Trajectory and Power Optimization for Buffer-Assisted Amplify-and-Forward Unmanned Aerial Vehicle Relay

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CERTIFICATE

It is certified that the work contained in this thesis titled "Trajectory and Power Optimization for Buffer-Assisted Amplify-and-Forward Unmanned Aerial Vehicle Relay" by Naga Manoj Makkena has been carried out under my supervision and is not submitted elsewhere for a degree.

Date

Advisor: Dr. P. Ubaidulla

To

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”If you go too deep, it will result in nothing”

Abstract

This paper proposes a buffer-assisted amplify-and-forward (AF) unmanned aerial vehicle (UAV) relay for communication between two ground nodes without a direct link. These communications are essential in disaster rescue areas where fairness plays a significant role. To achieve fairness, we aim to maximize the minimum information rate.

The traditional way of prefixed scheduling the time slots to transfer and receive at the UAV do not guarantee that the communication system uses high signal-to-noise ratio (SNR) communication links instead of low SNR links. Therefore, we choose to employ a buffer at the UAV to store the information and transfer it to the destination nodes in the high SNR links. The pairing of time slots is necessary here since we are using a buffer, and we do not know in which time slot data is transmitted to the destination node after it is received at the UAV. Consequently, we formulate a fairness maximization problem by jointly optimizing the trajectory and power control. Unfortunately, this formulation results in a non-convex problem. We propose a solution based on the principles of the minorize-maximize (MM) algorithm and linear programming relaxation techniques to solve the fairness problem and pairing of time slots.

Numerical results demonstrate that the trajectory, power control and paired slots favor the UAV and ground nodes to communicate in the high SNR channel links, thus maintaining fairness.

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List of Abbreviations

ACS	Airborne Communication Systems.
AF	Amplify-and-Forward.
BAF	Buffer-Assisted Amplify-and-Forward.
CN	Complex Normal.
D	Destination.
DF	Decode and amplify.
FDMA	Frequency division multiple access.
GDE	Gaussian-distributed error.
HAP	High Altitude Platforms.
IP	Integer Programming.
LAP	Low Altitude Platforms.
LoS	Line of Sight.
LP	Linear Programming.
LTE	Long-term evolution.
MM	Minorize-maximization.
PSC	Public Safety Communications.
S	Source.
SNR	Signal to noise ration.
UAV	Unmanned Aerial Vehicle.

List of Symbols

$x[i], y[i]$	x and y coordinates of location of the UAV relay.
D_{max}	Maximum distance between the two consecutive time slots of UAV relay.
X_s	Transmit signal at source.
y_u	Received signal at UAV relay.
h_{su}, h_{ud}	Channel gains from source to UAV relay and UAV to destination node respectively.
d_{su}, d_{ud}	Distance between source to UAV relay and UAV to destination node respectively.
$\mathbf{W}_1, \mathbf{W}_2$	Additive White Guassain Noise at relay node and destination node respectively.
$\mathbf{N}_1, \mathbf{N}_2$	Noise power at relay node and destination node respectively.
β_o	Reference channel coefficient.
$sp[i][j]$	Time slot pairing varibale between the UAV and the ground nodes.
$\alpha[i][j]$	The amplication factor for the data packet received at i^{th} index and transferred at j^{th} index at the UAV.
$SNR[i][j]$	Signal ratio noise for the data packet received at the i^{th} and transferred at the j^{th} time slot from the UAV.
$R[i][j]$	Information rate for the data packet received at the i^{th} and transferred at the j^{th} time slot from the UAV.
E_s	Average Transmit power at the Source.
E_u	Average Transmit power at the UAV relay.
P_s	Source power budget.
P_u	Relay node power budget.
V_{max}	Maximum velocity of the UAV relay.
f_c	Carrier frequency.
B	Bandwidth.
T	Time of flight.
N	Number of sub-time slots.

List of Notations

b	A scalar.
$\mathbf{b}$	A vector.
$\mathbf{B}$	A matrix.
$\mathcal{CN}\left(\boldsymbol{\mu}, \mathbf{C}\right)$	Circularly symmetric complex Gaussian vector with mean vector $\boldsymbol{\mu}$ and covariance matrix $\mathbf{C}$.
$f(\theta)$	A function with variable θ .

Chapter *1*

Introduction

This chapter introduces the study subject and numerous applications of the combined trajectory and power control optimization, time slot pairing, the MM algorithm, amplify and forward buffer assisted relay, and the scope of the thesis.

In recent years, there has been a rise in demand for aerial communication systems in both military and civil applications. Airborne communication systems (ACS) make it possible to both save people and communicate with them while they are trapped in dangerous locations [1], [2]. These communication systems have the appropriate hardware and software to accomplish their mission. There are two distinct types of ACS, known as high altitude platforms (HAP) and low altitude platforms (LAP), which are distinguished by the height at which they are operated [3]. HAP examples include airships and balloons, while LAP examples include low-altitude unmanned aerial vehicles (UAVs). When designing a UAV communication system, we need to consider several factors. These factors include whether the system will support a single or multiple UAVs, the payload that is associated with the UAV, the amount of latency that will be accepted in the communication system, and the data requirements of the communication system [4], [5]. Situations such as surveillance, navigation, and rescue operations often make use of many UAVs, which helps to make the communication system more effective [6], [7]. UAVs are put to use in the process of delivering the packages. Using techniques like machine learning and artificial intelligence, computer equipment equipped with UAVs can investigate the level of violence in public areas. In addition, UAVs can monitor forests, establish aerial base stations, and advance modern agriculture. As an aerial base station, a UAV can be used as a relay node to provide communication between the ground nodes, or it can be used as a data center to collect information from the ground sensor node and transfer it to the application's end user. Both uses require the UAV to collect data from the ground sensor node. UAV capability can be expressed and employed in various ways, depending on the application [8], [9].

In this research, we attempt to ensure fairness when a UAV functions as a relay node between two ground nodes in situations where direct connection is impossible owing to a severe blockage or a degraded terrestrial network [10], [11]. Achieving the desired level of fairness requires optimizing the minimum information rate. If we successfully maximize the information rate at the minimal level, we can maximize the information rate at the highest level. We restrict our discussion to only apply to times of emergency, where maintaining fairness is necessary to guarantee that information passed between nodes is entirely error-free. Communication in real-time has emerged as an important goal, not only for wired but also for wireless networks [12], [13], [14]. It is possible for communication systems that rely on infrastructure to collapse as a result of the damage caused by natural disasters and other catastrophic occurrences. There have been times throughout history when natural disasters have occurred. As a result, all connection between public safety officials and members of the general public has been completely severed. This occurs due to the damages inflicted upon the physical infrastructure of the communication system. The destruction of these communication systems will make it impossible for the rescue mission to be successful. In these predicaments, sending in the military to help with search and rescue efforts is one of the potential solutions. However, the number of individuals who may be rescued is restricted, and the process is slow because the military must investigate all available options to find a means to save the people. One can create a communication system that, in addition to providing a strong, easy-to-deploy, and dependable UAV network, is also capable of meeting the requirements of the current scenario. It is possible to accomplish maximum coverage of the affected region using either a single or many UAV systems. These systems can also be utilized to offer surveillance of the affected area and serve other objectives. The ease with which this system can be implemented is one of its many strengths. The system is responsible for controlling the location of the UAVs as well as the reconfiguration of the UAVs if a UAV is either added or withdrawn [6].

Natural calamities such as hurricanes, floods, and earthquakes often strike in many regions of the world. They can cause irreparable devastation to the lives of the people living there. Disruption of ground communication infrastructure and other connecting infrastructure, such as significant interruptions in communication due to power facilities, makes it extremely difficult to carry out rescue operations and creates additional obstacles [8], [15]. Restoring the communication system in this scenario is necessary in order to assist the rapid sharing of information between victims and rescuers on the circumstances, events, and severity of the situation that is now taking place. Public safety communication (PSC), another name for emergency communication, tackles these problems in natural or man-made calamities. This decade, personal communication technology has advanced from 3G to 4G to 5G. The technology used for emergency communication has not kept up with the times. Until very recently, private and professional mobile radios and land mobile radios were the primary means by which emergency communications were carried out. Narrow-band communication systems can provide extensive features centered on voice communication, such as push-to-talk and call priority; however, their data transmission capacity and interoperability could be much better. Broadband wireless technologies have been deployed in the field of emergency communications in order to transmit and receive various forms of data, including audio and video. The international standardization organization known as 3GPP has created 4G LTE for use in emergency communications. 5G may meet the requirements of current emergency communications for dependability and resilience. In a crisis, having access to emergency communication channels is necessary for carrying out rescue operations. When there is an emergency, maintaining open lines of communication between members of the public and first responders is critical to ensuring the public's safety. The employment of UAVs is becoming increasingly common in real-time evacuation planning. For example, these vehicles can direct people to exit burning buildings. They can also serve as mobile base stations, enabling them to offer cellular connectivity.

As a mobile relay system, UAVs have the potential to provide communication between the necessary source and destination nodes. A base station that acts as a transceiver between the ground nodes assists the UAV. When describing the application functionality a UAV is likely to attain, the height, trajectory, power capacity, size, and other elements play a significant role. There are a variety of uses for UAVs, which can be maximized through trajectory and power control optimization.

The joint trajectory and power optimization technique is used in various applications described in this paragraph. In reference [16], the likelihood of an outage occurring in the UAV relay network is reduced. In reference [17], a collaboration scheme is suggested to extend the time the UAV relay communication may be maintained. Increasing data use demands have led to the proposal of a combined cache placement mechanism in citation [18]. This is done in order to limit the amount of traffic offload. UAVs' energy efficiency is considered in [19]. Optimizing both the trajectory and the power control is possible by employing a series of convex optimization algorithms in successive order [20]. However, it is crucial for those working in disaster rescue regions always to maintain communication.

The decode-and-forward (DF) and amplify-and-forward (AF) relaying protocols are widely used in relay communications [21]. Real-time communication is impossible with DF since the data are encoded in the next time slot after being decoded in the current time slot. In this study, we make use of the AF method, which is a technique that instantly amplifies and transmits the signal coming from the relay. Static and mobile communication strategies are the two sorts of methods that can be used to communicate with a UAV.

Regardless of the signal-to-noise ratio (SNR) of the communication link, information received at the UAV and then sent to the destination during real-time communication is done so during the next time slot. In that case, we risk losing vital information that may be required during an emergency. In order to prevent scenarios like these, we plan to install a buffer at the UAV relay. We can apply adaptive link selection by utilizing a buffer at the UAV relay. This allows us to send the data to the destination node during periods in which the SNR is higher than in any of the other time slots [5]. Now, the data can be saved at the UAV relay and transmitted in a later time slot, one in which the SNR is either greater than or equal to that of the immediate next time slot. In order to compute the information rate, we need to couple the time slots that correspond to the transmission of the same data packet from the source to the UAV and from the UAV to the destination. Individual SNRs are considered when computing the rate (SNR of the source to UAV link and SNR of UAV to destination link). The addition of a buffer to the UAV, on the other hand, will cause a delay in the communication network. As a result, to make the network more tolerant of delays, we have designed the buffer's capacity to correspond to the requirements of the network. The following parts will talk about how different time slots couple up with one another.

