An Adaptive and Reliable Forward Error Correction Mechanism for Real-time Video Delivery from UAVs

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I, Batoul Sarvi Ghamsari, certify that this thesis is my own work and has not been submitted for another degree at University College Cork or elsewhere.

Batoul Sarvi Ghamsari

This study is dedicated to:

- My loving husband, whose unwavering support in morality, spirituality, emotion, and finance has been my cornerstone.
- My inspiring parents, who provided both inspiration and the strength to persevere.
- My encouraging sisters, an endless source of motivation.
- My esteemed supervisors, guiding lights on my academic journey.
- My UCC's friends, a constant source of strength.

Finally, I dedicate this study to the Almighty God in deep gratitude for divine guidance, strength, protection, skills, and good health, humbly offering these blessings.

Abstract

This thesis introduces the Adaptive and Reliable Forward Error Correction (AR-FEC) mechanism, an advanced protocol designed to enhance real-time video transmission in Unmanned Aerial Vehicles (UAVs) communications. Addressing the challenge of unreliable wireless channels, AR-FEC leverages edge computing principles at the application layer to incorporate adaptive FEC, dynamic video quality, and Unequal Error Protection (UEP). By dynamically adjusting redundancy frames within each video Group of Pictures (GoP) based on packet loss, round-trip times, and cross-layer network information, AR-FEC optimizes the balance between video quality and transmission reliability.

A significant portion of this work is dedicated to rigorous simulation-based validation using the NS3 network simulator. The simulation environment is carefully crafted to replicate a range of UAV operational conditions, including varying distances and network loads, to assess the AR-FEC protocol's performance under realistic scenarios. Key performance indicators such as deliverable frame count, latency, throughput, and real-time streaming constraints are meticulously evaluated, demonstrating AR-FEC's capacity to outperform existing error correction methods significantly.

The simulations also explore the protocol's behavior with multiple UAVs as senders, highlighting its robustness in complex network settings. The results indicate a marked improvement in video delivery quality, showcasing AR-FEC's potential for broad application across different UAV uses, from surveillance to disaster management.

In summary, the thesis articulates the development and validation of AR-FEC, illustrating its superior performance and adaptability. The proposed mechanism not only advances the field of UAV communication but also establishes a comprehensive simulation framework for future research, potentially guiding the development of more reliable and efficient UAV multimedia communication systems.

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Chapter 1

Introduction

The convergence of wireless networks with computer systems has been a pivotal factor in transforming computing and communication in human lives, but its impact doesn't stop at traditional communication methods. Wireless technologies have revolutionized connectivity, providing users with the convenience of communication without the constraints of fixed infrastructure. This paradigm shift has introduced unprecedented possibilities, facilitating real-time access to information from anywhere, at any time [1]. Moreover, wireless networks offer flexible mobility, allowing users to stay connected without being restricted to a fixed network connection, thus setting the stage for the seamless integration of wireless technology into the world of Unmanned Aerial Vehicles (UAVs).

Over the past decade, there has been a remarkable surge in the utilization of UAVs due to their ability to access remote areas easily and their relatively affordable operating costs [2, 3]. By incorporating cameras into UAVs, they can capture high-quality videos and/or seamlessly share them with control stations or operators for inspection and further analysis [4]. This integration of cameras has given rise to a new range of applications such as environmental monitoring, precision agriculture, search and rescue operations, target tracking, and firefighting [5, 6]. These diverse applications heavily rely on multimedia communications in UAV scenarios, showcasing the natural evolution of wireless networks into the realm of UAV networks, where data transmission and real-time communication are becoming increasingly critical.

Although UAV-based multimedia communication offers potential benefits, it entails inherent challenges because it relies on wireless communication channels to enable mobility. Researchers have extensively investigated various wireless technologies, such as Wi-Fi, Bluetooth, ZigBee [7], 5G, and cellular systems [8], for UAV communication [2, 9, 10, 11]. Among the widely employed wireless technologies for video communications, the IEEE 802.11 family of standards stands out due to its impressive data transmission rate capabilities [12]. However, one of the primary challenges in wireless communication, particularly over extended distances, is the combined impact of factors such as packet loss and interference from other technologies or transmitters. As a result, ensuring reliability becomes one of the most prominent challenges, which further leads towards a lot of research gaps in wireless multimedia communication for UAVs [5, 13].

