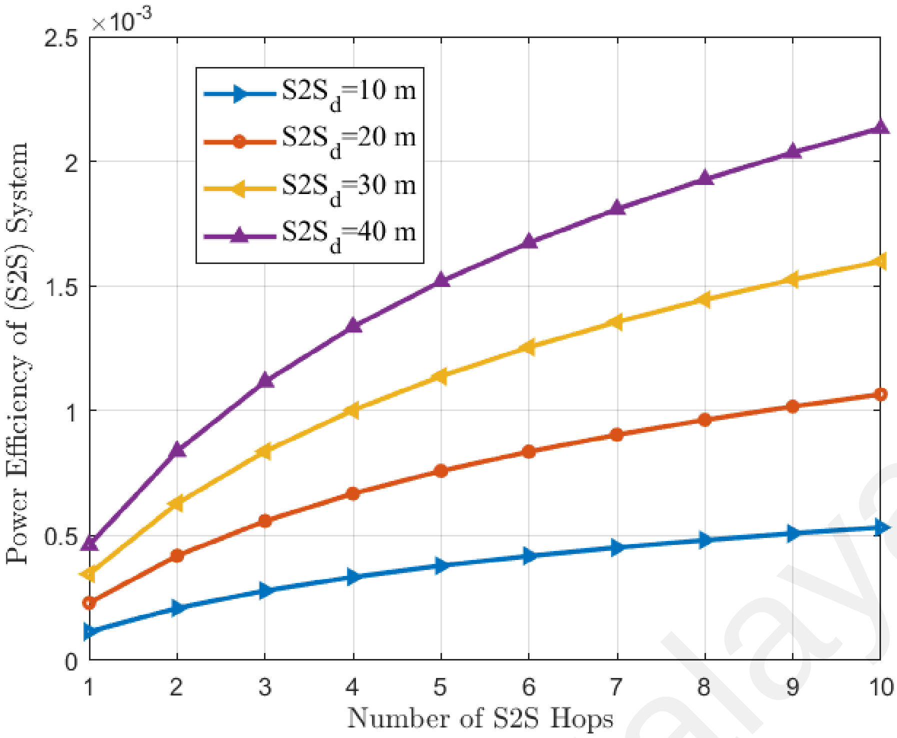

**Figure 4.14: Power Efficiency for Multi-hop S2S with various Sparsity Distances**

## 4.3 Single UAV Performance

Using the optimal CH technique, a single UAV with an ECS improves energy transfer efficiency for sustainable network connectivity. The UAV deployment model has been developed to be assisted by the clustering technique and D2D links capable of harvesting energy to increase the network lifetime. Therefore, a single UAV demonstrates improved performance with the deployment of optimal CHs, while the outage probability has been effectively reduced. Moreover, the proposed approach has been proven to reduce the computational complexity for a suitable network design to recover from natural disasters and potentially save many lives.

### 4.3.1 Energy Harvesting Performance for UAV

Energy harvesting is a possible way to satisfy the energy requirements for an ECS during the post-disaster phase. Hence, energy harvesting is employed to power communication devices and prolong the lifetime of the wireless communication network during a disaster.

Figure 4.15 shows the energy harvesting for various user device distances when the deployed UAVs change their altitudes. UAV altitudes are affected by the probability of LoS based on the change of elevation angle of user devices when the vertical distance of the UAV to user devices varies by up to 500 m. Thus, the UAV can adjust its altitude to improve network coverage for user devices. However, EH is affected by UAV altitudes when the large-scale path loss is considered for user distances when the bandwidth is fixed. In addition, the UAV altitude affects the EH performance because it needs a higher transmit power to compensate for the increasing user distance and more hops between UAV-CH and CH-CMs at higher altitudes.

This is demonstrated in Figure 4.15, which shows that EH decreases as a function of the user device distance. Therefore, the UAV moves up in altitude, increasing the probability of LoS and increasing path loss. For $100 \text{ m} \leq H \leq 200 \text{ m}$, Figure 4.15 shows that EH deceases from 1.2 joules to 0.1 joules with an increase in distance from 100 m to 500 m. Furthermore, UAV altitudes affect the EH because a higher transmit power will be needed with an increasing distance and an increasing number of hops between CH and D2D at higher altitudes.

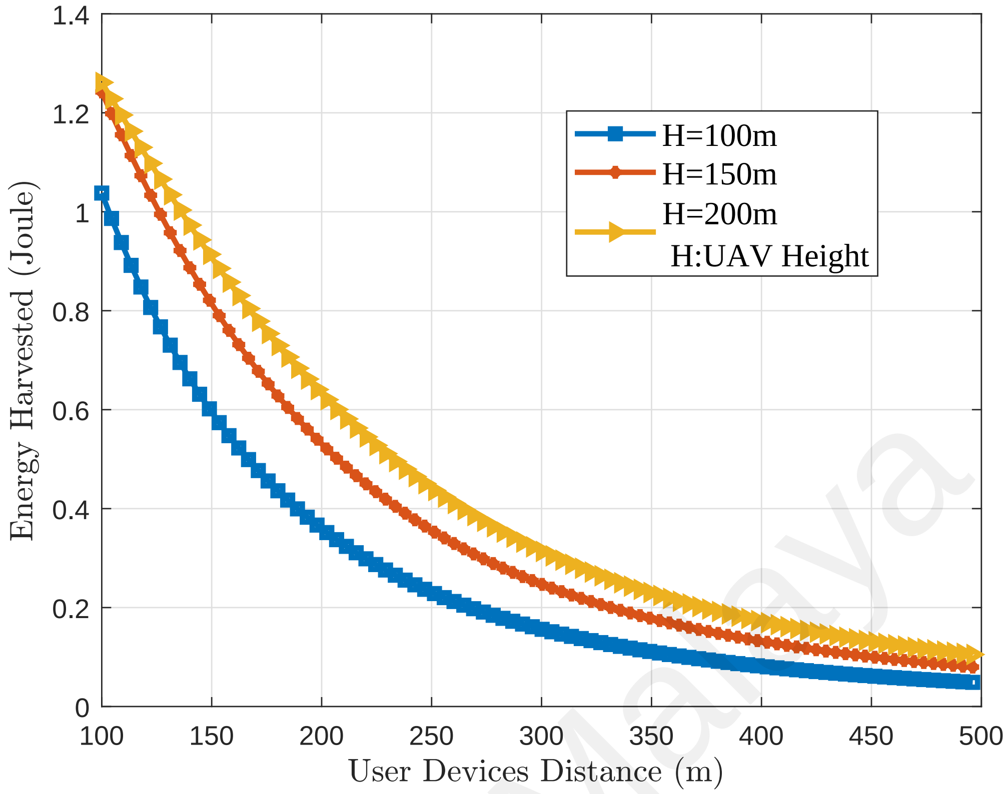

**Figure 4.15: Energy Harvested versus Distance at Different UAV Altitudes.**

In Figure 4.16, EH performance versus $\zeta$ is simulated for UAV and D2D communication. As shown in the figure, EH is equal to 1.5 joules at $\zeta = 0$ in the UAV scenario, while in the D2D scenario, it is equal to 0.6 joules. Hence, EH maximizes the UAV direct link scenario at approximately 50% for the UAV link scenario through CHs as D2D communication. Thus, it can be concluded that EH performance in the UAV scenario is better than that in the D2D communication. This is attributed to the substantial LoS propagation path gain between the UAV and CHs and the slight loss of received signals at the user device receivers. Additionally, EH in D2D communication is lower than that with UAVs due to the lower power needed for the CH to forward the wireless signal to CMs.