A UAV-assisted buffer increases the total throughput in [22] to its maximum potential. Time slot allocation is performed between the source and UAV link and the UAV and destination link in [22]. The flight time is split across the two links discussed earlier. If the same data packet is received at the destination in a low SNR connection while it was received at the UAV relay in a high SNR link, then there is a possibility that there is an error in the message sent from the source. Because of this, the quality of the communication that occurs between the nodes may suffer. To ensure everyone receives the same amount of information, we should optimize the minimum information rate rather than the total throughput. In an emergency, we present an algorithm to fulfill these needs. This algorithm considers a buffer-assisted UAV that uses the amplify-and-forward mobile relaying protocol to establish communication links in times of emergency when the links already in place fail. In order to accomplish fairness, it is necessary to solve for the ideal trajectory, power control, and matched time slots. The problem involving fairness needs to be more convex.

In our research, we first use the Minorize-Maximize (MM) algorithm to solve the non-convex function to obtain the optimum trajectory and power control values and the individual rates at various time slots [23]. Next, we use the linear programming relaxation method to obtain paired time slots to maximize the minimum information rate using the data rates we have obtained and the buffer space available on the UAV [24]. This is done so that we can maximize the minimum possible information rate. The information rate is the sum of the rates at which data is transmitted from the source to the UAV and from the UAV to the destination. In the following chapters, we will go into detail regarding the employment of the buffer and the pairing of the time slots.

1.1 Problem overview

One of the significant challenges faced by emergency communication systems is fairness. Fairness can be described as maximizing the minimum information rate of all available communication links. In this way if we transfer the information error-free since every communication link has efficient throughput for communicating data. We use the UAV as a relay in the system defined in the paper. To ensure the entire communication is effective, we must transfer information from source to UAV and to destination in a better time slot where the SNR link capacity is high instead of pre-fixed time slots. We need to pair the time slots where the data packet can be transferred from the source to UAV and destination so that the entire communication from source to destination via the relay is effective and error-free.

1.2 Contributions

Major contribution of thesis is proposing Buffer-Assisted Amplify-and-Forward UAV algorithm for jointly optimizing trajectory and power control. These can be summarized as follows:

(i) At first, we jointly optimize the trajectory and power control of the UAV relay by solving the non-convex optimization function using successive convex optimization algorithms. A minorization-maximization (MM) technique is employed to solve the non-convex function iteratively to obtain an optimal trajectory and power control solution. Now with obtained data for the trajectory and power budget of the UAV, we calculate the data rates from source to UAV and UAV to destination for different timeslots.

(ii) Now, with the obtained data rates, we employ a linear relaxation programming technique to pair the time slots by which the combined data rates from source to destination via UAV are maximized. Hence the communication system is viewed as a communication link from source to destination. We are maximizing the minimum information rate of the system by pairing the time slots in which the data rates from source to UAV and UAV to destination are higher.

(iii) The buffer capacity at the UAV plays a vital role in this optimization. Hence with the change in the buffer capacity, the efficiency of the communication system changes.

The performance of the proposed algorithm is demonstrated with results obtained from the MATLAB simulations. The obtained results are compared with the benchmark algorithm to validate the algorithm's efficiency in solving the problem.

1.3 Organization of the thesis

The rest of the thesis is organized as follows.

- *Chapter 2* gives a brief overview of Unmanned Aerial Communications technology and its applications in modern-day technology.
- *Chapter 3* presents the trajectory and power optimization for buffer-assisted amplify-and-forward UAV relay.
- *Chapter 4* presents the conclusion and future scope of the thesis.

Chapter *2*

Literature Survey

2.1 Introduction

This chapter discusses the history of wireless communications, increased demands of wireless connectivity, and the evolution of UAV communications, particularly the concepts related to UAV as a relay and joint power and trajectory optimization of UAV.

2.2 History of wireless communications

Wireless communications is the area of the communications industry experiencing the most rapid expansion by any metric. As a direct result, it has piqued the curiosity of the media and general curiosity. Over the last decade, there has been an exponential increase in the number of people subscribing to cellular services; at the moment, there are approximately two billion users across the globe. Mobile phones have become an essential tool for conducting business and an integral component of daily life in most wealthy nations. Furthermore, mobile phones are rapidly replacing antiquated landline networks in many developing nations. In addition, wired networks are being phased out in favor of wireless local area networks (LANs) in many private homes, commercial establishments, and academic campuses. Numerous innovative applications, including wireless sensor networks, automated highways and factories, smart homes and appliances, and remote telemedicine, are transitioning from the conceptual research stage into the implementation phase of system development

The advancements in the wireless communication is presented well in [25], [26], [27], [28], [29], [30] and [31], which are discussed in the following few paragraphs. The very first wireless networks were established in a period before the industrial revolution. Using smoke signals, torches, flashing mirrors, signal flares, and semaphore flags, these communication methods could transmit information over line-of-sight distances, which were later extended using telescopes. An intricate system of signal combinations was developed in order to enable the transmission of complex information using these simple signals. Observation stations were built on hilltops and along motorways to transmit these messages over wide distances. The telegraph network was invented in 1838 by Samuel Morse, and subsequently, the telephone came after these early communication networks became the dominant form of communication. In 1895, just a few decades after the development of the telephone, Marconi successfully demonstrated the first radio transmission by sending a signal from the Isle of Wight to a tugboat located 18 miles distant. This marked the beginning of radio communications. The University of Hawaii 1971 established ALOHANET, the world's first packet radio-based network. This network enabled radio communication between a central computer on Oahu and computer facilities in seven institutions spread out across four different islands. The network architecture was based on a star topology, and the central computer served as the network's hub. The combination of packet data and broadcast radio inherent to ALOHANET aroused the interest of the military of the United States of America. The Defense Advanced Research Projects Agency (DARPA) spent significant money on developing networks using packet radios for tactical communications on the battlefield throughout the 1970s and into the early 1980s. These networks were intended to be used on the battlefield.

In addition to providing wireless data services over long distances, packet radio networks have also found commercial applications in providing wireless data services over vast areas. These services, which were established in the early 1990s, make it possible to access data wirelessly (such as email, file transfer, and web browsing) at roughly 20 kilobits per second (Kbps). These wide-area wireless communication services could never capture a significant portion of the market since they had slow data transfer rates, were expensive, and did not have any ”killer applications.” These services were mainly rendered obsolete by the advent of wireless data capabilities in cellular cellphones and wireless LANs in the 1990s. In the 1970s, the introduction of technology known as wired Ethernet prompted many companies to discontinue their use of radio-based networking.

The Federal Communications Commission (FCC) granted permission in 1985 for the general public to use the frequency bands designated for use in industrial, scientific, and medical (ISM) applications, making it possible for businesses to begin developing wireless LANs. Wireless LAN suppliers were drawn to the ISM band because they did not need a license from the FCC to operate in this band. In addition, there was a considerable amount of interference from the primary users operating inside this frequency band. Consequently, the functionality of the first generation of wireless LANs regarding data rates and coverage needed to be improved.

The most recent iteration of wireless LANs uses the IEEE 802.11 standard family as its foundation. The performance difference between wired and wireless LANs is expected to worsen over time unless there is an increase in the spectrum allocation. Wired Ethernets already deliver data rates of 100 Mbps. Thus, this performance gap is already rather large. Despite significant differences in data rate, wireless LANs are rapidly becoming the dominant Internet connection in many families, companies, and university settings. On the other hand, the vast majority of wireless LANs support bandwidth-light services such as web browsing and email.

The mobile phone system has been the wireless networking application that has seen the most significant success. This technology can trace back to 1915 when the first wireless speech transmission was between New York City and San Francisco. In 1946, public mobile telephone service was made available in 25 cities across the United States; thirty years later, the New York system could only accommodate 543 customers. In 1946, public mobile telephone service was available in 25 cities across the United States. AT&T Bell Laboratories researchers came up with the cellular concept in the 1950s and 1960s as a response to the capacity problem that the company was facing. In 1947, ATT submitted a request to the FCC for spectrum to provide cellular service. The majority of the design was completed by the time the 1960s came to a close, the first test in the field took place in 1978, and the FCC granted authorization for service in 1982.

The concept of wireless communications facilitating the transmission of information between people or machines is the communications frontier of the coming decades, and the majority of it already exists in some form. This idea has been around for quite some time. This idea will enable multimedia communication from anywhere on the planet, employing a portable electronic gadget or a laptop computer. Wireless networks enable handheld, laptop, and desktop computers to communicate with one another from any position within an office building or on campus. This includes the local corner cafe. These networks will not only enable communication between computers, phones, and security/monitoring systems but also enable a new class of intelligent electronic devices in the home that can communicate with each other and the Internet. The elderly and people with disabilities can also receive an assisted living, patient monitoring, and emergency response from these innovative residences equipped with the latest technology. In the not-too-distant future, wireless entertainment will be available everywhere, including in private homes and public places. Travelers, such as the salesperson who just missed his airline connection or the CEO who is sailing through the Caribbean, will be able to join in the video teleconferences that will take place between the various buildings, regardless of how many blocks or continents divide them. Remote classrooms, remote training facilities, and distant hospitals will all be possible thanks to wireless video on a global scale.

The applications of wireless sensors in both commercial and military settings are pretty varied. Monitoring potential fire hazards, hazardous waste sites, stress and strain in buildings and bridges, the migration of carbon dioxide, and the spread of hazardous substances and gases at catastrophe sites are all examples of commercial applications of this technology. These wireless sensors will automatically connect to form a network, at which point they will process and interpret the sensor readings before transmitting them to a centralized control point. By connecting remote equipment, sensors, and actuators through wireless communication channels, wireless networks make it possible for control systems to be spread out. Some of its military uses include finding and keeping an eye on enemy targets, detecting chemical and biological attacks, helping robots drive themselves, and fighting terrorism. These networks allow the building of automated highways, mobile robots, and customizable industrial automation.

It is necessary to overcome a significant number of technical challenges in order to make future wireless applications possible. These challenges are present in every aspect of the design process for the system. These compact devices need to contain many modes of operation to cater to a wide range of application types and media types. Wireless terminals are becoming increasingly capable of doing more tasks. Data in audio, pictures, texts, and videos can all be processed by computers; however, breakthroughs in circuit design are required to include the same multi-mode functionality into a device that is inexpensive, lightweight, and lightweight portable. The portable terminal's transmission and signal processing must consume as little power as feasible because consumers do not want large batteries that need to be replenished regularly. The processing of signals necessary to provide networking capabilities and multimedia applications will need many resources.

It is becoming easier to envision how cellular connectivity will signal traffic to and from 50 billion developing gadgets within the next decade, given the rate at which so many things are wirelessly connecting to the Internet. This is because so many things are connected to the Internet now. Even though wireless carriers, chipset makers, tower owners, and infrastructure providers have many reasons to be optimistic about the future, more people are likely to use Wi-Fi. The technology, which stands out because it works on an unlicensed spectrum, has been multiplying and is becoming increasingly seen as a way to fill in where cellular signals are either too weak or too complicated and expensive to work. This is because the technology uses a band of radio waves for which no one has a license.