In addition, a substantial proportion of contemporary drone applications demand real-time wireless multimedia connections. This contrasts with using drones and receiver nodes over expansive distances where connections are often problematic. Consequently, it is essential to create reliable and real-time multimedia communication mechanisms on UAVs, with an emphasis on low latency and high-quality transmission, to meet the needs of the various applications that depend on these capabilities. Addressing these challenges and enhancing the efficiency of multimedia communication in UAV scenarios will be the primary focus of this thesis.

1.1 Challenges

The successful operation of UAVs in various scenarios relies on the availability of consistently high-quality video for analysis, ensuring safety and accuracy. This reliability is paramount in scenarios such as disaster response and management, where UAVs aid in damage assessment and emergency response coordination by providing real-time, high-quality video data. Furthermore, in infrastructure inspection, like power line and bridge monitoring, dependable video quality is crucial for early issue detection, averting costly and hazardous failures [14]. Surveillance and security applications also rely on high-quality video feeds from UAVs for precise threat identification in large areas [15]. Moreover, in environmental monitoring, UAVs equipped with reliable video systems offer valuable data for ecological assessment, wildlife tracking, and forest fire monitoring, underscoring the significance of reliable video quality in multiple UAV applications [16]. Figure 1.1 illustrates various UAV scenarios and highlights the challenges encountered within UAV networks.

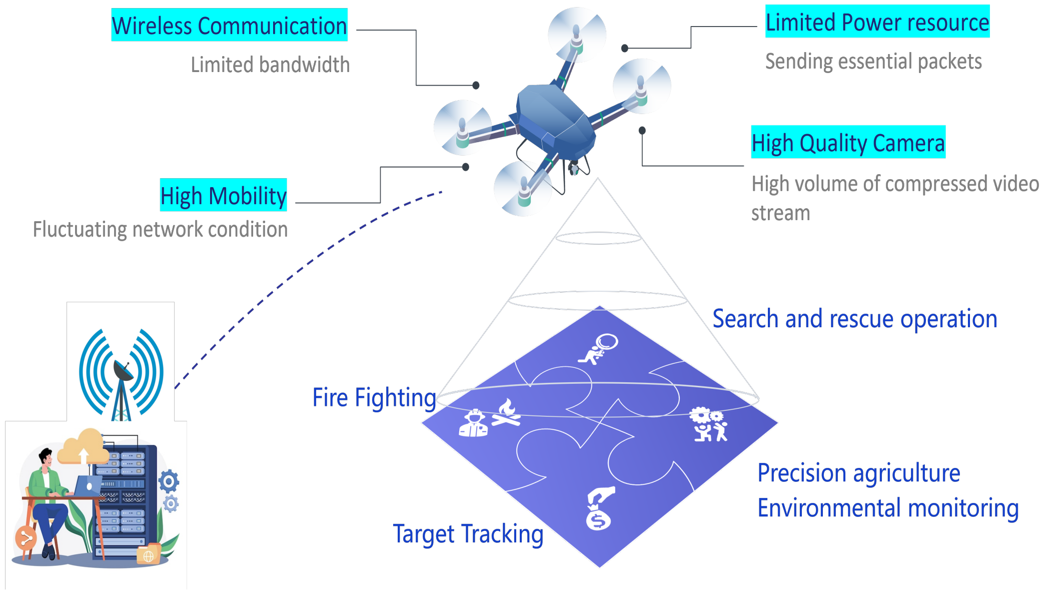


Figure 1.1: Visualization of some of the UAV scenarios and UAV's challenges

While multimedia applications with high compression ratios are suitable for low bit-rate wireless channels, the compressed stream becomes more susceptible to transmission errors due to predictive coding. Moreover, time-constrained video analysis and subsequent actions are essential for maintaining control over UAV flight and sensing activities. However, UAV-based streaming media transmission requires both stable network conditions and sufficient bandwidth, as network instability can significantly impact the quality experienced on video analysis servers, especially in real-time scenarios. Consequently, adaptive and reliable error control mechanisms are essential for achieving Quality of Service (QoS) in multimedia communication over UAV networks. Employing robust error protection techniques is critical to ensure acceptable video quality.