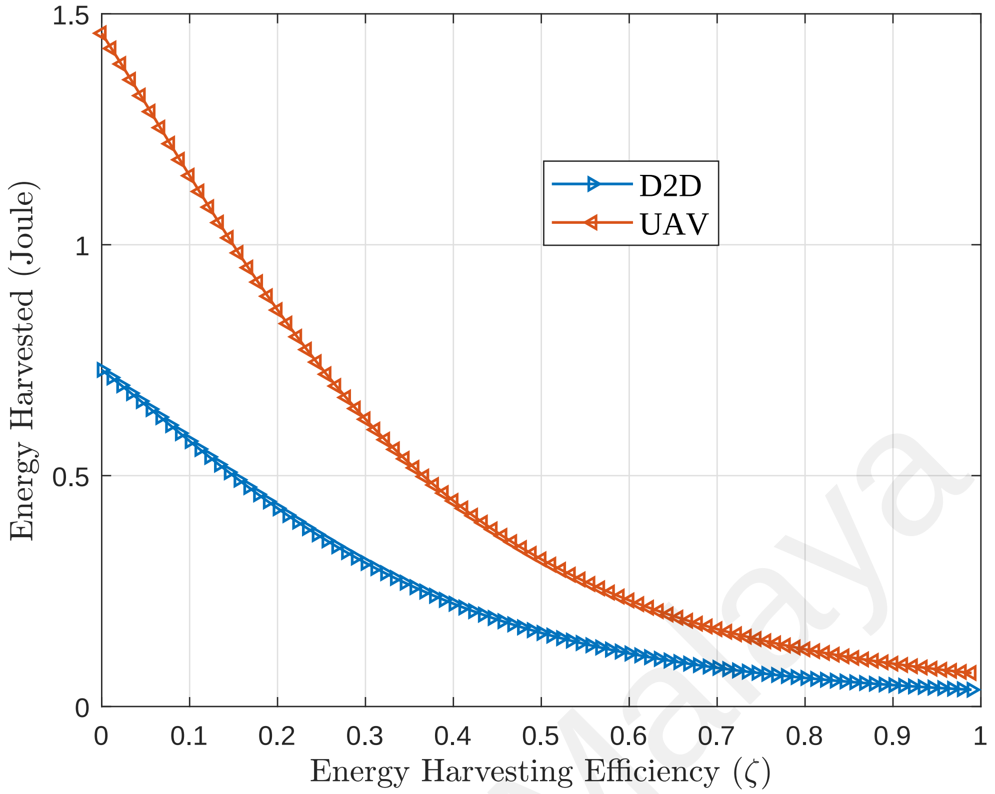

**Figure 4.16: EH Performance versus $\zeta$ for UAV and D2D communications**

### 4.3.2 Energy Harvesting Based on D2D Communication

Efficient resource distribution was used to improve the channel link quality based on D2D energy harvesting (D2D-EH) and minimize the communication outage probability in post-disaster situations. For many users, the network has proven to be resilient and scalable. It aids in reducing the impact of resource and service constraints in crises such as power outages, traffic congestion, and network capacity.

Figure. 4.17 represents the energy harvesting capability for the nonoptimal CH and optimal CH. It is evident from the figure that the D2D communication between the optimal CH and CMs harvests more energy than that between the nonoptimal CH and CMs. Therefore, determining the optimal location of the CH is crucial because it reduces the transmission power between the UAV and user devices thus, it improves the harvested energy. Furthermore, the optimal CH will reduce communication latency between the CH and CMs due to the shorter communication range.

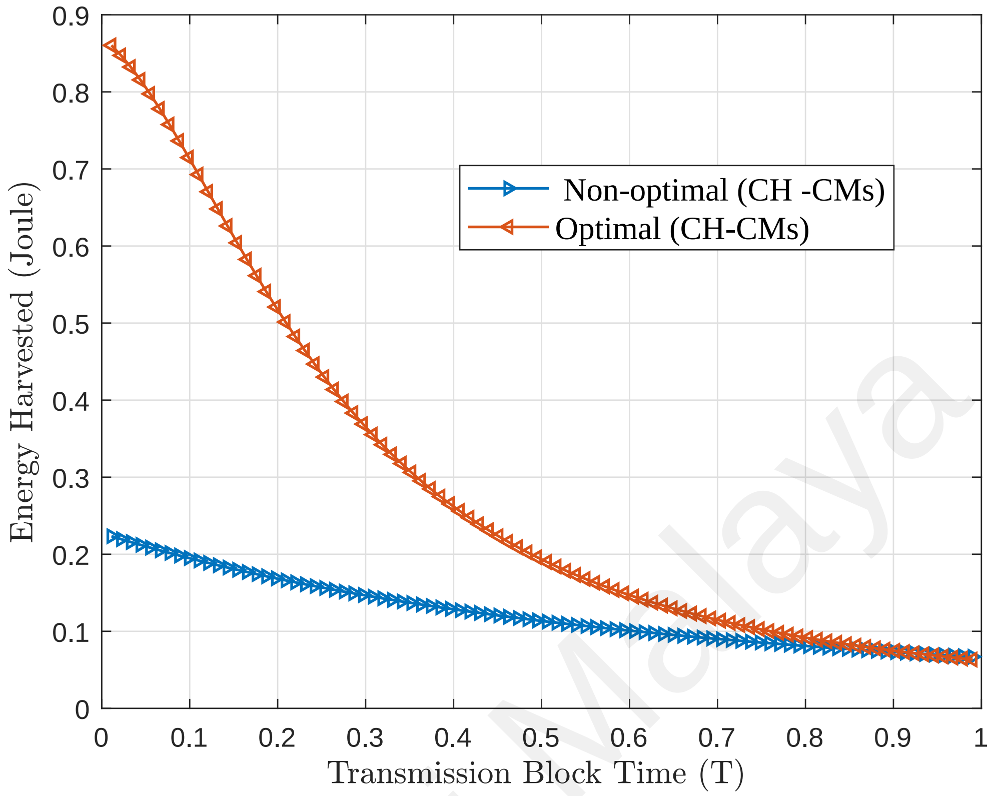

**Figure 4.17: Energy Harvested versus Transmission Block Time with the CHs.**

It is understood that more energy is required to increase the UAV coverage range. Thus, the next step is to analyze the energy harvested by multiantenna UAVs. As anticipated, the amount of energy harvested through multiantenna UAVs is more than that of a single-antenna UAV, as shown in Figure 4.18. For example, at transmission block time 0.3, the amount of energy harvested is 0.1 joule for a single-antenna UAV, while for a four-antenna UAV, it is 0.45 joules. Therefore, energy harvesting using a multiantenna UAV will increase energy efficiency and thus serve a larger coverage area.

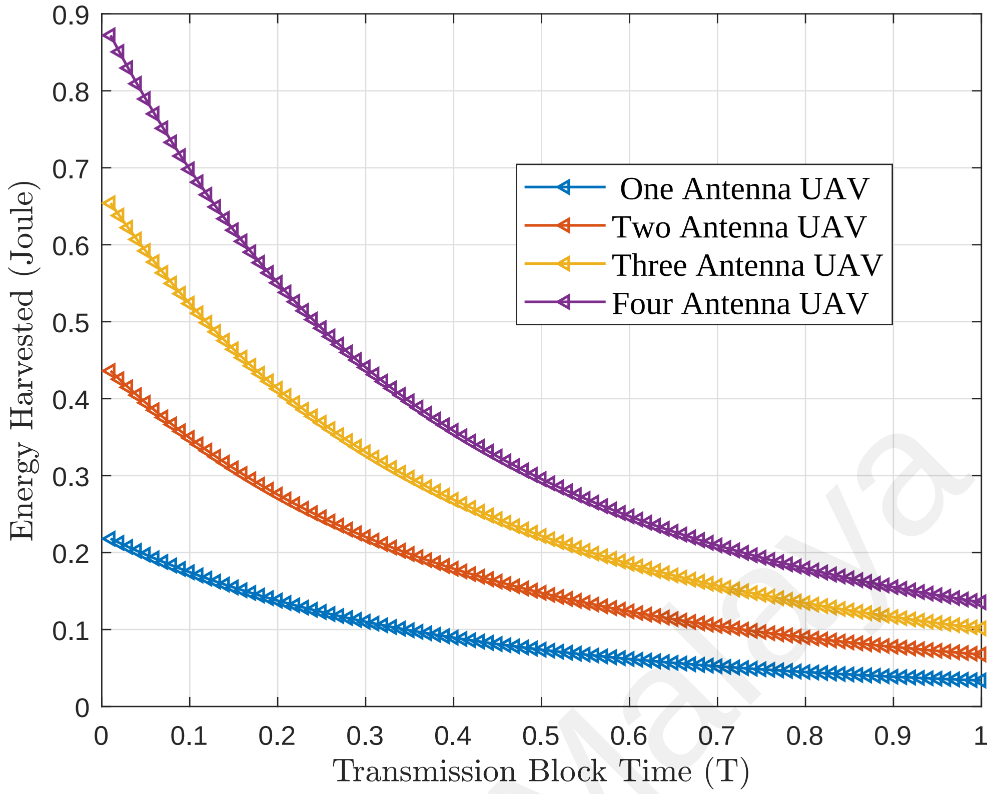

**Figure 4.18: Analysis of Energy Harvesting versus Time Interval with Multi-antenna UAVs.**

### 4.3.3 Outage Probability Performance

Figure 4.19 shows that the outage probability is improved when the elevation angle of the CHs is at its optimal value. The outage probability with an elevation angle based on nonoptimal CHs ranges from 0.6 to 0.95, whereas the outage probability for the optimal elevation angle ranges from 0.1 to 0.95. Therefore, the optimal elevation angle of CHs provides more sustainable connectivity during a disaster scenario. The optimal location of the CH can effectively increase the coverage probability and decrease the outage probability.