2.3 UAV demand in market and use cases

UAVs, more generally known as drones, are finding various applications across a wide variety of industries, including the military and defense, civic and commercial, logistics and transportation, agricultural, construction and mining, and other fields [7], [9], [32] and [33]. The rise in demand is primarily attributable to the mobility of the equipment, as well as the cost efficiency of the equipment when contrasted with its counterpart technologies, such as ground infrastructure. The functionality of the drone equipment available on the market determines the variety of different types of drone equipment.

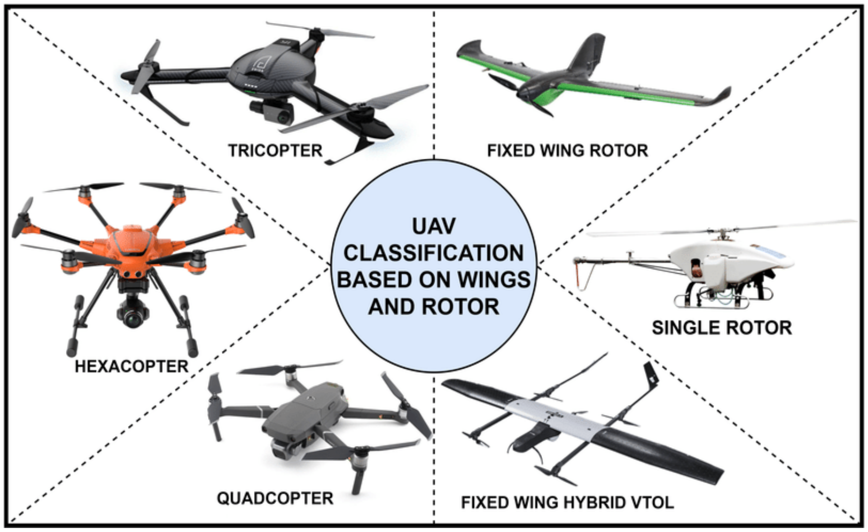

Figure 2.1: Types of Unmanned aerial vehicles

UAVs come in various configurations, including single-rotor, fixed-wing rotor, tri-copter, hexacopter, quadcopter, and fixed-wing hybrid vertical takeoff and landing drones, as shown in Fig. 2.1, [34]. Accessibility, user-friendliness, reasonable camera control, payload capacity, coverage area, and many additional features are among the numerous characteristics associated with drones, depending on the functionality.

The UAV can establish Line of Sight (LoS) links with ground nodes described in [35]. In some circumstances, such as when there is a battery power shortage, the ground nodes in IoT devices may reduce the amount of power they send out. In such circumstances, the UAV might facilitate the transmission of the standard files. Inspecting some systems, particularly those that are difficult to access or require more cash than usual to perform certain functions, is another potential application for UAVs. They can carry out these inspections since operating a UAV is relatively inexpensive. Several businesses are now working on the technology required for these kinds of intersections, which are seeing enormous demand in the market.

Because they can be used to record recordings of natural settings or to provide an aerial perspective of an artistic performance, cameras supported by UAVs hold a large amount of relevance in the market. The entertainment industry is beginning to notice the fresh perspective presented to the user [34]. The news industry is also deploying cameras mounted on UAVs to provide a more comprehensive knowledge of the situation from an aerial perspective. Because the user interface for operating this technology is relatively straightforward and straightforward to comprehend, the market share of drones used for these applications is anticipated to expand soon.

The drone industry serves more customers in North America than any other region [32]. Compared to the market demand of 23.60 billion in 2021, the market demand is anticipated to be 77.69 billion in 2023. The majority of the growth can be attributed to rising applications in the military. Large quantities of equipment are being purchased by the wealthiest countries globally. One of the most important reasons contributing to this pattern's development is the growing combination of machine learning and artificial intelligence. Demand is growing due to improvements made to UAV technology, sometimes known as drones. It is possible to use drones to conduct surveillance at the borders of countries, thereby determining whether or not there is a danger to the nation. One significant benefit of using drones is that they do not require a pilot to operate them. More than 50 different nations have created unique drone technology forms for use in their armed forces.

During the COVID-19 epidemic, there was a surge in the utilization of drone technology. The physical presence of humans outside the house should be reduced. Thus, these drones are utilized for border security instead of those people. Experiments were conducted with the participation of government agencies and law enforcement. Additionally, it is utilized in the commercial and public sectors for the transportation of medical supplies and for taking aerial photographs for entertainment and reporting the news.

Some drones can process billions of photos, providing decision-makers in various fields with precise data upon which to base their deliberations. Many industries are interested in the accurate data and information analysis the software provides, ultimately leading to increased global corporate production. Customers can now construct real-time maps with the help of enhanced cameras, more processing power, and fast microprocessors, all of which are components of the current hardware technology.

Depending on the mission, the UAV can perform various functions and find applications in various growing fields [36]. This technology is utilized in order to construct communication networks that are dependable and resilient. Google and Meta plan to bring high-speed Internet access to underserved regions by deploying vast UAV networks. The Amazon Prime Air project intends to use drones to deliver products to customers but faces several challenges. These challenges include avoiding collisions with other drones, managing the payload (since different kinds of products have varying weights), and determining whether a single type of drone or multiple types of drones should be used, taking into account factors such as payload, coverage area, travel time, and so on.

The desire for communication links that are capable of high speeds is going to be a necessity for the future generation of communication networks [32]. Maintaining wireless communication to the ground terminals is essential if the terrestrial network becomes unavailable. Under these conditions, we can use the communications provided by the UAVs, which offer wireless access at the lowest possible additional cost. For this technology to advance in the near future, the degree to which it can be deployed and moved about will play a significant role.

The usage of UAVs is possible within cellphone networks. The wireless connectivity available today needs to be improved to satisfy the standards set for traffic in the wireless domain. Numerous technological advancements, such as Massive MIMO, dense small cell networks, beamforming, mobile edge computing, cognitive networks, orthogonal frequency-division multiple access, and mmWave communications, are being implemented in wireless networks order to expand their capacity and improve their coverage [32]. In order to make progress with these technologies, we will need to construct new infrastructure for fairly distributing spectrum usage. When these kinds of circumstances arise, aerial communication plays a significant role in enhancing the network's capacity and coverage. One of the wireless technologies that can be utilized to satisfy the demand for a communication network is a base station mounted on a UAV.

Existing terrestrial networks are frequently rendered inoperable when natural disasters strike. There is frequent deterioration in both the cellular base stations and the ground communication lines. In an emergency, communication is essential for carrying out public safety operations such as rescue and giving frontline employees up-to-date information in real-time [12]. Under these circumstances, an aerial base station can serve as the communication network that transfers information between first responders and the general population. Compared to more conventional approaches, the operational costs associated with establishing these networks are low. In addition to the low cost of operations, the UAV's compact size and easy portability can work in our favor. When navigating a region inaccessible to humans, we can send out the UAV. UAVs can rapidly arrive at the scene, allowing aid to be delivered to the populace immediately. As a result of these properties, the base station mounted on the UAV is a precious asset in communication networks of this type.

As a result of the low cost of drone technology, they are being used in a wide variety of innovative applications, some of which will be discussed further [9]. Collecting data from ground nodes can be done with a UAV. Some locations that humans either need help accessing or have a high risk. In such circumstances, UAVs might be sent out to collect the data. As a result, this helps maintain applications centered on the Internet of Things. Monitoring and surveillance are two more applications for UAVs. This line of inquiry led to many applications in the communication networks allowed by UAVs. It has been demonstrated that unmanned aerial vehicles can provide more effective traffic management than the existing infrastructure. With appropriate sensors and processing technology, a UAV might monitor criminal activities using cutting-edge technologies such as artificial intelligence and machine learning. In addition, a vast region can be protected by a combination of UAVs.

UAV communications can be separated into two groups depending on the payload and latency of the communication lines. In communication applications involving critical and safety concerns and in which the provision of real-time updates plays a crucial part, the latency of the communication system should be minimized [4]. Although the data rate might need to be lowered in specific applications, the latency should be kept to a minimum. On the other hand, the data rate is of the utmost significance when it comes to payload transmission, but the latency can be compromised. The application's functionality should perform the configuration of the UAV communication system. The data rate is significant when transmitting photos, videos, or backhauling data packets. When giving real-time updates in the navigation to the ground nodes or engaging in emergency communications, it is essential to keep the delay to a minimum.

The present state of the art in UAV communication allows for direct connectivity to ground nodes, satellite-assisted applications, and flying ad-hoc networks (FANET) [9]. When it comes to communications with non-critical payloads, maintaining continuous connectivity and keeping latency to a minimum is necessary to reach the goal of the application. In contrast, the data rate the communication system can handle is of the utmost importance for payload communication. In addition, the confidentiality of the data transmitted by aerial UAVs is ensured. Cellular technology is the finest option for UAV communications and should be used to enable these communication systems. The long-term evolution (LTE) technology that cellular technology provides enables applications such as flexible scheduling, resource management, and multiple access solution. However, because cellular technology was designed for use by ground nodes, it will need to be modified before it can be considered for use in the communication of UAVs.

Communication between cellular UAVs can be built to function in a manner analogous to that of device-to-device communication between ground nodes. Communication between UAVs allows for increased throughput and more effective energy use [37]. UAVs can communicate with one another. However, to make efficient use of these technologies, we need to consider how to minimize collisions and fairly divide resources among UAVs based on the task at hand. By working together, UAVs have the potential to establish communication systems with high reliability and low latency, both of which could be valuable assets for the communication systems of the next generation.

2.4 UAV as a relay

UAVs have three significant applications [33]. They are UAVs as base stations, providing real-time wireless coverage in case of emergencies or where terrestrial communication fails. The second type is UAV, as a relay to connect the ground nodes which cannot communicate directly with each other with the help of a relay. The third is UAV-assisted Internet of Things (IOT) applications, where UAV helps the IOT network by transmitting data or charging the nodes or surveillance of the IOT nodes.

The relays are classified depending on how it receives and processes its signals. They are amplify-and-forward relay, decode-and-forward relay, compressed-and-forward relay and so on [22]. The AF protocol is widely used out of the many existing relay protocols since it linearly processes the signals and re-transmits them to the destination. Since this protocol is not affected by noise, it is known to be the best protocol for transferring the signals due to its benefits compared to the practical implementation expenditure.

With the help of a relay, a source sends a message to a destination in cooperative wireless communication [17]. The relay listens to the transmission from the source and may send the message to the destination again. By combining the transmissions from the source and the relay, and depending on the protocol used for the relay, the destination can get diversity against fading without an antenna array at any terminal.

Another kind of classification is a half-duplex and full-duplex relay, which depends on the capacity of the relay to transmit and receive information simultaneously [38]. In a full-duplex relay, the relay can transmit and receive information simultaneously, whereas in a half-duplex relay, it can transmit or receive information at a particular instant. Half-duplex relay is widely used due to the multiple practical limits on power consumption and implementation expenditure of wireless communication systems.