One of the primary challenges in real-time video streaming for UAVs is error resilience in communication channels. Researchers have been dedicated to developing algorithms that enhance QoS mainly through automated repeat request (ARQ) and forward error correction (FEC) at different OSI model layers. Numerous studies have been done on error control strategies, including FEC and ARQ, to address wireless transmission problems in multimedia streaming applications. ARQ can be applied at either the application or the data link layers. However, it suffers from drawbacks such as variable network delay and the requirement of a reverse channel. When real-time transport protocol packets are transmitted via UDP/IP, UAVs cannot effectively employ ARQ due to the potential drawbacks. In this context, the retransmission of a substantial volume of video packets not only escalates delay but also leads to increased power consumption, rendering ARQ impractical for UAVs [17]. To overcome this issue, FEC schemes are commonly employed [18]. Pure FEC schemes, used for real-time video streaming, operate without feedback by dividing the data into blocks and introducing bit or packet redundancy for error correction. Nonetheless, burst errors caused by wireless connections pose a challenge for FEC. Hence, determining the appropriate level of redundancy becomes vital, considering the unstable topology of UAV networks and the varying packet error rates they experience [19].

In addition to FEC and ARQ, researchers have explored leveraging cross-layer information from the protocol stack to enhance system efficiency, improve video quality, optimize network resource utilization, minimize latency, and conserve energy [20]. Such cross-layer approaches enable better coordination between different layers of the communication system, resulting in a more intelligent and adaptive UAV multimedia communication network. By sharing relevant information between layers, the system can dynamically adjust parameters and protocols to suit the changing conditions of UAV operation, thus improving the overall performance and user experience.

As UAVs continue to gain prominence in a wide array of applications, it becomes increasingly evident that addressing the unique challenges of error control and optimizing real-time multimedia communication within UAV networks is a pressing concern. While the importance of reliability is well understood, it is imperative to highlight that UAV communications present distinct issues that demand innovative solutions beyond the established error control methods. These issues specific to UAV networks may necessitate the development of novel techniques to ensure the seamless operation of UAV-based multimedia applications. By delving into these specialized challenges, we can shed light on the necessity for pioneering approaches in this domain, ultimately paving the way for safer, more efficient, and dependable UAV operations across diverse sectors.

1.2 Solutions

The solution presented in this thesis employs adaptive redundancy within FEC to tackle the complexities of introducing redundancy in constrained and vulnerable UAV networks. Functioning at the application layer, this approach capitalizes on insights into the video's structure, with a specific focus on classifying video frames based on their significance and impact on quality. The central aim is to enhance delivered video quality, reduce latency, and ensure efficient resource utilization by excluding redundant packets that do not significantly contribute to video quality or reliability.

Compression is necessary for UAV networks to distribute high-quality video over restricted-capacity wireless links. The compressed video employs I-frames, B-frames, and P-frames to encode video data efficiently. I-frames act as complete snapshots of the scene, serving as reference points for decoding. Protecting I-frames is crucial as they ensure video integrity in cases of data loss or transmission errors. P-frames rely on I/B-frames for reconstruction and store differences from previous reference frames, while B-frames reference both preceding and subsequent frames. Figure 1.2 demonstrates a simplified representation of video frames within a Group of Pictures (GoP) framework commonly used in video compression approaches. Safeguarding I-frames is essential for maintaining video quality and seamless decoding in compressed video formats, making it especially valuable for real-time video streaming and storage applications.

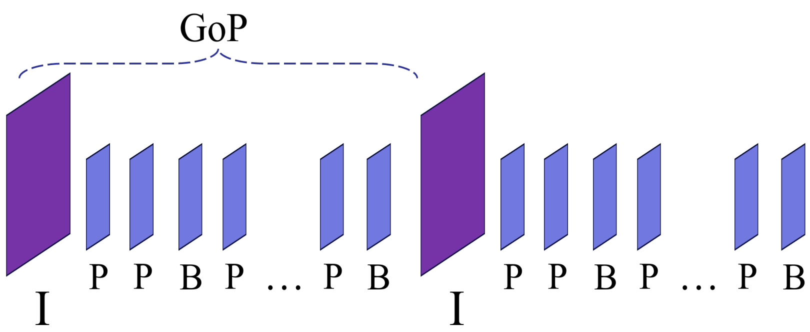


Figure 1.2: Visualization of a sample of Video Frames in a Group of Pictures (GoP)

Delivering high-quality video feeds is critical in the aforementioned UAV scenarios, involving numerous frames of substantial size. However, if the transmission of the I-frame fails, lower priority frames in the Group of Pictures (such as P and B frames) are not decodable at the receiver. To protect frames with higher priority, an Unequal Error Protection (UEP) method is employed, specifically providing redundancy packets for I-frame packets. This strategy safeguards high-priority frames and reduces the likelihood of congestion resulting from a large number of redundancy packets associated with low-priority video frames. Therefore, the P/B frames are not protected by the redundancy packet.