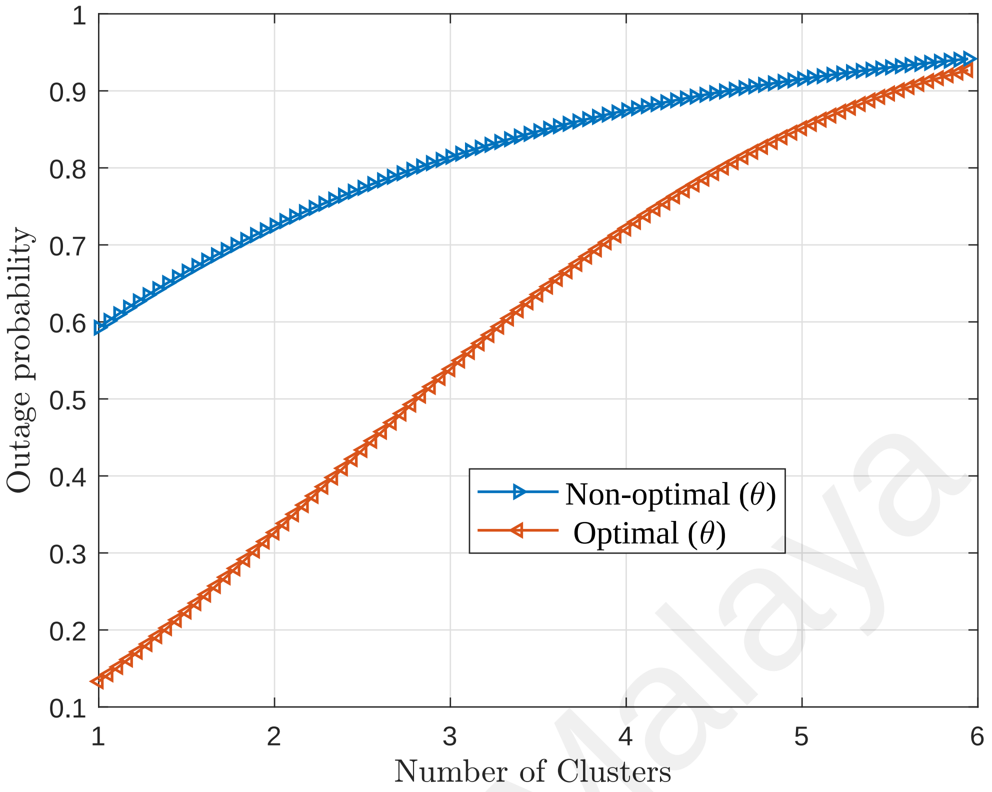

**Figure 4.19: Outage probability versus Number of Clusters for Optimal and nonoptimal CHs.**

Further analysis of the overall outage probability for the UAV and D2D user devices versus the transmission block time $(T)$ at two different post-disaster scenarios is shown in Figure 4.20. As the number of retransmissions (transmission block time) increases, the overall outage probability also increases. In other words, the possibility of a failure during retransmissions increases for the higher number of $(T)$. Furthermore, the UAV is an interference source for the D2D user devices, and the higher number of stop points leads to a higher outage probability. As a result, the outage probability of the UAV is lower than that of D2D due to the strong LoS link between the source and destination and the slight loss of the received signals at the user device receivers. Moreover, the outage probability of the UAV while communicating with user devices is much better than the outage performance of the D2D communication mode, primarily due to the higher channel quality associated with the UAV scenario. Hence, the LoS propagation gain of the UAV outage probability performance is better than that of D2D, which maintains short distance connectivity and distance between the end nodes, which is greater than the UAV coverage radius.

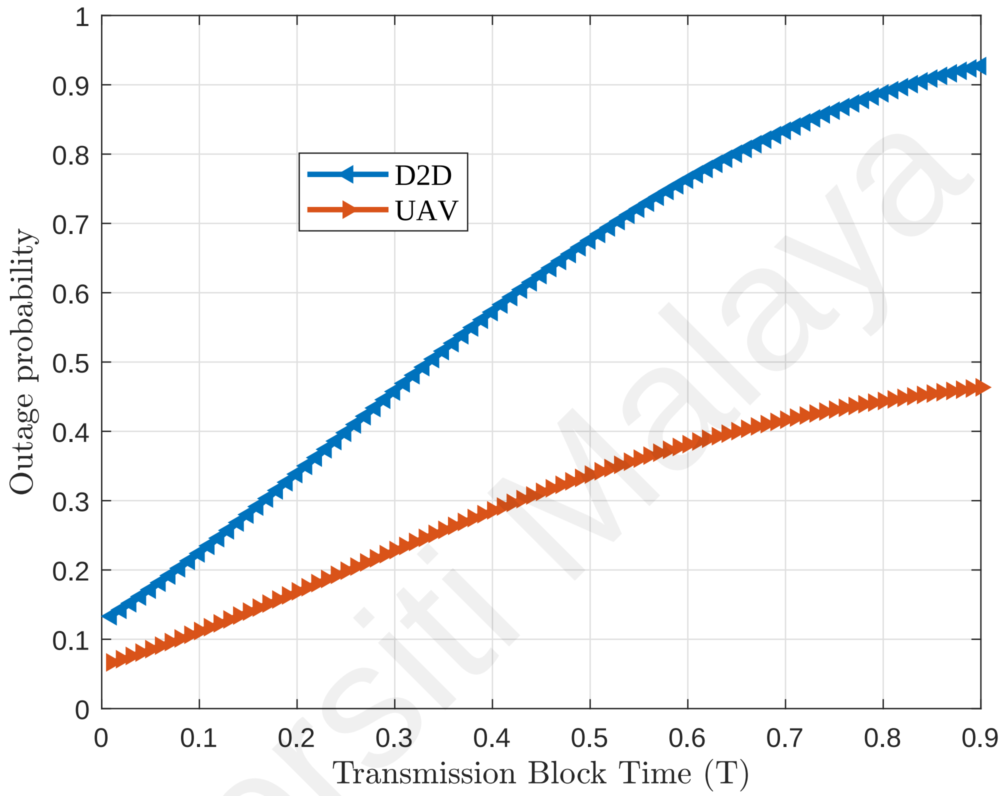

**Figure 4.20: Performance of Outage Probability versus Transmission Block Time for the UAV Link and D2D Link.**

A higher number of antennas eventually increases the transmission power, which improves wireless coverage services. Figure 4.21 shows the EH performance when the elevation angle of user devices varies for up to three UAV transmission antennas. The EH increases when user device elevation angles are raised for the same level of coverage in multiantenna UAVs. Moreover, the maximum EH of 1.1 joules is achieved at a maximum elevation angle of 90° in the case of a three-antenna UAV. However, the minimum EH performance is 0.4 joules, which is achieved at a maximum elevation angle of 90° in the case of single-antenna UAVs. Thus, the EH efficiency of UAVs can be improved to enable flying for a longer duration and operating optimally within the receiver's LoS range using multiple antennas.