Amplify-and-Forward relay is a protocol defined for cooperative wireless communications [19]. The relay network is an example of a wireless communication network in which cooperation improves the performance of the system. Cooperation happens when a neighboring node helps make direct communication between a source and a destination better. This neighboring node is called a relay when it does not have its data to send. It can also be a node with its data to send, but it can also help the source and destination talk to each other.

In DF schemes, the relay decodes the received signal, re-encodes it, and forwards it to the destination node. In AF schemes, the received signal is only amplified by a factor G, which normalizes the received power and is sent to the destination node. In [39], AF asymptotically approaches the DF scheme regarding diversity performance. Moreover, in some cases avoiding the decoding of the signal at the relay prevents decoding errors.

Studies have shown that the buffer-assisted relaying method is an excellent way to fix the problems caused by time-varying channels. It allows relays to store data, breaks away from the traditional transmission mode, and uses the best channel flexibly [7,8]. So, in this paper, it is assumed that all UAV relays have a buffer and are used in applications that can handle delays [4]. UAV relays with a buffer can

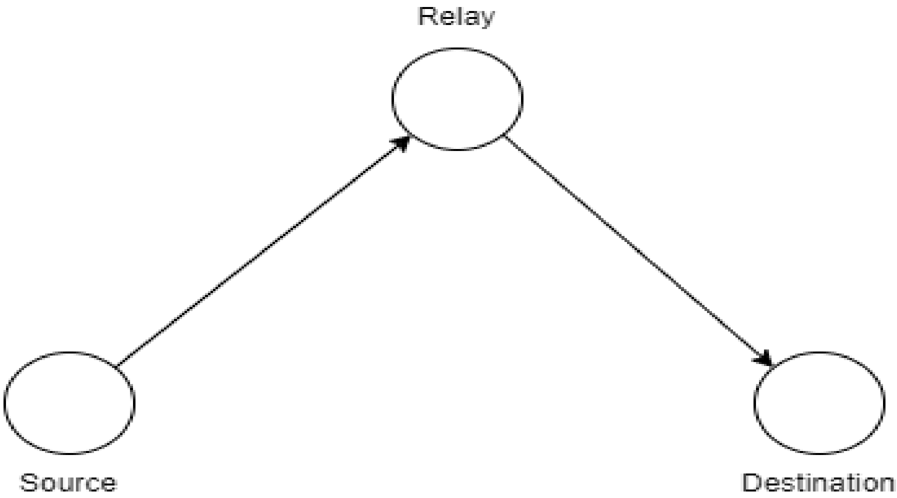

Figure 2.2: Three node Relay model

store and send information under better conditions when certain quality-of-service (QoS) requirements are met. The relay node is mobile, and the buffer helps the relaying.

2.5 Trajectory and Power control optimization for UAV

There are two types of UAV-assisted wireless communications divided into two sections they are static UAV communications and mobile UAV communications. In the Static UAV case, primary importance is given to the UAV's placement and deployment positions for improving the system's communication performance. In mobile UAV communications, the UAV takes advantage of mobility by optimizing the trajectory to improve capacity performance. The trajectory and power optimization are considered to achieve secure communication links in [9]. The throughput of the UAV-BS is maximized by optimizing the trajectory along with the user scheduling and transmit power allocation [17]. An amplify and forward UAV relay is considered in [10] to minimize outage probability through trajectory and power optimization.

Most UAVs have small battery capacities and use much energy when hovering and flying. With limited resources, like transmit power, reaching the goal performance in these situations may be challenging. If the locations or paths of UAVs are not optimized, more resources may be used, or longer flight times may be needed to reach a specific performance goal. In a UAV-enabled communication system, finding the best places for and paths for UAVs is essential.

UAV deployment and path planning are essential factors regarding the performance of the UAV communication system. The path planning, i.e., the trajectory of the UAV, plays an essential role in reducing the distance between the communication nodes, thus increasing the information rate of the communication system as described in [8]. The larger the distance between the UAV relay and the ground nodes, the lesser the channel gain of the system. It is very challenging to find the optimized trajectory of the UAV since it involves various other parameters in the application. The trajectory of the UAV is application specific. The practical limitations like the payload of the UAV, fuel capacity, and cooperative deployment affect the UAV's path, which is a time-variant. We can describe the trajectory with a discrete-time state system with the position and the velocity parameters. The position of the UAV can be given by the sequence of discrete time sate values subjected to finite constraints. For instance, in a multi-UAV communication system, the distance between the UAVs should also be considered in optimization problems to avoid collision and interference among the UAVs. In this case, cooperative deployment is necessary to achieve the goal of the application. In UAV-aided cellular communication, the UAV can stay fixed at a position or hover in a specific area to provide coverage to the ground nodes. The UAV altitude also plays an essential role in achieving the goal of the application. With the UAV's altitude increase, the probability of LoS links increases. At the same time, with an increase in altitude, the channel gain decreases since it is inversely proportional to the distance between the nodes. To achieve the application goal, a trade-off should be established between the altitude and the channel gain for maximum coverage.

There are several applications of UAV-based communication systems. In most of these communication systems, the UAV is assumed to be at a stationary point or following a fixed trajectory. However, the mobility of the UAV can also be utilized to improve the performance of the communication system. Line-of-sight communication links can be established in these communication systems since they are no possible obstacles between the communication nodes. Trajectory optimization is essential for enhancing the channel's capacity in this communication system. In [14], the UAV's propulsion energy and the system's throughput are considered for achieving the system's energy efficiency using trajectory optimization. UAV propulsion energy is defined as a function of UAV speed, direction, and acceleration. Energy efficiency is defined as the number of communication bits transferred normalized to UAV propulsion energy. It is shown that the energy efficiency is negligible for both rate-maximization and energy-minimization in an unconstrained trajectory design but achieves decent energy efficiency for circular trajectories with optimized radius and rectilinear general constrained trajectory. This proves the importance of trajectory optimization. Ideally, UAVs can remain stationary above ground nodes but should be in movement for maximum coverage.

In [18], a multi-UAV-enabled communication system is taken into the discussion, designed to serve a group of users on the ground. The main goal of the design is to achieve fairness in the users' performance. The fairness is achieved by maximizing the minimum throughput of ground users in downlink communication scheduling and joint trajectory and power control. The optimization problem is a mixed integer non-convex function solved iteratively by block coordinate descent and successive convex optimization technique. To achieve the optimal solution, user scheduling, joint trajectory, and power control are solved alternatively. To prove the impact of trajectory optimization, the proposed algorithm is compared with various benchmark cases like circular trajectory with a fixed radius and static trajectory. It is proven that the throughput is increased multiple times with an optimized trajectory. The results displayed in [18] show that UAV mobility can be crucial in achieving better communication links. However, optimizing altitude and the 2-D position of the UAV will be challenging. The 3-D UAV trajectory design optimization would be more valuable and challenging since the altitude has a trade-off with channel gain. A trade-off can be achieved between the altitude and channel gain to achieve fairness in the communication system.

The trade-off should be achieved between the trajectory and power control(source transmit power and relay transmit power) in the UAV communication relay system as discussed in [16]. The trajectory of the UAV should be achieved by efficiently using power control. Depending on the power control, the UAV trajectory design is optimized, i.e., the UAV trajectory is a power control function. Depending upon these values, the UAV designs its trajectory. Moreover, depending on the trajectory of the UAV, the power control is optimized to make the best use of the UAV when it is closer to ground nodes for achieving maximum throughput.

There are several established algorithms for solving the trajectory and power control of the UAV. The optimization algorithms target optimizing the non-linear objective function to obtain optimal solutions. The various optimization algorithms are Sequential quadratic programming(SQP) [40], Interior-point method(IPM) [41], Second-order cone programming(SOCP) [42], Semidefinite programming(SDP) [43], etc. SQP method can be applied to obtain optimal flight trajectory, but the exact solution is to be obtained. Hence, this method requires more computation power to complete the task. At the same time, the IPM can be applied to obtain optimal solutions with less computation power. In IPM, all the inequality constraints are converted into equality constraints by introducing slack variables into the optimization. However, the IPM should consider the penalty function and its initialization. SDP has the ability to obtain the most optimal solution. It has to utilize high computation power, as SOCP can be applied by using a second-order cone such that it requires less computational power.

2.6 Majorization-Minimization algorithm

The MM method (Minimization-Maximization) is a general optimization approach for finding the local maxima of a given objective function. It is a repetitive method used in statistics, data mining, and machine learning to solve many problems. The MM algorithm is practical when working with non-convex functions, which can be hard to optimize with other methods [23].

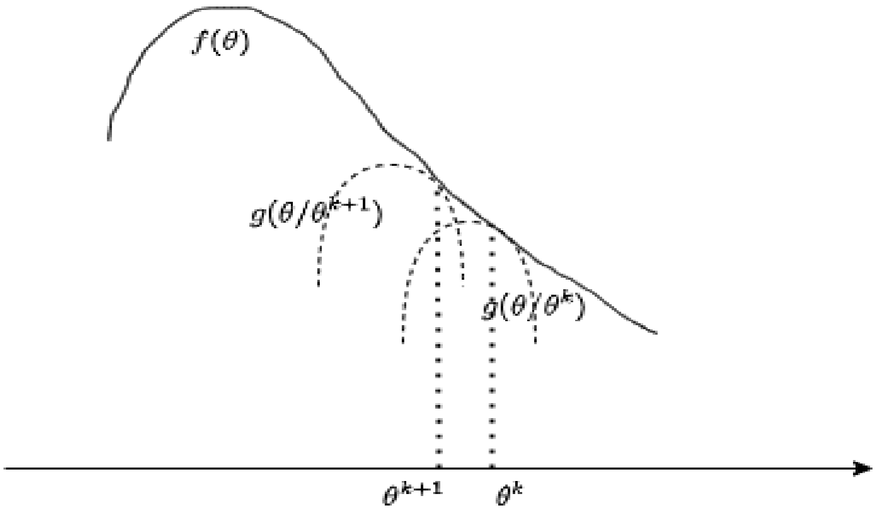

Figure 2.3: Convergence of MM algorithm

The main idea behind the MM algorithm is to get as close as possible to the target function by using a simpler function that is easy to maximize, as described in Fig. 2.3. The steps are as follows:

(i) Set the typical values for the model's properties.

(ii) Find an easier-to-optimize minorizing (or lower-bounding) function for the target function at each step. At the current estimates of the parameters, this function should meet the original goal function.

(iii) Maximize the minorizing function concerning the parameters to get the updated parameter values.

(iv) Steps 2 and 3 must be done repeatedly until a convergence condition is met, such as a slight change in the goal function or estimates of parameters between iterations.

In the above figure, fig. 2.3, $f(\theta)$ is the actual function and $g(\theta/\theta^k)$ is the surrogate function . The widely used applications of MM algorithms are listed below:

(i) Avoiding large matrix inversions,

(ii) Linearizing an optimization problem,

(iii) Separating the parameters of an optimization problem,

(iv) Dealing with equality and inequality constraints smoothly, or

(v) Turning a problem that cannot be differentiated into a smooth problem. Iteration is the price we have to pay to make the original problem easier to understand.