Additionally, the proposed method incorporates an adaptive video quality module that strives to deliver video frames even in low quality, while also protecting other frame types without the need for additional packets.

Furthermore, the utilization of edge computing during the processing stage enhances the performance of adaptive FEC algorithms and reduces latency. This involves implementing an adaptation algorithm at the edge device (i.e., the UAV) and utilizing a streaming protocol that receives explicit feedback from the receiver (i.e., the control station). By leveraging edge computing technology, significant improvements can be achieved in the performance of UAV networks through the offloading of computational tasks from the control station to the UAV. This approach reduces data volume during transmission and mitigates issues related to latency and congestion.

To the best of my knowledge, this work represents the first attempt to introduce an adaptive and reliable forward error correction mechanism for real-time video streaming on UAV networks. A comprehensive simulation study using NS3 demonstrates that the proposed approach outperforms other methods that lack FEC or employ static redundancy. The evaluation encompasses different operating distances between the drone and receiver, as well as various maximum acceptable application thresholds. The performance assessment considers the number of decodable frames, throughput, and frame latency, highlighting the superiority of the adaptive and reliable FEC approach.

1.3 Contribution of this Thesis

This thesis introduces a novel approach for the reliable delivery of real-time video from UAVs, called Adaptive and Reliable Forward Error Correction (AR-FEC). This seeks to predict the most suitable amount of FEC redundancy, taking into account information about the video and the wireless link conditions. Through simulation, this is demonstrated to yield improved video quality at the control station. The contributions of this thesis are summarized as follows:

- **Designing and implementing an adaptive and reliable cross-layer application layer FEC scheme:**

  This section details the implementation of AR-FEC by considering parameters such as packet loss rate, latency, bandwidth usage, and queue length, the scheme enhances delivery reliability by dynamically adjusting FEC redundancy. This ensures smoother transmission even in challenging network conditions. Key parameters influencing the scheme include:

- Packet loss rate
- Average latency per GoP
- Average bandwidth usage per GoP
- The current length of the sending queue
- The RTP (Real-time Transport Protocol) and RTCP (RTP Control Protocol) protocols
- An Unequal Error Protection (UEP) mechanism based on the type of video frames

- **Preparing a simulation framework for real-time video streaming over UAV networks in NS3**:

  Due to the importance of evaluating the proposed FEC method and the high costs associated with real-device implementation, selecting a suitable simulator framework compatible with the drone environment is crucial. After a comparative assessment, NS3 emerged as the preferred choice for its compatibility and functionality. Consequently, the proposed method's components are completely implemented within this simulator framework.

- **Designing and implementing a video adaptation module**:

  The adaptation of real-time video encoding is pivotal within the AR-FEC framework, requiring compatibility with the simulator framework. Hence, the design and implementation of this module represent a novel and distinctive aspect of the AR-FEC method.

- **Implementing all of the proposed modules in NS3:**

  Several novel modules are required to complete the AR-FEC method, all of which need implementation within the NS3 network simulator.

- **Comprehensive performance evaluation of different error control scenarios based on:**

  This section undertakes a comprehensive performance evaluation of the proposed error control mechanism, underscoring its pivotal role in UAV communications. Through systematic analyses, the evaluation delves into critical aspects of the AR-FEC mechanism across various operational parameters, notably including varying operation distances and maximum acceptable application thresholds. These parameters are of paramount importance as they significantly influence the efficacy of the AR-FEC method. Furthermore, the assessment of AR-FEC extends to scenarios involving multiple UAVs as senders, offering insights into the complexities of error control within intricate communication networks. By examining these diverse scenarios, this section aims to provide valuable insights into the adaptability, robustness, and scalability of the proposed adaptive error control approach in multimedia UAV communication systems, thereby contributing to the advancement of this field.