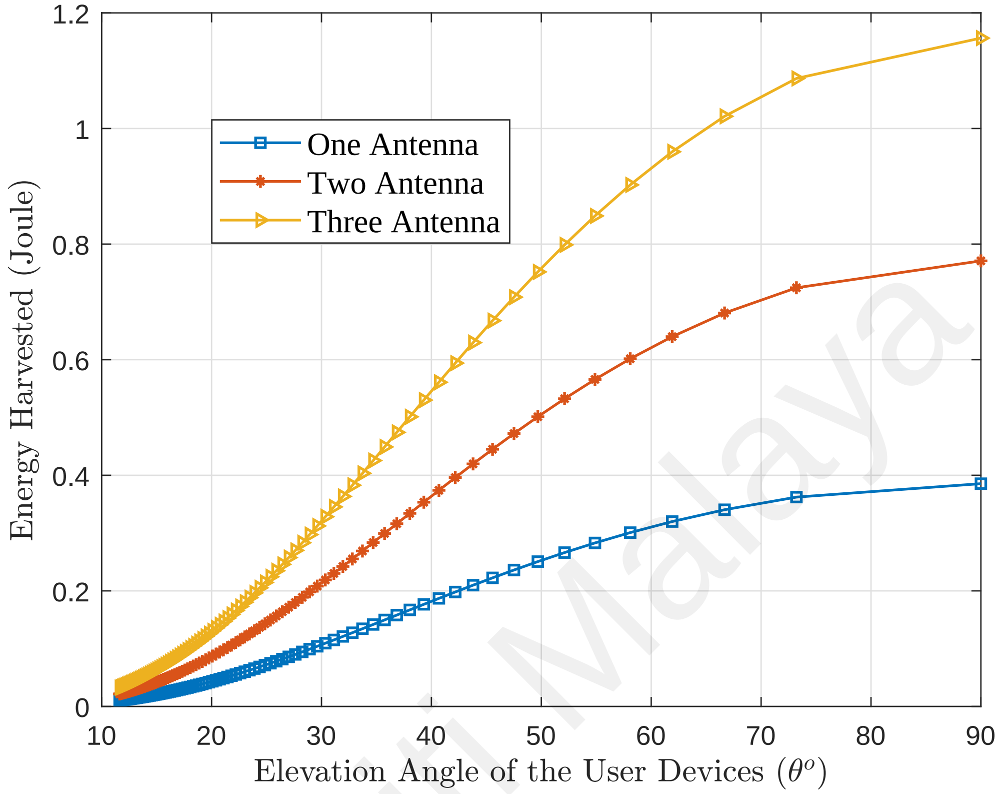

**Figure 4.21: Energy Harvested (joule) versus Elevation Angle with Single-antenna and Multi-antenna UAVs.**

### 4.3.4 Spectral Efficiency Performance

Spectral efficiency (SE) is a dynamic requirement for designing an ECS due to the limitations of spectral resources during emergencies. The SE is improved through multi-hop D2D communication by effectively using the scarce cellular spectrum. As previously mentioned, a UAV is deployed to ensure uninterrupted wireless coverage in the disaster area, while D2D communication increases the coverage area and improves spectral efficiency.

Figure 4.22 shows spectral efficiency performance with various CH densities. The spectral efficiency increases when the number of CHs increases because the optimal reuse of radio resources and densities affects the energy of the network coverage. The wideband channel for the link between the UAV and optimal/non-optimal CHs acts for widely deployed user devices with low-power channel-sounding solutions. In addition to the system model's wideband channel, it helps to increase the system efficiency based on the optimal CH approach that integrates EH and PC in the emergency communication system.

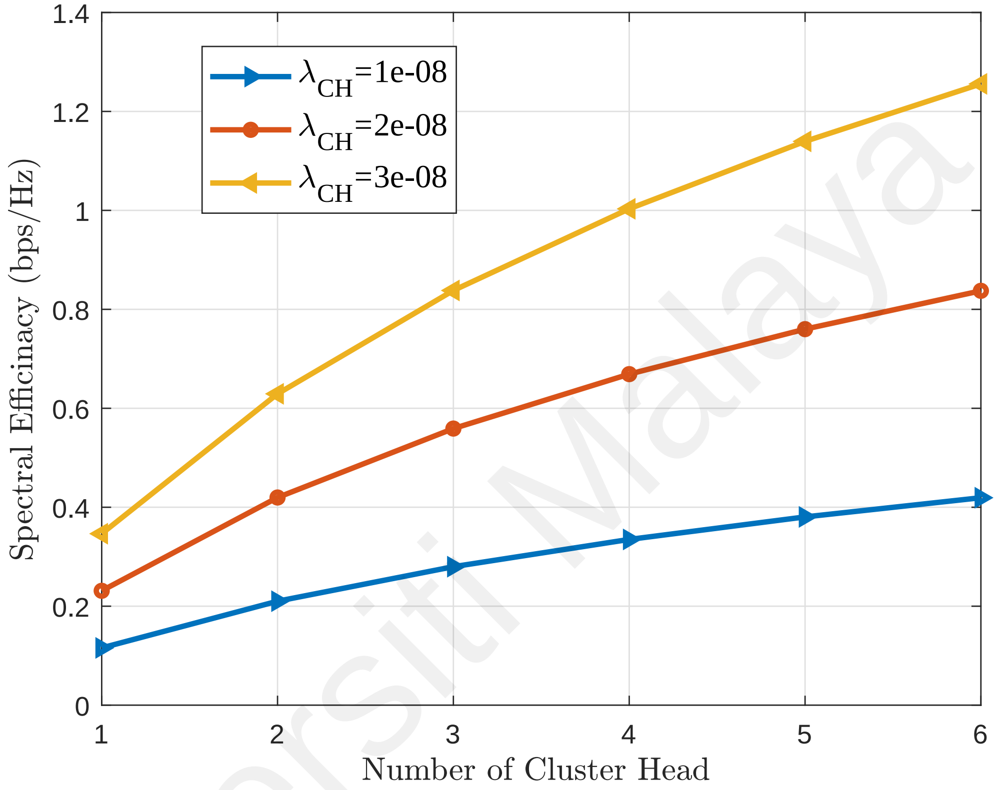

**Figure 4.22: Spectral Efficiency versus the number of CHs with Different Densities.**

It has been further investigated that the higher CH densities will improve the spectral efficiency in the considered network scenario. For instance, when the CHs are increased from 1 to 6 at CH density $\lambda_{CH} = 10^{-8}$, the spectral efficiency increases from 0.1 bps/Hz to 0.4 bps/Hz. Similarly, spectral efficiency improves from 0.2 bps/Hz to 0.8 bps/Hz and from 0.4 bps/Hz to 1.3 bps/Hz at CH densities of $\lambda_{CH} = 2 \times 10^{-8}$ and $\lambda_{CH} = 3 \times 10^{-8}$, respectively. A higher spatial density of CHs can serve more CMs based on the cluster formation and D2D communication pairs to achieve the same level of system spectral efficiency. The clustering technique is applied to reduce the computational complexity, trim the data and expand the connectivity. However, a further increase in the number of clusters may disrupt the performance of the post-disaster communication system due to the transmission power limitation and the distance of the wireless coverage. Figure 4.23 shows EH performance for various transmission time slots with optimal power allocation for two-hop EH systems, i.e., UAV–CHs, and CH–CMs. Based on these results, it is apparent that the LoS in the first-hop communication, i.e., UAV–CHs, is better than that in the second-hop link, i.e., CH–CMs.