In this paper, we aim to maximize the minimum information rate. Let $f(\theta)$ be the non-convex function for which we want to achieve the approximate optimal solution by optimizing a surrogate function $g(\theta/\theta^k)$. The function $g(\theta/\theta^k)$ is said to be minorize $f(\theta)$ at point θ^k iff

(i) $f(\theta) \geqslant g(\theta/\theta^k)$,

(ii) $f(\theta^k) = g(\theta^k/\theta^k)$

Now we should maximize $g(\theta/\theta^k)$ instead of $f(\theta)$.
θ^{k+1} is the variable where $g(\theta/\theta^k)$ achieves the maximum value.
$f(\theta^{k+1}) >= g(\theta^{k+1}/\theta^k) >= g(\theta^k/\theta^k)(= f(\theta^k))$
Solving by the above method guarantees that the function will converge to obtain the approximate optimal solution.
In this way, MM algorithm approach will be used to solve the non-convex optimization problem.

2.7 Integer Linear Relaxation Programming

Variables x_i in Linear Program (LP) in [44] can be fractional values but in the Integer Linear Programming (ILP), variables should be integers.

$$\max_{x} \quad c^T b \tag{2.1a}$$

$$\text{s.t.} \quad Ax \leqslant b, \tag{2.1b}$$

$$x_i \in R \tag{2.1c}$$

$$\tag{2.1d}$$

We restrict the values to either 0 or 1. These values are known as indicator variables.

$$
\begin{aligned}
\max_{x} \quad & c^T b && (2.2a)\\
\text{s.t.} \quad & Ax \leqslant b, && (2.2b)\\
& x_i \in \{0,1\} && (2.2c)\\
& && (2.2d)
\end{aligned}
$$

The Binary ILP is similar to the knapsack problem of n items. Each item is given a weight w_i and value v_i, and we tried to maximize the value limits of the selected item concerning the weight.

Steps for formulating Binary ILP as ILP

$$
\begin{aligned}
\max_{x} \quad & \sum v_i x_i && (2.3a)\\
\text{s.t.} \quad & \sum w_i x_i \leqslant c, && (2.3b)\\
& 0 \leqslant x_i \leqslant 1 && (2.3c)\\
& && (2.3d)
\end{aligned}
$$

(i) We introduce the indicator variable x_i for each item to encode whether we select it or not.

(ii) The value of the selected item is equal to the sum of each item times its indicator variable.

(iii) Note that the variable is one if we take the item and 0 if we do not. The sum corresponds to the value of the selected items.

(iv) We can write the total weight of the selected items as the sum of the weight of each item times its indicator value being less or equal to the weight c. Unfortunately, unlike LP, no efficient algorithm for solving the ILP is Known. One possible solution is relaxing the integer constraints for the variables. Instead of forcing them to be either 0 or 1, we reduce the variables to between 0 and 1.

(v) Then, we can use the simplex algorithm to solve the LP and round the variables to the nearest possible point.

Unfortunately, Linear Relaxation is not guaranteed to find the optimum solution. Moreover, sometimes the found solution can even be arbitrarily wrong. The best answer to the LP does not have to be integral. However, since the feasible region of the LP is more significant than the feasible region of the IP, the optimal value of the LP is not worse than the optimal value of the IP. This means that the optimal value for the LP is a lower bound on OPT, the optimal value for the problem we started with. Even though the rounded solution might not be the best for the original problem, since we start with the best LP solution, we want to show that the rounded solution is pretty close to the best.

The rounding of the found solution gives the correct answer. However, we could also end up with an infeasible solution for the integer version of the LP. Even if we can round to the closest possible point, we might end up at a no longer optimal node. However, for some specific types of problems, we guarantee that we can always find the correct answer using Linear Relaxation.

However, we can arrive at the optimal solution to the assignment problem. In the assignment problems, we are given a list of customers and a list of cabs. We know how long the travel time to each cab is for each customer. We want to match the cabs to customers to minimize the total waiting time. We can solve the assignment problem by using ILP in the following way.

$$
\begin{aligned}
\max_{x} \quad & \sum x_{i,j} w_{i,j} && \text{(2.4a)} \\
\text{s.t.} \quad & \sum_{j} x_{i,j} = 1 \quad \forall i, && \text{(2.4b)} \\
& \sum_{i} x_{i,j} \leqslant 1 \forall j, && \text{(2.4c)} \\
& x_{i,j} \in \{0, 1\} && \text{(2.4d)} \\
& && \text{(2.4e)}
\end{aligned}
$$

(i) We introduce an indicator variable for each arrow between a customer i and cab j. This encodes if cab j picks up customer i.

(ii) Each cab can pick up at most 1 passenger. Therefore, all the outgoing arrows can be at most 1.

(iii) Each Passenger must be picked up by 1 cab, so the sum of all the incoming arrows must be exactly 1.

(iv) The total travel time is then equal to the sum of the times it takes for the cab to get to the passenger multiplied by the corresponding indicator variable. This describes the objective and completes our ILP.

In this problem, the constraint matrix is unimodular, and the determinant of each sub-matrix is either -1,0, or 1. This is a non-trivial property to check and is usually hard to determine. However, the matrices are known to be unimodular for a particular class of tasks that includes assignment problems. We guarantee that the linear relaxation will give us the correct answer whenever this is the case. Therefore, we can apply linear relaxation and solve the assignment problem. In other words, solving this linear program is guaranteed to give us a solution where every indicator variable is 0 or 1.

$$
\begin{aligned}
\max_{x} \quad & \sum x_{i,j} w_{i,j} && \text{(2.5a)} \\
\text{s.t.} \quad & \sum_{j} x_{i,j} = 1 \quad \forall i, && \text{(2.5b)} \\
& \sum_{i} x_{i,j} \leqslant 1 \quad \forall j, && \text{(2.5c)} \\
& 0 \leqslant x_{i,j} \leqslant 1 && \text{(2.5d)} \\
& && \text{(2.5e)}
\end{aligned}
$$

Chapter *3*

Trajectory and Power optimization for Buffer-Assisted Amplify-and-Forward UAV Relay

3.1 Introduction

This chapter deals with the proposed algorithm for achieving fairness in UAV communication systems in emergencies by maximizing the minimum information rate. We proposed the trajectory and power optimization for buffer-assisted amplify-and-forward relay to achieve fairness. The system model, proposed algorithm, and simulation results of the proposed algorithm are discussed in this chapter.

3.2 System Model

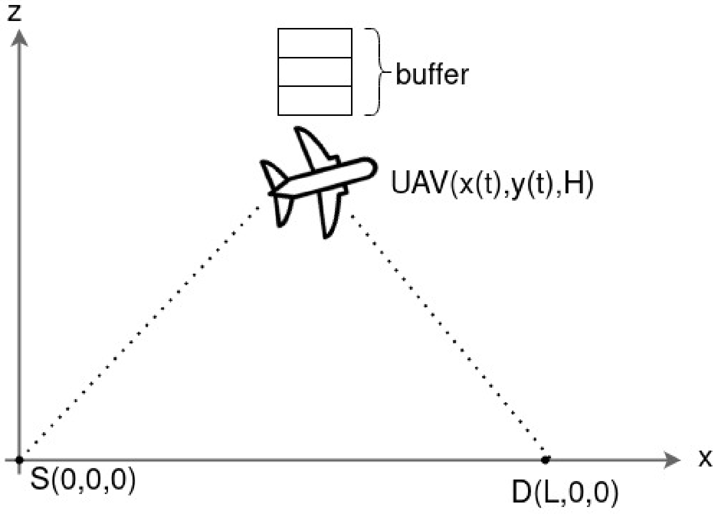

Figure 3.1: Geometrical model for Buffer-Assisted UAV relay

The UAV assisted with the base station acts as a mobile relay between the fixed source (S) and destination (D) ground nodes. A buffer is employed at the UAV to store the information. We assume there is no direct link between the source and destination nodes due to long-distance or severe blockage between them. UAV flies in a 2-dimensional space with cartesian coordinates $(x(i), y(i), H)$, with fixed altitude H and varying x and y coordinates. We consider the source at $S(0,0,0)$ and the destination at $D(L,0,0)$, separated by a horizontal distance L. The geometrical description of the model is shown in (3.1). Let T be the time of flight of the UAV. In general, the time of flight T depends on the UAV deployment. The time of flight T is divided into N smaller time slots so that the UAV location remains relatively constant in consecutive time slots. UAV travels with a maximum speed of V_{max}. UAVs have predetermined launching and landing positions. Depending on the maximum velocity V_{max}, and the number of sub-slots N, the maximum displacement in a single sub-slot can be defined as $D_{max} = V_{max}(T/N)$. The distance between the adjacent trajectory points should not exceed D_{max} since it is the maximum distance the UAV travels in a single sub-slot.

$$\begin{aligned}\sqrt{(x[i]-x[i-1])^2+(y[i]-y[i-1])^2)} \\ \leqslant D_{max}, i=1,\ldots,N\end{aligned} \tag{3.1}$$

Since line-of-sight (LOS) links dominate the channel, we assume a free-space path loss model. LoS propagation is a property of electromagnetic radiation in which two stations can only transmit and receive data signals with an unobstructed LoS. Satellite and microwave transmission are two prevalent types of LoS communication. The free-space propagation model must be comprehended as a foundation for understanding more complex models. The free-space propagation model is applicable when there are no barriers other than the LoS path from the transmitter to the receiver. More specifically, the free-space propagation model is accurate when there are no objects other than the transmitter and receiver, as the presence of any other item could result in reflected routes. This paradigm is appropriate only when the receiver is within the transmitter antenna's far field. The UAV is located at an altitude with no obstacles between the UAV and the ground nodes. Hence there is no signal blockage, and direct communication links can be established. The signal received by the UAV from the source S in the i^{th} time slot is given by

$$y_u[i] = \sqrt{P_s[i]h_{su}[i]}X_s[i] + W_1[i], \tag{3.2}$$

Where $P_s[i]$ is the source transmit power, $h_{su}[i]$ is the channel gain between the source and UAV, $X_s[i]$ is the transmitted signal from the source, and $W_1[i]$ is the additive white Gaussian noise observed at the UAV. The transmitted information $X_s[i]$ and $W_1[i]$ follows circularly symmetric Gaussian distribution $CN(0,1)$ and $CN(0,N_1)$, respectively. The channel gain $h_{su}[i]$, is given by

$$h_{su}[i] = \beta_0(d_{su}[i])^{-2}, \tag{3.3}$$

β_0 is the reference channel coefficient at $d_0 = 1m$, $d_{su}[i]$ is the distance between source and UAV relay at the i^{th} time interval, $d_{su}[i] = \sqrt{(x[i])^2+(y[i])^2+H^2}$, $x[i]$ and $y[i]$ represents the coordinates of the UAV at the i^{th} time slot.