1.4 Publications

The journey of a research endeavor is marked not only by its conclusion but also by the dissemination of its findings to the scholarly community. The ensuing list of publications represents key milestones in the scholarly discourse that has been prompted by this research. These outputs demonstrate the application and impact of the findings of this thesis in the realm of real-time video delivery from UAVs. Through these publications, the research transcends the pages of a thesis to contribute to the collective understanding and progression of network technology and multimedia communication.

1. B. Sarvi, C. J. Sreenan, and A. Zahran, "An adaptive and reliable forward error correction mechanism for real-time video delivery from UAVs," in the Proceedings of the 14th International Conference on Network of the Future (NoF), 2023, pp. 141–149.

    - Aligned with this thesis, the research was selected for inclusion in the Proceedings of the 14th IEEE International Conference on Network of the Future (NoF 2023), convened in October 2023. This esteemed conference offers a vital forum for scholars and industry experts to discuss and exchange breakthroughs in network technologies and their forthcoming applications. Our paper, featured in the conference, introduces a groundbreaking solution to the challenges of delivering real-time video from UAVs, centering around an adaptive and reliable Forward Error Correction mechanism. This recognition from NoF 2023 not only affirms the significance of our work but also highlights its potential impact within the academic and professional community.

- I had the privilege of presenting our findings on 6th October 2023 at Ege University in Izmir, Turkey, contributing to the ongoing discourse on future advancements in network technology. Further adding to our achievement, this paper has been indexed by IEEE and is now accessible on the IEEE website. This ensures more comprehensive visibility and accessibility to our research within the global scientific community [21].

2. B. Sarvi, "Multimedia communications for autonomous drones," in The Boolean: Snapshots of Doctoral Research at University College Cork, vol. 6, no. 1, pp. 52–58, 2022.

   - The Boolean, a student-driven publication at University College Cork, provides a unique platform for doctoral students from varied disciplines to present their research in a manner that's engaging and easy to comprehend for a broad audience. It undergoes an internal peer-review process focused on ensuring clarity, showcasing the wide array of research conducted within the university in an enjoyable and approachable way. This particular paper adheres to these principles, employing a clear and straightforward style of writing. It is crafted to convey complex thesis topics in a simplified manner, making them accessible and understandable to readers without specialized knowledge [22].

1.5 Thesis Overview

The creation and evaluation of the Adaptive and Reliable Forward Error Correction technique serves as the centerpiece of this thesis, which spans many chapters and launches an academic conversation on error control in UAV multimedia transmission. An overview of the chapters and the paths they take is shown below:

Chapter 2 lays the foundational knowledge required to understand the intricacies of UAV communication. It delves into the essential characteristics, the role of multimedia communication in UAVs, and the prevalent error control methods for real-time multimedia communication.

Chapter 3 is dedicated to a detailed literature review, discussing existing solutions for error correction on UAVs, the role of forward error correction strategies, and the potential of mobile edge computing to enhance error correction approach on UAV communication.

In Chapter 4, the thesis presents the AR-FEC method, a novel approach to ensure adaptive and reliable video transmission from UAVs. It provides an extensive overview of the AR-FEC system, its design, network monitoring, error protection, and quality adaptation strategies.

Chapter 5 details the simulation environment used to evaluate the AR-FEC method. It reviews various network simulators, justifies the choice of NS3, and outlines the simulation setup, parameters, and performance metrics.

Chapter 6 is an evaluation of AR-FEC, presenting an in-depth analysis of the results. It assesses the impact of factors such as operating distance, maximum acceptable application thresholds, and the use of multiple drones on video transmission quality via the AR-FEC mechanism.

Finally, Chapter 7 concludes the thesis, summarizing the findings and offering avenues for future research. It reflects on the implications of this work and its potential to influence future advancements in the field of UAV-based video delivery systems.

Chapter 2

Background

This background chapter offers an in-depth investigation into UAV communications, commencing with a thorough review of the prevailing challenges in this sector. Subsequently, the focus shifts to multimedia communication on UAVs, where the associated literature is rigorously analyzed. The aim is to glean insights into the methodologies, advancements, and challenges associated with multimedia transmission and reception within UAV environments.