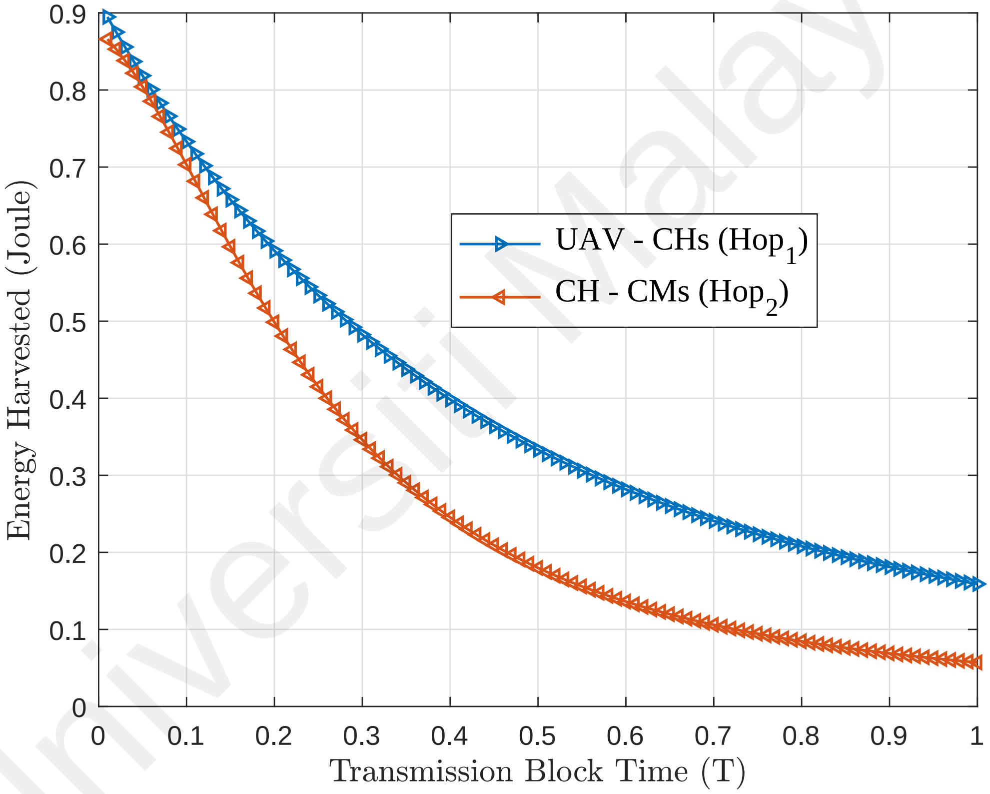

**Figure 4.23: Energy Harvested versus Transmission Block Time in a Two-hop Network.**

Next, the configuration setting the D2D distance to 20 m, 30 m, 40 m, and 50 m apart and measuring the harvested energy versus the energy harvesting efficiency is analyzed. Figure 4.24 shows that the harvested energy decreases as the sparsity distance increases. This is attributed to lower user density as the sparsity distance increases, and there is less D2D link interference. Moreover, when the distance between CH and CMs increases by more than 20 m, the EH performance is stably degraded because of a higher path loss or a lower received SINR when the distance is increased.

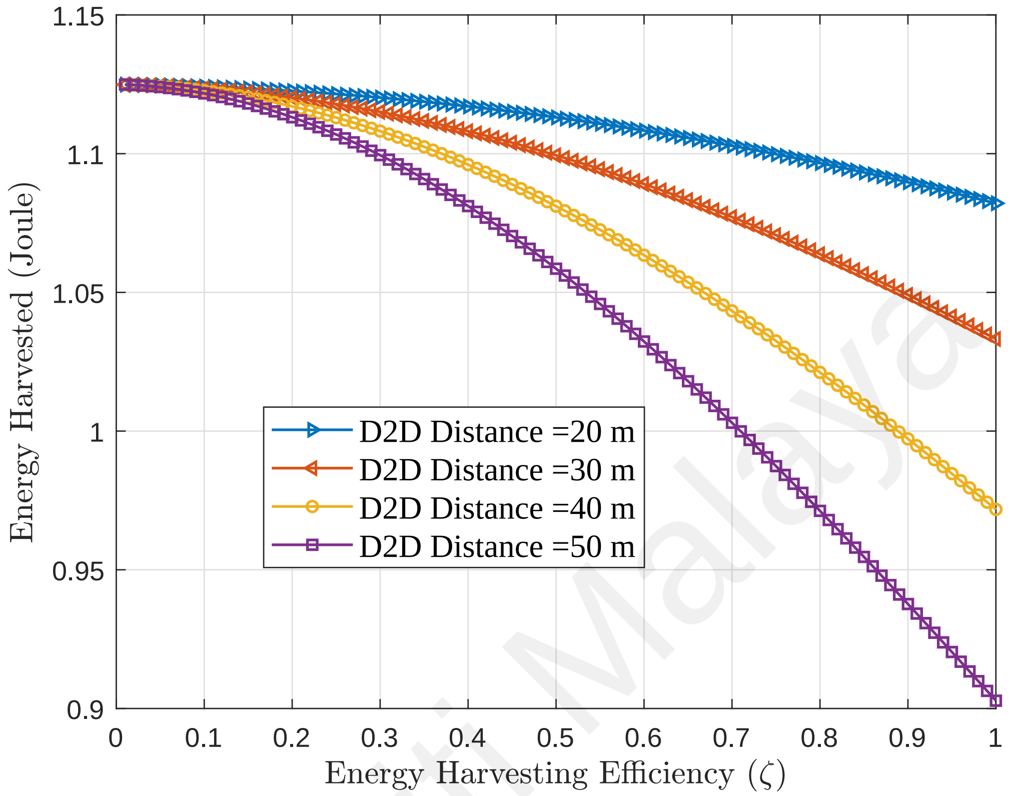

**Figure 4.24: Energy Harvested versus Energy Harvesting Efficiency at Different D2D Distances.**

Figure 4.25 shows an analysis of EH for various user device distances with a clustering and unclustered networks. The clustering network contributes more to increasing EH due to the decentralized control and the low path loss of received signals based on the communication distance. The clustering network decreases harvested energy from 1.8 joules to 0.2 joules when user device distances increase from 100 m to 350 m. However, the unclustered network decreases harvested energy from 0.8 joules to 0.2 joules. Therefore, clustering is an appropriate approach for wireless communication in post-disaster scenarios as it will be able to prolong the network energy lifetime. Furthermore, the EH with the clustered network will be scalable to overcome challenges in disaster events, e.g., limited resources and network capacity.

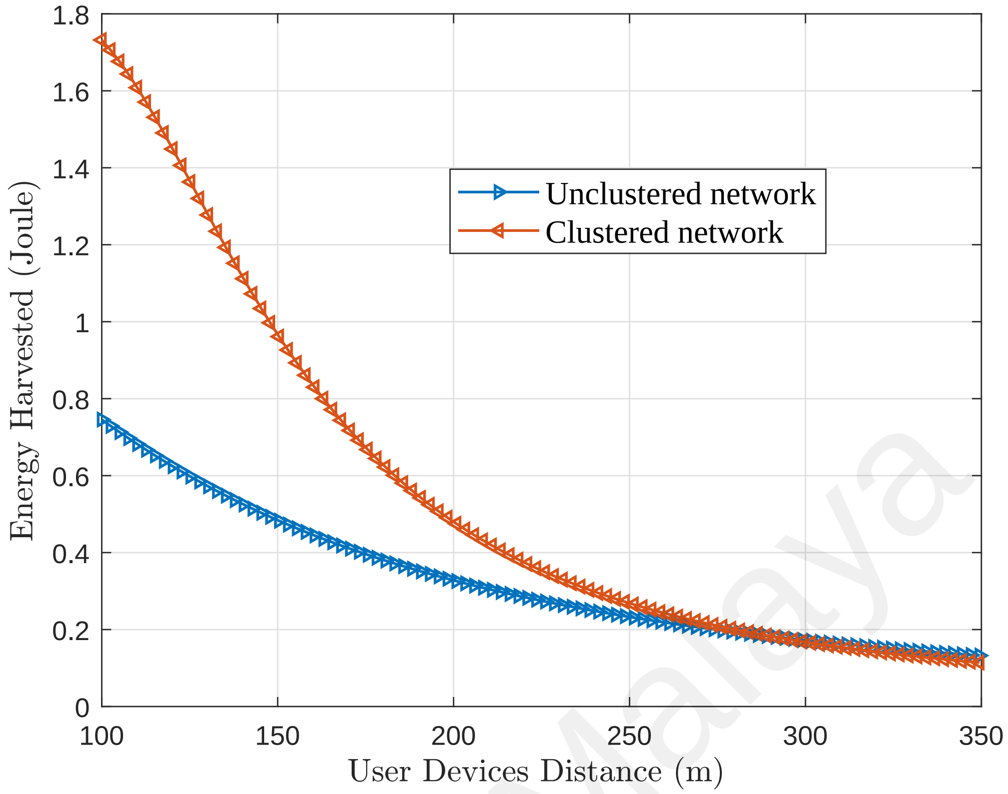

**Figure 4.25: Energy Harvested versus User Device Distance with Clustering and Unclustered Networks.**

Figure 4.26 demonstrates the outage probability of the CH for a different number of clusters. Similar to the findings depicted in Figure 4.26, the optimal CH also achieves a lower outage probability than the nonoptimal CH in both UAV–CHs and CH–CMs links, which will improve the stability of the networks. Another important observation in this figure is that with an optimal CH, communication latency between the CH and CMs is reduced due to the shorter propagation distance; hence, the outage probability is reduced while maintaining the superiority of the optimal CH concerning the nonoptimal CH.