The data obtained from the unmanned aerial vehicle (UAV) during the ith time slot can be transmitted during the jth time slot $(j \geqslant i)$. The communication system's objectives should be considered while determining the UAV's buffer capacity. Regarding pairing time slots, the buffer capacity is an essential factor. The larger the buffer capacity, the longer a data packet can wait at the UAV while the operator searches for a channel with a higher signal-to-noise ratio before the packet can be transmitted from the UAV. Since we transmit the signal at the same time slot received at the UAV, this approach is analogous to the instantaneous AF method when the paired time slots are equal (i==j). The time slots received and transferred from the source to the UAV and from the UAV to the destination are described as paired time slots. Having paired time slots to guarantee fairness inside the communication system is essential. For example, if the data packet is transferred to the UAV over a communication link with a high SNR and then the same data packet is transferred to the destination over a communication link with a low SNR, the data packet will be corrupted because the SNR on the link from the UAV to the destination will be low, which will cause the entire communication to be prone to errors. Similarly, if the data packet is transferred to the UAV from the source in a link with a lower SNR and it is then transferred from the UAV to the destination in a link with a higher SNR, then the data packet may become corrupted because the SNR capacity from the source to the UAV is lower, which makes the entire communication system more prone to errors. In order to keep the communication system balanced, we need to select both communication links—that is, the link from the source to the UAV and the link from the UAV to the destination—so that the entire communication will be free of errors. In order to accomplish this, we will need to combine the periods in which the SNR from the source to the UAV is higher with the time slots in which the SNR from the UAV to the destination connections is higher. The following binary variable is what specifies the pairing for the time slot:

$$sp[i][j] = \begin{cases} 1 & \text{if } i^{th} \text{ and } j^{th} \text{ slots are paired,} \\ 0 & \text{otherwise.} \end{cases} \tag{3.4}$$

If the output of the binary variable $sp[i][j]$ is 1 for a particular i^{th} and j^{th} indices, then the data packet is transferred to UAV from the source in i^{th} time slot and it is transferred from UAV to destination in the j^{th} time slot. If the output of the binary variable $sp[i][j]$ is 0, then that particular i^{th} and j^{th} indices are not paired together. Hence these indices pairs should not be considered while transferring data packets from source to destination through a UAV relay. The relation between the i^{th} and j^{th} highly depends on the buffer capacity. If the buffer capacity changes, the duration for a data packet to be stored UAV changes, hence the time slots' pairing changes.

While optimizing the $sp[i][j]$ variable, we must consider the following two conditions. First, if a data packet is transmitted from the UAV at the j^{th} time slot, it should be received at the UAV before or at the j^{th} time slot. The summation of $sp[i][j]$ should satisfy the below inequality $\forall\, j \ \in 1 \cdots N$. The inequality in the equation ensures that the data transferred at the j^{th} index is received at only one of the i^{th} $(i \leqslant j)$ index. Suppose a particular data packet is transferred from the UAV at a particular j^{th} time slot. In that case, it is received at the UAV only at a particular i^{th} time slot, then that particular data packet cannot be received at any other i^{th} time slot. This condition ensures that there are no exact time slots paired.

$$\sum_{i=1}^{j} sp[i][j] \leqslant 1, \forall j \in \{1, \ldots, N\}. \tag{3.5}$$

Next, if the data packet is received in the i^{th} time slot, it should be transmitted only after or at the i^{th} time slot. The summation of $sp[i][j]$ should satisfy the below inequality $\forall\ i\ \in 1 \cdots N$. The inequality in the equation ensures that the data is transferred from the UAV at the j^{th} $(j \geqslant i)$ index only once after it is received at the i^{th} index. Suppose a particular data packet is received at the UAV at a particular i^{th} index and transferred to the destination at a particular j^{th}. Then that particular data packet cannot be transferred in any other j^{th} time slot. This condition ensures that there are no exact time slot pairs.

$$\sum_{j=i}^{N} sp[i][j] \leqslant 1, \forall i \in \{1, \ldots, N\}. \tag{3.6}$$

In equations (3.5) and (3.6), we considered that the summation is $\leqslant 1$ to ensure that there is no duplicate time pairing, i.e., a particular data packet is received and transferred at the UAV only once. If $sp[i][j] = 1$, it implies that the data packet received in the i^{th} time slot at UAV is transmitted in the $j^{th}(j \geqslant i)$ time slot satisfying the constraints in (3.5) and (3.6). $sp[i][j] = 0$, for $I > j$, since the data packet cannot be transmitted from the UAV before it is received at the UAV. $sp[i][j]$ can only take binary input, i.e., either 0 or 1, since the possibility of the specific i^{th} and specific j^{th} index to be paired is either true or false. The signal transmitted by the UAV in the j^{th} time slot is given by

$$x_u[j] = \alpha[i][j] y_u[i], \tag{3.7}$$

Where $y_u[i]$ is the received signal at UAV in the i^{th} time slot, $x_u[j]$ is the transmitted signal from UAV in the j^{th} time slot, and $\alpha[i][j]$ is the amplification factor at the UAV for the respective i^{th} and j^{th} time slots is given by

$$\alpha[i][j] = \sqrt{\frac{P_u[j]}{P_s[i] h_{su}[i] + N_1}}, \tag{3.8}$$

With $P_u[j]$ being the transmit power of the UAV. From (3.2), (3.7), (3.8), the signal received by the destination node in the j^{th} time slot is given by

$$
\begin{aligned}
y_d[j] =& \sqrt{h_{ud}[j]} x_u[j] + W_2[j] && (3.9a)\\
=& \alpha[i][j] \sqrt{h_{ud}[j] P_s[i] h_{su}[i]} X_s[i] \\
& + \alpha[i][j] \sqrt{h_{ud}[j]} W_1[i] + W_2[j] && (3.9b)\\
=& \sqrt{\frac{P_s[i] h_{su}[i] P_u[j] h_{ud}[j]}{P_s[i] h_{su}[i] + N_1}} X_s[j] \\
& + \sqrt{\frac{P_u[j] h_{ud}[j]}{P_s[i] h_{su}[i] + N_1}} W_1[j] + W_2[j], && (3.9c)
\end{aligned}
$$

Where $W_2[j]$ is the additive circularly symmetric Gaussian noise with zero mean and variance N_2, $h_{ud}[j]$ is the channel gain between the UAV and the destination node at the j^{th} time slot given by

$$
h_{ud}[j] = \beta_0 (d_{ud}[j])^{-2}, \tag{3.10}
$$

Where $d_{ud}[j] = \sqrt{(x[j] - L)^2 + (y[j] - 0)^2 + H^2}$, To calculate the joint signal-to-noise ratio (SNR), we must view the entire system model as a single system with a transmitted signal at the source node and a received signal at the destination node. The following equation gives the joint SNR for a paired time slot:

$$
\text{SNR}[i][j] = \frac{P_s[i] h_{su}[i] P_u[j] h_{ud}[j]}{P_s[i] h_{su}[i] N_2 + P_u[j] h_{ud}[j] N_1 + N_1 N_2} \tag{3.11}
$$

The above equation represents the SNR of the system if the data packet is transferred to UAV in the i^{th} time slot and the same data packet is transferred from UAV in the j^{th} time slot. The achievable rate for the paired i^{th} and j^{th} time slot is given by:

$$
\text{R}[i][j] = \log_2(1 + \text{SNR}[i][j]). \tag{3.12}
$$

In this paper, we jointly optimize the power allocation and trajectory of the UAV as well as time slot pairing. Let $P = [P_s[i], P_u[j]]$ and $X = [[x[i], y[i]]$. The optimization problem can be written as

(P1)

$$\max_{sp[i][j],P,X} \quad \min sp[i][j]R[i][j] \tag{3.13a}$$

$$\text{s.t.} \quad sp[i][j] \in \{0,1\}, \forall i, j \in \{1, \ldots, N\}, \tag{3.13b}$$

$$\sum_{i=1}^{j} sp[i][j] \leqslant 1, \forall j \in \{1, \ldots, N\}, \tag{3.13c}$$

$$\sum_{j=i}^{N} sp[i][j] \leqslant 1, \forall i \in \{1, \ldots, N\}, \tag{3.13d}$$

$$sp[i][j] = 0, \forall j < i, \forall i, j \in \{1, \ldots, N\}, \tag{3.13e}$$

$$\sum_{i=1}^{N} P_s[i] \leqslant NE_S, \sum_{j=1}^{N} P_u[j] \leqslant NE_U, \tag{3.13f}$$

$$P_s[i] > 0, P_u[j] > 0, \forall i, j \in \{1, \ldots, N\}, \tag{3.13g}$$

$$\tag{3.13h}$$

$$\sqrt{(x[i] - x[i-1])^2 + (y[i] - y[i-1])^2} \leqslant D_{max}, i = 1, 2, ..., N, \tag{3.13i}$$

E_s is the average maximum transmitted power at the source node, and E_u is the average maximum transmitted power at the UAV. As the above problem is a non-convex optimization, it takes work to obtain the optimal solution. Hence, we use the successive convex optimization technique in which we first solve the optimal solution for the joint power and trajectory of the UAV. Then we solve for the best time slot pairs for achieving a higher information rate, which will be discussed in the next section.

We did not limit the UAV's buffer capacity in the preceding problem formulation. We cannot have an unlimited buffer, so we must limit the buffer's capacity. Let the buffer's capacity be m. Then, the relationship between the ith and jth time slots will be determined as follows: $sp[i][j] = 0$, for $j > i + m$. It indicates that the UAV can hold information until m time slots after receiving it. Hence the signal must be transmitted before this limit. We can design the buffer capacity m to meet our specifications.

3.3 Proposed Algorithm

In this section, we divide problem (P1) into two sub-problems; first, we solve the optimal bounds for rate, and then we pair the time slots to utilize the high SNR links

(P1.1)

$$\begin{aligned}\max_{P,X}\quad & \min R[i][j] && (3.14a)\\ \text{s.t.}\quad & \sum_{i=1}^{N} P_s[i] \leqslant NE_S, && (3.14b)\\ & \sum_{j=1}^{N} P_u[j] \leqslant NE_U, && (3.14c)\\ & P_s[i] > 0, P_u[j] > 0, \quad \forall i, j, && (3.14d)\\ & \sqrt{(x[i]-x[i-1])^2 + (y[i]-y[i-1])^2)} && (3.14e)\\ \leqslant D_{max}; \forall \quad & i = 1, \ldots, N. &&\end{aligned}$$

The objective function in (3.14), is a non-convex function. We solve this function by using a successive convex optimization algorithm. We apply MM algorithm approximation [23], to the objective function and solve the resulting function through successive convex optimization methods. In the MM algorithm, to maximize a function, say $f(\theta)$, we have to find a surrogate minorize function $g(\theta)$ that satisfies two conditions, *viz.* $f(\theta) \geqslant g(\theta/\theta^k)$ and $f(\theta^k) = g(\theta^k/\theta^k)$, where θ is the current iteration parameters and θ^k is the previous iteration parameters. Let $\lambda_1[i] = \frac{1}{P_s[i]h_{su}[i]}$ and $\lambda_2[j] = \frac{1}{P_u[j]h_{ud}[j]}$, which are convex with respect to $\{x[n], y[n], P_s[n], P_u[n]\}$. Then, from equation (3.11), the equivalent SNR can be expressed as

$$\text{SNR}[i][j] = \frac{1}{\lambda_1[i]N_1 + \lambda_2[j]N_2 + N_1N_2}. \tag{3.15}$$