Reliability emerges as a pivotal concern in real-time multimedia communication. In addressing this, error control mechanisms are underscored as vital tools, promising both reliability and timeliness in multimedia streaming. Recognizing their import, this chapter delves into seminal works that place significant emphasis on error control mechanisms in the context of real-time multimedia communication. To anchor this discourse, a foundational overview of traditional error control mechanisms is provided.

2.1 UAV Communication: Essentiality and Characteristics

UAV communication involves transmitting data, signals, and information between unmanned aerial vehicles and other entities, including ground control stations, satellites, and other UAVs. This communication facilitates various functions, including real-time video transmission, data exchange, command and control operations, and telemetry. The characteristics of UAV communication systems often include requirements for low latency, high reliability, robustness against interference, and adaptability to dynamic and unpredictable environments. These systems are vital for enabling a wide range of applications, spanning surveillance, reconnaissance, disaster response, precision agriculture, infrastructure inspection, environmental monitoring, and beyond. In essence, UAV communication networks form the backbone of the operational capabilities of unmanned aerial vehicles, facilitating their integration into diverse missions and applications with efficiency and effectiveness. This section delves into the multifaceted nature of UAV communication, exploring its requirements and its diverse roles in ensuring the success of UAV missions.

The authors of [12] have conducted an extensive comparative analysis of various communication technologies tailored for UAVs. They have thoughtfully compiled a list of potential candidates for both UAV-to-UAV (U2U) and UAV-to-Infrastructure (U2I) communication links, presenting this information in a clear and informative format within Table 2.1. The table serves as a valuable resource, highlighting the key characteristics of each communication technology, including factors such as mobility, data rates, communication range, and latency. The selection of the most appropriate technology is contingent on the specific requirements of the application and the type of mission being undertaken. This comprehensive comparison aids in making informed choices regarding the technology best suited to meet the objectives and demands of UAV communication in diverse scenarios.

Research focused on UAV communication networks has primarily addressed challenges and optimized opportunities to enhance UAV capabilities. This section endeavor involves the analysis of insights from various surveys and innovative solutions, shedding light on the complexities and potential of UAV communication. Current surveys are instrumental in comprehending the evolving issues and solutions for improving UAV communication networks, making them a valuable resource for optimizing UAV operations.

In the field of UAVs research, the [5] provides a comprehensive insight into the overarching challenges facing UAV technology. Notably, the paper underscores the critical issue of path planning for UAVs and its associated challenges, emphasizing the need for efficient, safe, and optimal navigation paths. The challenges outlined in the article span various dimensions, including path length, optimality, integrity, cost-efficiency, time efficiency, energy efficiency, stability, and collision avoidance. These challenges are fundamental to the development and deployment of UAVs, as they directly impact the functionality, safety, and reliability of these autonomous systems. This paper serves as an invaluable resource for understanding the complexities and obstacles that researchers and engineers must address when advancing UAV technology.

In their extensive investigation, [11] offers a comprehensive exploration of UAV cellular communication, with a notable emphasis on its profound implications for the future landscape of cellular networks. The research highlights UAVs' growing importance and potential opportunities for cellular network providers. A pivotal proposition within this research revolves around the deployment of UAVs as aerial base stations, an innovative strategy poised to extend network coverage and optimize data transfer efficiency. The authors meticulously categorize diverse UAV models, accentuating the specific communication challenges associated with each type, with particular attention given to the intricate issue of interference. Moreover, the study shines a spotlight on the remarkable potential of UAVs in serving as dynamic mobile relays and base stations, offering inventive solutions to augment network capabilities. Additionally, the paper touches upon the evolving regulatory framework governing commercial UAV operations, demonstrating the necessity of rigorous security protocols in this rapidly advancing and transformative field.

In the scholarly discourse surrounding UAV communication, the [23] provides a comprehensive assessment of multifaceted challenges. It accentuates the essential function of antennas in augmenting signal reception fidelity and protracting coverage, especially in contexts characterized by pronounced distances and diminished elevation angles. Furthermore, the treatise emphasizes the burgeoning confluence of UAVs with avant-garde technologies such as IoT and 5G, underscoring their salient role in the evolving communication paradigm. Nonetheless, amidst these technological strides resides a plethora of intricate conundrums in UAV communication, necessitating meticulous channel modeling across a diverse array of applications. From the pragmatic impediments of instituting aerial FSO (Free-Space Optical) links to the exigencies of vertical industrial applications, these challenges epitomize the complicated landscape of UAV communications, beckoning further scholastic inquiry and innovative problem-solving.