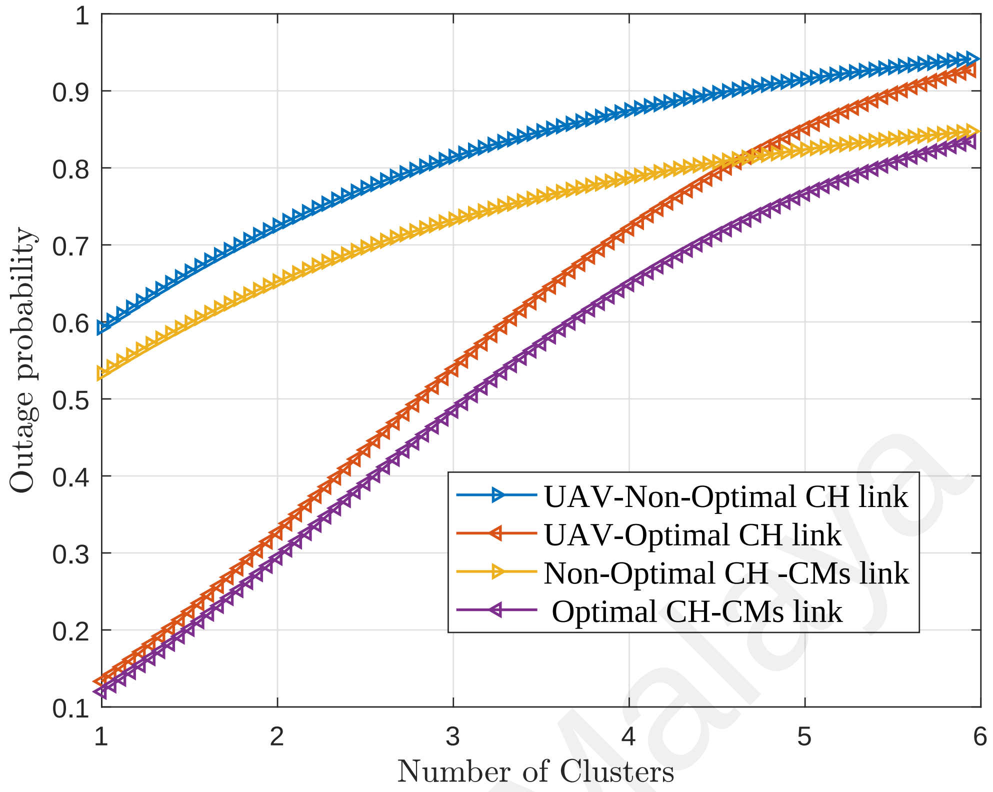

**Figure 4.26: Comparison of Outage Probability of Best CHs Selection Approach Based on the Optimal Location for CHs and CMs.**

Figure 4.27 compares the D2D outage probability of the proposed solution, i.e., the UAV connected to optimal CHs, with the work presented in (Selim et al., 2019). It can be observed that the outage probability of the proposed solution is approximately 10% better than that of the work in Selim et al. (2019). It can be seen that, for example, when the D2D pair communications are 20, the outage probability of the proposed solution is 0.86%, while it is 0.95% in (Selim et al., 2019). This is attributed to the higher channel quality associated with optimal CHs.

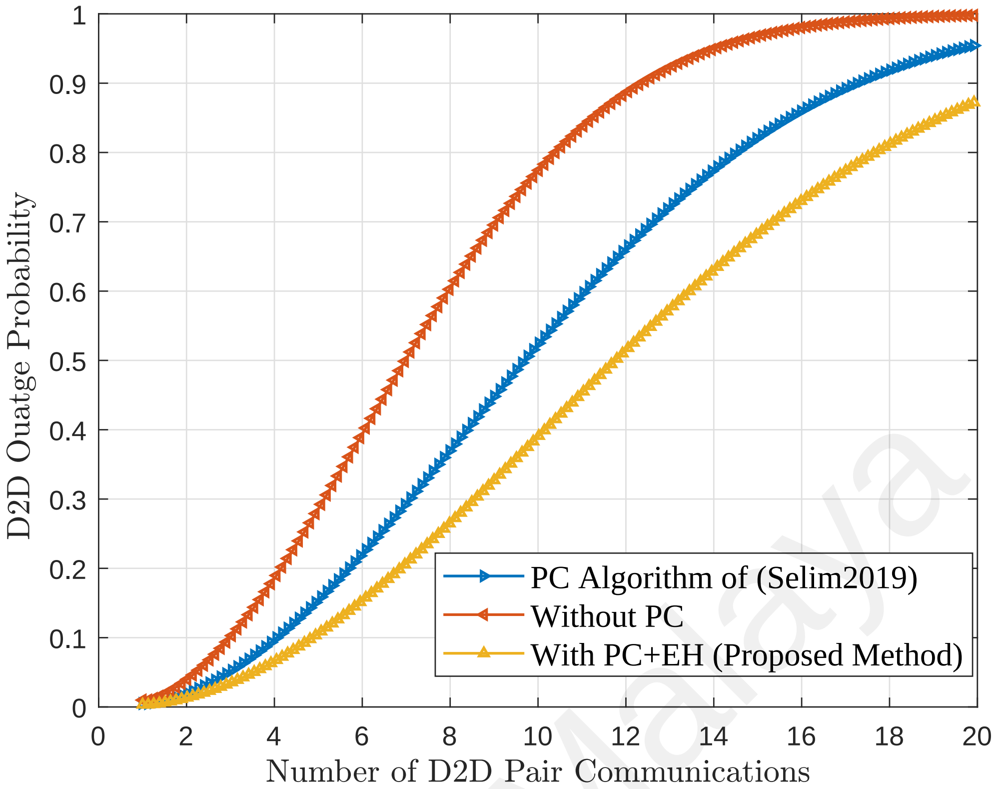

**Figure 4.27: Comparison of D2D Outage Probability versus Number of D2D Pair Communications Based on the PC and EH performance.**

Figure 4.28 shows the performance of the outage capacity versus the number of D2D pair communications. It can be seen that when the number of D2D links is equal to 10, the outage capacity of the proposed solution is 2.5 Mbps, while it is at 0.9 Mbps in Selim et al. (2019), an increase of approximately 90%. This can be credited to eliminating the battery power barriers and interference of UAVs and user devices through a combination of EH and PC. This will guarantee the communication link quality between the optimal CH-CMs as D2D communication pairs.

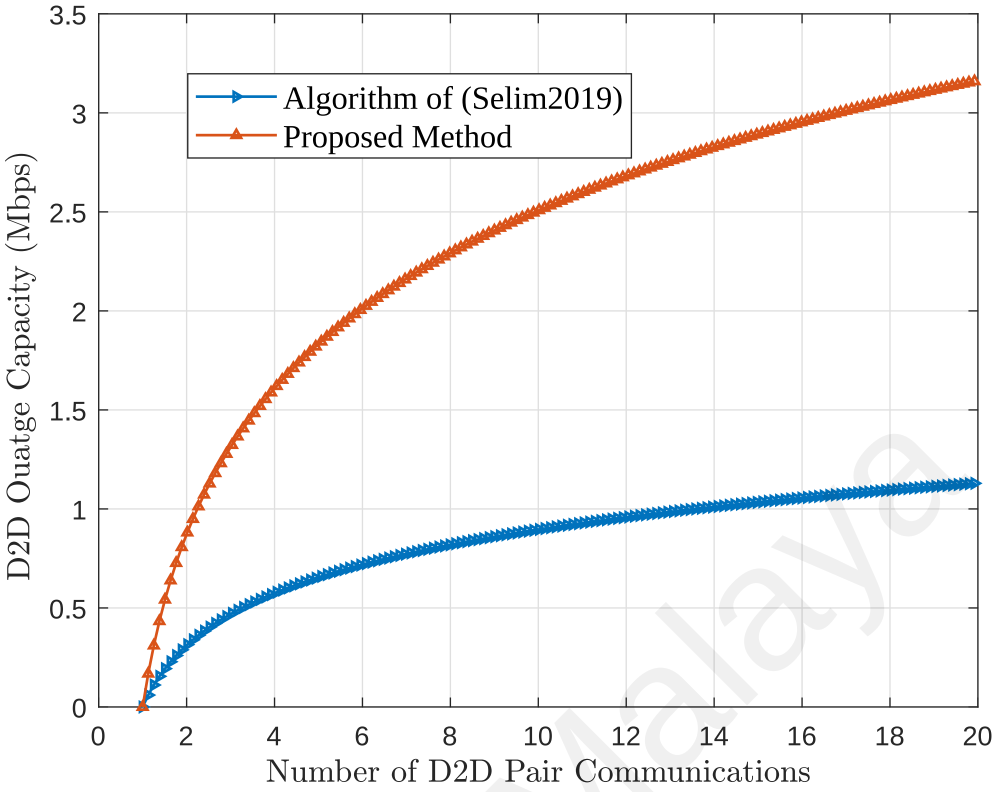

**Figure 4.28: Comparison of D2D Outage Capacity versus Number of D2D pair Communications Based on the PC and EH performance.**

### 4.3.5 Energy Consumption of D2D Communication

This section presents the power consumption and the convergence rate in the proposed power control algorithm. The results have shown that higher convergence might be achieved with lesser power usage while still meeting the SINR threshold. Therefore, the essential priority of D2D communication satisfies the SINR threshold to achieve reliable and sustainable connectivity to improve the quality of the coverage. As a result, in this case, an important consideration is the quantity of power consumption required to meet the SINR threshold. In this regard, the proposed algorithm for power control has proved that energy could be saved in the different values of $0 < \alpha < 1$. Furthermore, the proposed power control method has used less power consumption while communicating with a significantly greater number of D2Ds and met the QoS requirements and the network system's data rate.