Taking logarithm on both sides of the equation, we get $f(\theta) = \log(\text{SNR}[i][j])$ as given by

$$f(\theta) = -\log(\lambda_1[i]N_1 + \lambda_2[j]N_2 + N_1N_2). \tag{3.16}$$

We can apply the MM algorithm to $f(\theta)$ to get a lower bound, as $f(\theta)$ is convex in terms of $\lambda_1[i]$ and $\lambda_2[j]$. We can apply minorization via supporting hyperplane to maximize $f(\theta)$. We get the following relation

$$\begin{aligned}&-\log(\lambda_1[i]^{k+1}N_1 + \lambda_2[j]^{k+1}N_2 + N_1N_2)\\ &\quad \geqslant -\log(\lambda_1[i]^{k}N_1 + \lambda_2[j]^{k}N_2 + N_1N_2)\\ &\quad -\frac{\lambda_1[i]^{k+1}N_1 + \lambda_2[j]^{k+1}N_2 + N_1N_2}{\lambda_1[i]^{k}N_1 + \lambda_2[j]^{k}N_2 + N_1N_2} + 1\end{aligned} \tag{3.17}$$

Let the right side of inequality be $g(\theta/\theta^k)$. It satisfies both the conditions necessary for applying the MM algorithm, proof is described as follows:

From equations (3.16) and (3.17), the $f(\theta)$ and $g(\theta/\theta^k)$ should satisfy the two conditions of the MM algorithm, *viz.* 1) $f(\theta) \geqslant g(\theta/\theta^k)$, 2) $f(\theta^k) = g(\theta^k/\theta^k)$, where θ is the current iteration parameters and θ^k is the previous iteration parameters.

It is evident from (3.17), that the first condition is satisfied. By substituting θ^k in place of θ in $g(\theta/\theta^k)$ we get

$$\begin{aligned} g(\theta^k/\theta^k) &= -\log(\lambda_1[i]^k N_1 + \lambda_2[j]^k N_2 + N_1 N_2) \\ &\quad - \frac{\lambda_1[i]^k N_1 + \lambda_2[j]^k N_2 + N_1 N_2}{\lambda_1[i]^k N_1 + \lambda_2[j]^k N_2 + N_1 N_2} + 1 \\ &= -\log(\lambda_1[i]^k N_1 + \lambda_2[j]^k N_2 + N_1 N_2) = f(\theta^k) \end{aligned} \tag{3.18}$$

So from (3.18), the second condition is also satisfied. Therefore, by the principles of the MM algorithm, we can solve $g(\theta/\theta^k)$ to obtain a solution for $f(\theta)$.

Now we can maximize the minimum information rate by maximizing the minimum lower bound on rate among all slots, and we are maximizing the minimum of $g(\theta/\theta^k)$, which is a surrogate minorize function of $f(\theta)$. After obtaining optimal P_s, P_u, x, and y values in (P1.1), we calculate the rate $R[i][j]$, $\forall\, i, j \in \{1, 2, 3, ...N\}$. Using the above values, we solve the second part of the problem, i.e., time slot pairing for maximizing the minimum information rate as given below

(P1.2)

$$\max_{sp[i][j]} \quad (sp[i][j]R[i][j]), \tag{3.19a}$$

$$\text{s.t.} \quad sp[i][j] \in \{0,1\} \forall i, j \in \{1, \dots, N\}, \tag{3.19b}$$

$$\sum_{i=1}^{j} sp[i][j] \leqslant 1, \forall j \in \{1, \dots, N\}, \tag{3.19c}$$

$$\sum_{j=i}^{N} sp[i][j] \leqslant 1, \forall i \in \{1, \dots, N\}, \tag{3.19d}$$

$$sp[i][j] = 0, \forall j < i, \forall i, j \in \{1, \dots, N\}. \tag{3.19e}$$

(P1.2) can be solved by using the linear programming relaxation method [24]. (P1.2) is the same as solving the optimal edges for a bipartite graph to maximize the overall weight associated with the required edges. In our problem, two sets of vertices are i^{th} and j^{th} time slots and weights of the graph are the channel capacity associated with the corresponding i^{th} and j^{th} time slots. Suppose there is an edge from the i^{th} vertex to the j^{th} vertex in the optimal solution, then the i, j, are paired together. The edges are selected to maximize the total weight. In the linear programming relaxation method, we initially obtain a linear solution, and the rounding technique is applied to make the fractional values either 0 or 1 in the linear solution.

The problem (P1) can be solved by solving (P 1.1), at first, followed by solving (P 1.2), as summarised in the following Algorithm 1.

(i) Initially at $k = 0$, the values are predetermined to typical average values and then optimized to obtain optimal values $\{P_{s,k}[n], P_{u,k}[n], x_k[n], y_k[n]\}\ \forall n \in \{1, \dots, N\}$.

(ii) **Start the iteration**

(iii) Solve the Problem (P 1.1) using the MM algorithm.

(iv) Update the values for $k \to k+1$.

(v) **Repeat 3 & 4 until the algorithm converges.**

(vi) Now set bits for $sp[i][j]$ to select the best capacity channels, depending on the $R[i][j]$, obtained from the above steps such that the minimum information rate is maximized.

3.4 Simulation Results

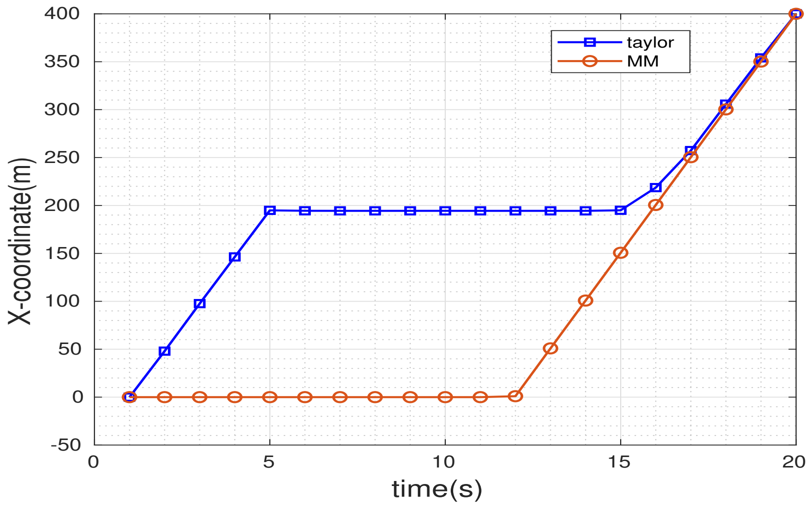

Figure 3.2: The X-coordinate values for UAV using MM and taylor series approximations.

In this section, numerical results are presented to demonstrate the performance of the proposed UAV system model. For simulation, the following constraints are considered. The distance between the source and destination is $L = 400m$, the average transmission power (E_S) and received power (E_U) at UAV $E_U = E_S = 10mW$, and the maximum allowable velocity $V_{max} = 50m/s$. The noise power spectral density at UAV and the destination node is $N_1 = N_2 = -169dBm/Hz$. The link carrier frequency, $f_c = 5GHz$ and bandwidth, $B = 20MHz$. The period is $T = 20$ seconds, and the number of slots is $N = 20$.

The above experimental setup is run on the Matlab platform to identify the UAV's trajectory and the UAV's power budget in every time slot. The time slots in which information is transferred from UAV and received by UAV are also calculated to identify the impact of the buffer in the scheduling of the time slots. The average information rate, i.e., the sum of information rates across all time slots, is divided by

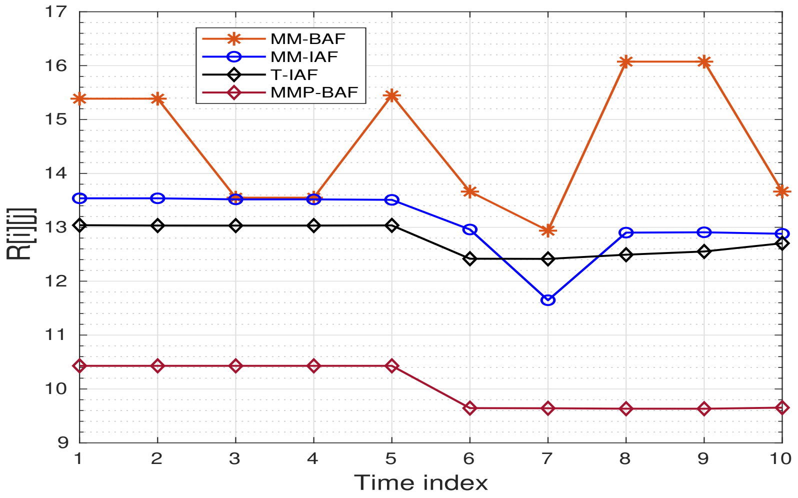

Figure 3.3: Information rates vs received time index for MM-BAF, MM-IAF, MMP-BAF and IAF using taylor series approximation(T-IAF)

the number of time slots information is transferred is calculated for different buffer capacities. All the analyses are presented in the below figures in Fig. 3.2, Fig. 3.3 and the Tables 3.1, 3.2.

In the literature survey, the taylor series approximation provides the best optimal solution to the joint trajectory and power control problem. We compare the results obtained from the proposed algorithm with the taylor series approximation algorithm for better understanding. In Fig. 3.2, we observe that in the MM case, the UAV travels close to the source than in the taylor case. In MM's case, the UAV stays close to the source in the first half of the time, and the communication link between the source and UAV has more SNR when compared with the UAV and destination since the channel gain is inversely proportional to the distance between the nodes. In the second half, the UAV travels toward the destination node since the trajectory constraint is to be satisfied, i.e., the UAV should reach the destination point in the last time slot. In these time slots, the channel link capacities from UAV to the destination are higher than the source to UAV. UAV's y-coordinate remains zero throughout the trajectory to obtain minimum link distance.

In Fig. 3.3, the transmitted indices (i.e., the time slots at which the data is received at the UAV) are considered for plotting the rate. In Fig. 3.3, the MM-buffer assistant AF relay rate is more when compared to the taylor series. This demonstrates that using the MM algorithm is better and more efficient. We can observe the increase in the data rate in the MM-buffer assistant AF relay when compared to the MM-instant AF relay. This increase in data rate is due to the successful usage of adaptive link selection by installing a buffer at the UAV relay. We also observe that in Fig. 3.3, the information rates for buffer-assisted AF relay using the MM algorithm with optimized power control (MM-BAF) is more significant than the buffer-assisted AF relay using the MM algorithm with average power for each time slot (MMP-BAF). This proves that power control optimization is vital for achieving fairness.

Table 3.1: Time slot pairing

Received Index	Transmitted Index
2	10
4	7
5	6
6	8
7	9
8	11
9	19
10	14
12	16
13	17

Table 3.2: Buffer Capacity vs Average Rate

Buffer capacity	Average rate
2	13.09
5	13.26
8	13.30
10	13.38
12	14.36
14	14.85

The numerical results in Fig. 3.3 prove the importance of the MM-BAF algorithm in optimizing the trajectory and power control and pairing of time slots to achieve fairness. For example, in the fifth time index, the information rate is more when compared to the other algorithms in the same channel conditions. This demonstrates that our proposed algorithm maintains fairness.