Figure 4.29 demonstrates the iteration effect for D2Ds communication. The algorithm has been tested by setting the value of $\alpha = [0, 0.02]$ and the number of D2D $N = 20$. The iteration ranges from 0 to 90, and the average power is $10^{-10}$ (w) to $10^{-7}$ (w). As shown in Figure 4.29, the number of D2D and iteration increases in the case of $\alpha = 0$ and decreases in the case of $\alpha = 0.02$ with an increase in D2D communications. However, D2D increased versus the iteration increased. Hence, for any value of $\alpha$ between $0 < \alpha < 1$, the more iteration decreases, and the more significant number of D2D achieve its maximum value. Therefore, this result has proved the power control algorithm's effectiveness for increasing D2D communication based on the cost coefficient, $\alpha$.

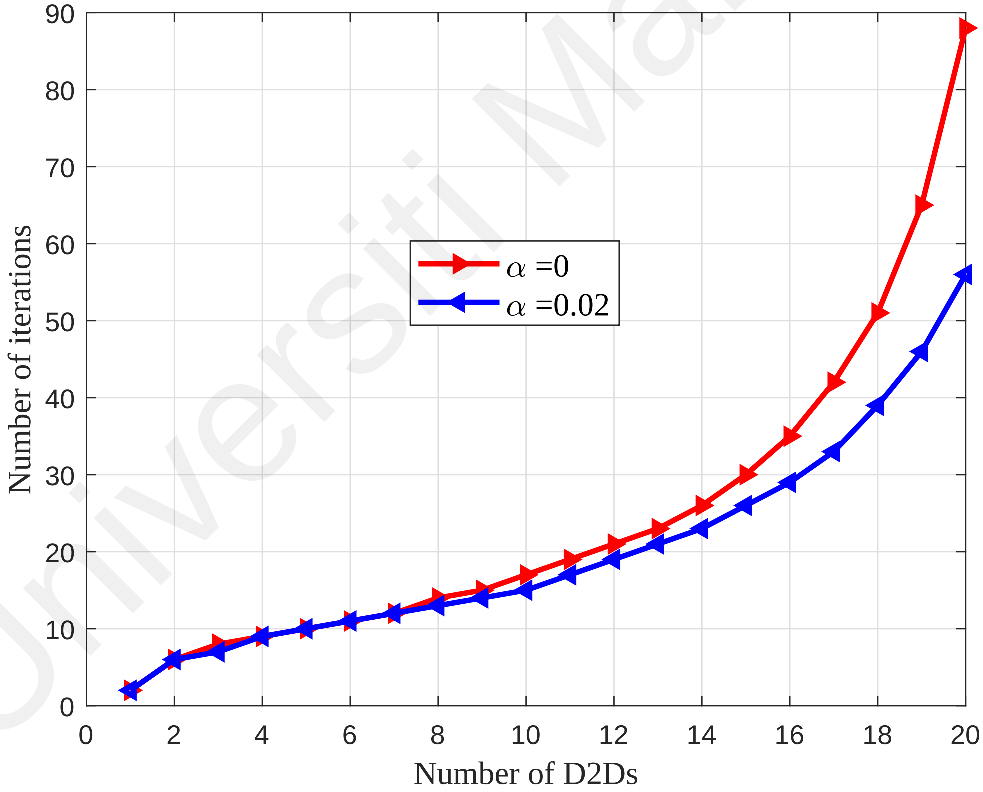

**Figure 4.29: Number of Iterations versus Number of D2D Communication**

Figure 4.30 shows the average power consumption of the proposed power control algorithm and compares it with other related work presented in Yousef Ali (2017) based on user devices' average power consumption and the number of iterations. It was evident from the figure that the proposed algorithm is performing better than other algorithms in average power consumption versus the number of iterations. For example, the proposed power control algorithm's average power increases with the number of iterations from 0 to 0.2 mW. However, the other algorithm's sequences rise from 0 to 0.25, 0.3, 0.37, and 0.25 for the (Yousef, 2017) algorithm, hyperbolic algorithm, norm2 algorithm, and CDPC algorithm, respectively.

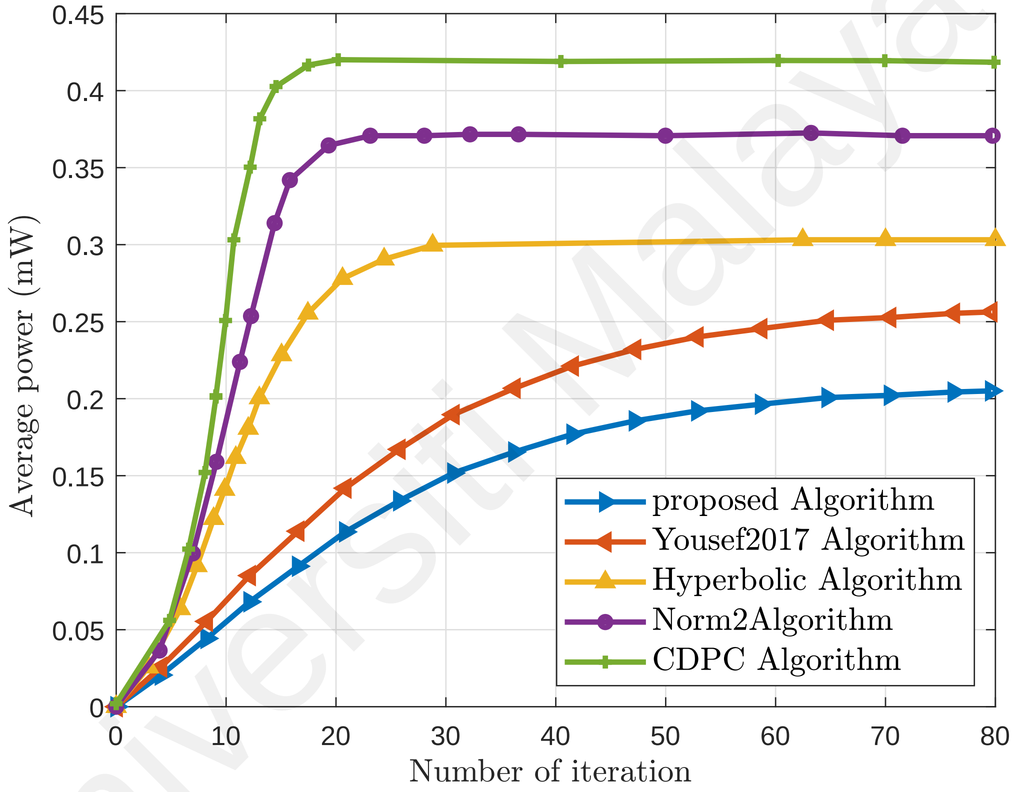

**Figure 4.30: Comparison of Average Power versus Iteration for the Proposed Power Control Algorithms with Related Work**

### 4.3.5.1 Comparison of Average Power and Convergence

For Table (4.1), the proposed approach leads to a slower convergence rate and low power consumption with a high number of iterations. Therefore, this indicates that a trade-off between average power consumption and convergence rate is essential.

**Table 4.1: Comparison Convergence Summary**

| Algorithms | Average power (mW) | Iterations |
|---|---|---|
| CDPC Algorithm | 0.43 | 20 |
| Norm2 Algoritm | 0.37 | 25 |
| Hyperbolic Algorithm | 0.3 | 30 |
| Yousef, 2017 Algorithm | 0.25 | 60 |
| Proposed Algorithm | 0.2 | 62 |

# CHAPTER 5: CONCLUSION AND FUTURE DIRECTION

## 5.1 Conclusion

This chapter will conclude the study by summarizing the significant achievements of the research work concerning the objectives, values, and contribution thereof. It will also review the several exciting research directions in which this work can be extended. Telecommunication infrastructure is regularly destroyed by natural disasters such as earthquakes, hurricanes, tornadoes, and heavy snowstorms. The PSN helps rescue and relief personnel accomplish their tasks more efficiently by coping with the lack of terrestrial communications infrastructure during and after the disaster. The current wireless technologies utilized for public safety coordination are 4G-LTE, WLAN, dedicated PSNs such as TETRA and APCO, LMRS narrow-band technology, and 3GPP-based digital radio communications.

The primary objective of this research is to identify the replacement of damaged terrestrial communications during and post-disaster recovery. This study aimed to investigate the design of an ECS to provide wireless coverage service during disasters for reliable connectivity, eliminate the battery power barriers, and provide a sustainable solution to extend the network's coverage. An ECS refers to communication services during an emergency when the cellular network is damaged, linking the SAR teams inside the disaster area with SAR teams outside the disaster area for information exchange and smooth search and rescue operations. Moreover, the ECS is an alternative system with robust, fast, effective communication between EFR and trapped victims during public safety operations.

UAVs that act as data relays have a lot of potential for supplying on-demand connections, providing public safety services, and assisting in the recovery of communication infrastructure that natural disasters have damaged. UAVs may be the most efficient option for temporarily substituting and replacing damaged terrestrial assets in disaster management operations, particularly for disaster preparedness and recovery. The energy harvesting techniques were investigated to prolong the energy network lifetime and achieve better outage probability and efficiency for sustainable operations during disasters. EH offers an appealing solution to overcome the battery power limitations of UAVs and user devices, as well as a long-term solution to extend the network's lifetime. An optimal CH algorithm was introduced and utilized to harvest energy for stable networks that enhanced the network coverage, minimizing outage probability and energy consumption. The result indicates that the ECS scenario increased the UAV coverage area with lower energy consumption by clustering and D2D communication based on the proposed optimal CH. Compared to previous studies, the computational complexity and convergence rate have all been lowered. Further findings show that the EH of the optimal CH links was better than that of the nonoptimal CH links, leading to a better outage probability for optimal links. The performance of the outage capacity versus the number of D2D pair communications can be credited to eliminating the battery power barriers and interference of UAVs and user devices through a combination of EH and PC. D2D offloading reduces the load by asking mobile nodes to download content directly from the storage of neighbouring helpers via short-range links. In addition, D2D communication integration has primarily emerged to offload rising data traffic and improve ECS energy efficiency. This will guarantee the communication link quality between the optimal CH and CMs as D2D communication pairs. The power control was applied to the optimal CH nodes to eliminate interference to save power consumption. Therefore, the power control algorithms increase the convergence rate achieved with lesser power usage while still meeting the SINR threshold to meet the quality of service requirements and the network system's data rate. The achievement in the study is that the proposed solution has a 10% lower outage probability than that in previous work. For example, when the number of D2D pair communications is 20, the proposed approach has an outage probability of 0.86%, but similar work has an outage probability of 0.95%. Meanwhile, when the number of D2D links is equal to 10, the outage capacity of the proposed solution is 2.5 Mbps, while it is at 0.9 Mbps in previous work. This can be attributed to using a combination of EH and PC to eliminate battery power barriers and user device interference. The CH considers the relay function to forward the coverage services into destination nodes in a poor coverage area. It was also proven that the EH of the communication with optimal CH was better than that of the communication with nonoptimal CH, leading to a better outage probability for optimal links. Therefore, the value of the study based on EH offers an attractive solution to satisfy the energy requirements for the ECS-PSN due to its capability to prolong the network lifetime and hence keep the network running during disasters.

The power control strategies are viable to enhance wireless network throughput performance by reducing D2D communication consumption power and eliminating interference with other user devices. In the D2D power control, each device can independently select and transmit its ability to maximize (or minimize) the utility function to establish connectivity with network resources and reduce the interference between the UAV links and D2D links. The proposed algorithms of this study solve the problem, as compared to the recent literature, by power consumption and convergence rate are able to minimize outage probability, with low computational complexity.

The following points summarize the overall findings of this study:

- The optimal CH algorithm is able to minimize the outage probability for the edge UAV coverage. The results confirmed that UAV links to the optimal nodes perform better than the UAV link to non-optimal nodes.

- The outage capacity results of D2D outage probability and D2D outage capacity for the proposed method are better than the related work.
- The computational complexity of the proposed algorithms has been determined based on the iteration loop applying to all user device nodes in the disaster region.

## 5.2 Future Direction

Future research can be carried out in several directions to improve the management of emergency response processes, especially in the face of increasing demand uncertainty and resource shortage.

### 5.2.1 Autonomous ECS (A-ECS)

Based on the thesis objectives, the scope of future research directions is to develop the design of an autonomous ECS (A-ECS) based on AI/Machine learning (ML), reinforcement learning (RL), and deep learning (DL) techniques solutions. An A-ECS has yet to be realized entirely in current networking architecture techniques for UAV sensing for environmental monitoring, a Design of a Scheduling System of UAVs, routing, spectrum sharing, path planning, and resource allocation have been used to solve this problem. The design of an A-ECS is based on multi/single-UAVs with an AI framework and ML/DL in auto-detection of RF signals of victims that assist the SAR teams for fast discovery and smooth evacuation in search and rescue operations tasks. In this context, the A-ESC framework integrates with a UAV GPS antenna to locate the areas with more injured persons and guides the SAR teams to the location of victims. Therefore, the A-ECS can sense the RF signals that refer to available victims.

### 5.2.2 Tethered (TUAV) for ECS

The other direction is a collaboration between a tethered (TUAV) used in a disaster for stable energy connectivity with an Untethered UAV (UTUAV) that has the mobility to provide wireless coverage to victims. Therefore, controlling the TUAV/UTUAV flight to realize a good service is a challenging direction. In addition, when multiple UTUAVs collaborate, collision avoidance also becomes a significant development for UTUAV safe operation. On the other hand, the channel communication of sources TUAV to destinations UTUAV models are considered to lack detailed propagation connectivity and are still in their infancy.

### 5.2.3 EH for Un-tethered (TUAV)

It remains a topic for future research based on battery designs that are limited in energy optimization trends. As a first step toward resolving this problem, energy-efficient networking to expand mission time and coverage area and leverage radio frequency (RF) transmission for wireless power transfer (WPT) must be built. Therefore, the open research problem is designing an efficient trajectory with minimal energy consumption to meet UTUAV computing tasks and efficient connectivity applications for link failures and network energy lifetime. In the multi-UTUAV communication collaboration scenario, energy constraints are the bottleneck. Furthermore, the design of an ECS is based on the TUAV and UTUAV for stable continuous network energy and prolonging energy lifetime. In this scenario, the TUAV is connected to the fixed ground recharge power supply and able to power the UTUAV through RF-EH to increase the capacity of UTUAV batteries. The optimal location of the TUAV considers the TUAV head of the cluster and the other UTUAV-m as members of the same cluster. A multipath clustering approach for the channel model between the TUAV and UTUAV will be further investigated to increase communication reliability in post-disaster scenarios. An ECS connectivity with TUAV and UTUAV models can increase the scale-able of coverage area in disaster situations. Energy harvesting is utilized to prolong flight periods by employing green energy sources, thanks to recent advancements in battery technology such as upgraded lithium-ion batteries and hydrogen fuel cells (such as solar energy). Due to longer distances and random energy arrivals, however, energy harvesting efficiency is comparatively lower. Thus, new energy-delivery methods, such as energy beamforming using multiantenna approaches and distributed multi-point WPT, are attracting a lot of attention to improve charging efficiency. A lack of spectrum availability can cause the loss of command and control of the collaboration of UTUAVs. In a separate line of research, some models propose using fibre-optic communications, lasers, and LiFi to provide a faster and more efficient way of transferring massive volumes of data over great distances to meet the growing need for bandwidth. These techniques would help to solve the spectrum scarcity problem. The framework of AI-based spectrum sharing and leasing systems is able to increase the spectrum efficiency and date rate through a connected TUAV through the fixed point of fibre optic link and UTUAV receive the coverage service through wireless optical communication. Therefore, in TUAV/UTUAV networks, enabling high-rate, low-latency, and ultra-reliable wireless communications is necessary for future applications such as AtA and AtG channel communications within various communication protocols, including Wi-Fi, LTE, LoRA, and 5G.

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