Buffer capacity is utilized as much as possible since a wide gap exists between transmitted and received indices, as shown in Table 3.1. The data packet waits at the buffer to choose the maximum SNR link. Table 3.2 lists the average rate values for different buffer capacities. Though the increment is marginal, there can be an appreciated gap with the increase in time slots. Overall, the proposed algorithm maximizes the minimum rate of the UAV system while optimizing the trajectory and power control and pairing of time slots by utilizing a buffer at the relay.

Chapter *4*

Conclusion

4.1 Conclusion

We propose the design of a mobile UAV relay that utilizes adaptive links to amplify the data and send it onward. A buffer would assist this relay. Maximizing the minimum information rate is how the system's fairness is kept intact. The adaptive link selection method ensures that communication links with a higher SNR capacity are chosen while working within the constraints of a given data packet's buffer capacity. In order to obtain the optimal trajectory and power control, we first formulate the fairness problem while considering the appropriate constraints described above. Because this formulation is not convex, we employ the MM algorithm to obtain a solution more aligned with global optimality. The linear relaxation method is then used to pair the available time slots with links with higher SNR capacity, both from the source to the UAV and from the UAV to the destination. Because of the UAV's mobility, this system has the benefit of a more excellent range of communication, which is a distinct advantage. In order to test the algorithm that was developed in the paper, we restricted our discussion to the values in this range. The objectives of the communication system can alter the range of the constraints. Additionally, the transmitted information will be protected because adaptive link selection will be used. This is because both the received and transmitted time slots will be coded, making them unintelligible to an eavesdropper. This algorithm, essential in emergency communications, can be modified to achieve data secrecy by adding additional steps.

4.2 Future Scope

UAV communications can be elevated by optimizing several parameters responsible for drone technology's success. Introducing Re-configurable Intelligent Surfaces (RIS) into the UAV communication will help in increasing the throughput of the system. An extension of this algorithm presented in this paper can be used for variable height UAV relay, i.e., flexibility can be given to the z-variable.

Related Publications

Accepted Paper:

1. N. M. Makkena and P. Ubaidulla, ”Trajectory and Power Optimization for Buffer-Assisted Amplify-and-Forward UAV Relay,” 2022 IEEE International Conference on Communication, Networks and Satellite (COMNETSAT), Solo, Indonesia, 2022, pp. 415-421, doi: 10.1109/COMNETSAT56033.2022.9994482.

Bibliography

[1] Y. Zeng, Q. Wu, and R. Zhang, “Accessing from the sky: A tutorial on uav communications for 5g and beyond,” *Proceedings of the IEEE*, vol. 107, no. 12, pp. 2327–2375, 2019.

[2] M. Asadpour, B. Van den Bergh, D. Giustiniano, K. A. Hummel, S. Pollin, and B. Plattner, “Micro aerial vehicle networks: an experimental analysis of challenges and opportunities,” *IEEE Communications Magazine*, vol. 52, no. 7, pp. 141–149, 2014.

[3] M. M. Azari, F. Rosas, K.-C. Chen, and S. Pollin, “Ultra reliable uav communication using altitude and cooperation diversity,” *IEEE Transactions on Communications*, vol. 66, no. 1, pp. 330–344, 2018.

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

[5] N. Zlatanov, A. Ikhlef, T. Islam, and R. Schober, “Buffer-aided cooperative communications: opportunities and challenges,” *IEEE Communications Magazine*, vol. 52, no. 4, pp. 146–153, 2014.

[6] K. Katayama, H. Takahashi, N. Yokota, K. Sugiyasu, G. Kitagata, and T. Kinoshita, “An effective multi-uavs-based evacuation guidance support for disaster risk reduction,” in *2019 IEEE International Conference on Big Data and Smart Computing (BigComp)*, 2019, pp. 1–6.

[7] S. Hayat, E. Yanmaz, and R. Muzaffar, “Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint,” *IEEE Communications Surveys Tutorials*, vol. 18, no. 4, pp. 2624–2661, 2016.

[8] Y. Zeng, R. Zhang, and T. J. Lim, “Wireless communications with unmanned aerial vehicles: opportunities and challenges,” *IEEE Communications Magazine*, vol. 54, no. 5, pp. 36–42, 2016.

[9] A. Fotouhi, H. Qiang, M. Ding, M. Hassan, L. G. Giordano, A. Garcia-Rodriguez, and J. Yuan, “Survey on uav cellular communications: Practical aspects, standardization advancements, regulation, and security challenges,” *IEEE Communications Surveys Tutorials*, vol. 21, no. 4, pp. 3417–3442, 2019.

[10] J. Laneman, D. Tse, and G. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[11] Y. Emami, K. Li, and E. Tovar, “Buffer-aware scheduling for uav relay networks with energy fairness,” in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, 2020, pp. 1–5.

[12] K. G. Panda, S. Das, D. Sen, and W. Arif, “Design and deployment of uav-aided post-disaster emergency network,” *IEEE Access*, vol. 7, pp. 102 985–102 999, 2019.

[13] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, “Mobile unmanned aerial vehicles (uavs) for energy-efficient internet of things communications,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 11, pp. 7574–7589, 2017.

[14] Y. Zeng and R. Zhang, “Energy-efficient uav communication with trajectory optimization,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 6, pp. 3747–3760, 2017.

[15] Yong, R. Zhang, and Z. Lim, Teng Joon, “Wireless communications with unmanned aerial vehicles: opportunities and challenges,” *IEEE Communications Magazine*, vol. 54, no. 5, pp. 36–42, 2016.

[16] S. Zhang, H. Zhang, Q. He, K. Bian, and L. Song, “Joint trajectory and power optimization for uav relay networks,” *IEEE Communications Letters*, vol. 22, no. 1, pp. 161–164, 2018.

[17] G. Zhang, X. Ou, M. Cui, Q. Wu, S. Ma, and W. Chen, “Cooperative uav enabled relaying systems: Joint trajectory and transmit power optimization,” *IEEE Transactions on Green Communications and Networking*, pp. 1–1, 2021.

[18] J. Ji, K. Zhu, D. Niyato, and R. Wang, “Joint cache placement, flight trajectory, and transmission power optimization for multi-uav assisted wireless networks,” *IEEE Transactions on Wireless Communications*, vol. 19, no. 8, pp. 5389–5403, 2020.

[19] X. Jiang, Z. Wu, Z. Yin, and Z. Yang, “Power and trajectory optimization for uav-enabled amplify-and-forward relay networks,” *IEEE Access*, vol. 6, pp. 48 688–48 696, 2018.

[20] S. Boyd, S. P. Boyd, and L. Vandenberghe, *Convex optimization.* Cambridge university press, 2004.

[21] M. Yu and J. Li, “Is amplify-and-forward practically better than decode-and-forward or vice versa?” in *Proceedings. (ICASSP ’05). IEEE International Conference on Acoustics, Speech, and Signal Processing, 2005.*, vol. 3, 2005, pp. iii/365–iii/368 Vol. 3.

[22] X. Jiang, Z. Wu, Z. Yin, and Z. Yang, “Joint power and trajectory design for uav-relayed wireless systems,” *IEEE Wireless Communications Letters*, vol. 8, no. 3, pp. 697–700, 2018.

[23] D. R. Hunter and K. Lange, “A tutorial on MM algorithms,” *The American Statistician*, no. 58, 2004.

[24] V. V. Vazirani, *Approximation algorithms.* Springer, 2001.

[25] T. Seymour and A. T. Shaheen, “History of wireless communication,” in *Business Information Systems*, 2011.

[26] T. Rappaport, *Wireless communications: Principles and practice*, 2nd ed., ser. Prentice Hall communications engineering and emerging technologies series. Prentice Hall, 2002, includes bibliographical references and index.

[27] W. Stallings, *Wireless Communications amp; Networks (2nd Edition).* USA: Prentice-Hall, Inc., 2004.

[28] K. Pahlavan and P. Krishnamurthy, *Principles of Wireless Networks: A Unified Approach*, 1st ed. USA: Prentice Hall PTR, 2001.

[29] V. H. M. Donald, “Advanced mobile phone service: The cellular concept,” *The Bell System Technical Journal*, vol. 58, pp. 15–41, 1979.

[30] S. Schiesel, “Paging allies focus strategy on the internet.”

[31] F. Abrishamkar and Z. Siveski, “Pcs global mobile satellites,” *IEEE Communications Magazine*, vol. 34, no. 9, pp. 132–136, 1996.

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

[33] H. Ghazzai, H. Menouar, A. Kadri, and Y. Massoud, “Future uav-based its: A comprehensive scheduling framework,” *IEEE Access*, vol. 7, pp. 75 678–75 695, 2019.

[34] S. J. Kim, Y. Jeong, S. Park, K. Ryu, and G. Oh, “A survey of drone use for entertainment and avr (augmented and virtual reality),” 2018.

[35] I. Guvenc, W. Saad, M. Bennis, C. Wietfeld, M. Ding, and L. Pike, “Wireless communications, networking, and positioning with unmanned aerial vehicles [guest editorial],” *IEEE Communications Magazine*, vol. 54, no. 5, pp. 24–25, 2016.

[36] H. Eskandaripour and E. Boldsaikhan, “Last-mile drone delivery: Past, present, and future,” *Drones*, vol. 7, no. 2, 2023. [Online]. Available: https://www.mdpi.com/2504-446X/7/2/77

[37] Y. Zeng and R. Zhang, “Energy-efficient uav communication with trajectory optimization,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 6, pp. 3747–3760, 2017.

[38] N. V. Shende, Gürbüz, and E. Erkip, “Half-duplex or full-duplex communications: Degrees of freedom analysis under self-interference,” *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, pp. 1081–1093, 2018.

[39] J. Laneman, D. Tse, and G. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[40] P. Boggs and J. Tolle, “Sequential quadratic programming,” *Acta Numerica*, vol. 4, pp. 1–51, 01 1995.

[41] V. Quintana, G. Torres, and J. Medina-Palomo, “Interior-point methods and their applications to power systems: a classification of publications and software codes,” *IEEE Transactions on Power Systems*, vol. 15, no. 1, pp. 170–176, 2000.

[42] M. S. Lobo, L. Vandenberghe, S. Boyd, and H. Lebret, “Applications of second-order cone programming,” *Linear Algebra and its Applications*, vol. 284, no. 1, pp. 193–228, 1998, international Linear Algebra Society (ILAS) Symposium on Fast Algorithms for Control, Signals and Image Processing. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0024379598100320

[43] H. Wolkowicz, R. Saigal, and L. Vandenberghe, Eds., *Handbook of Semidefinite Programming*. Springer US, 2000. [Online]. Available: https://doi.org/10.10072F978-1-4615-4381-7

[44] R. Vanderbe, “Linear programming : Foundations and extensions,” *Boston: Kluwer Academic; 1996.*