Table 2.1: Comparison between different communication technologies for UAVs

Communication Technology	IEEE Standard	Frequency/Medium	Spectrum Type	Theoretical Data Rate	Latency	Advantages	Limitations
Wi-Fi	802.11	2.4 GHz	Unlicensed	Up to 2 Mbps	<5 ms	High speed and cheap	Limited range
	802.11a	5 GHz	Unlicensed	Up to 54 Mbps			
	802.11b	2.4 GHz	Unlicensed	Up to 11 Mbps			
	802.11n	2.4/5 GHz	Unlicensed	Up to 600 Mbps			
	802.11g	2.4 GHz	Unlicensed	Up to 54 Mbps			
	802.11ac	5 GHz	Unlicensed	Up to 3466 Mbps			
Bluetooth 5	802.15.1	2.4 GHz	Unlicensed	Up to 2 Mbps	3 ms	Energy-efficient	Low data rate
ZigBee	802.15.4	2.4 GHz	Unlicensed	250 Kbps	15 ms	Low cost	Low data rate
WiMAX	802.16a	2 to 11 GHz	Licensed	Up to 75 Mbps	30 ms	High throughput	Interference issues
LTE	LTE	Up to 20 MHz	Licensed	Up to 300 Mbps	5 ms	High bandwidth	Expensive
5G	5G (eMBB)	28 GHz	Licensed	Up to 20 Gbps	1 ms	High data rate	Expensive
Satellite	Satellite	Up to 40 GHz	Licensed	Up to 1 Gbps	550 ms	Wide coverage	High delay and high cost

The integration of UAVs into wireless communication networks is a crucial subject surveyed in [24]. Challenges stemming from UAV communications' mobility, fluid network topology, and energy constraints are recognized as significant obstacles requiring effective and reliable solutions. To achieve dependable and efficient communication on UAVs, researchers prioritize the development of robust routing mechanisms, seamless handover protocols, and energy-efficient strategies. The ultimate goal of this integration is to ensure reliable and efficient UAV communications, with a strong emphasis on addressing these challenges as the highest priority in this type of network. By focusing on providing reliable and efficient communication for UAVs, the seamless integration of these unmanned vehicles into communication networks can be achieved successfully.

In [25], the authors present a detailed solution for ensuring high-quality video streaming services in topographically challenging areas, like mountainous terrains. Using a fleet of N UAVs, these drones are suggested to function as aerial relays to bridge the gap where direct access to the video source station is compromised by natural obstructions. The essence of the paper is the continuous optimization of UAV trajectories to ensure equitable and efficient service delivery. A standout feature is the adaptive video streaming utility model, designed to align playback bitrates with real-time streaming capacities, minimizing video disruptions and enhancing QoE. However, it's worth noting that such models often face challenges related to UAV energy consumption, potential interference with other aerial devices, and scalability concerns when deployed in denser user environments. Additionally, ensuring consistent and reliable UAV-to-UAV communication can also be a concern, especially in adverse weather conditions.

In the study presented by [1], an in-depth examination of Unmanned Aerial Vehicle Communication Networks (UAVCN) is undertaken, emphasizing the critical role of UAVs in shaping versatile and dynamic communication networks for a myriad of applications. A primary concern highlighted is the inherent challenges posed by the high-speed maneuverability of UAVs. Such rapid mobility frequently destabilizes communication links, culminating in traffic routing inefficiencies, suboptimal quality of service, and overall performance setbacks. Moreover, power management emerges as a paramount consideration, necessitating the conceptualization and deployment of energy-conscious strategies to bolster UAV efficiency. The research covers a wide range of UAVCN topics, from fundamental design concerns to practical implementations. Nonetheless, it emphasizes the importance of forward-thinking research efforts to address current difficulties and strengthen resilience and efficacy.

In [2], a detailed exploration of contemporary UAV communication technologies is conducted. The research comprehensively covers task modules and antennas, stressing the innovative integration of machine learning with path planning to elevate communication strategies. Data security and integrity are pivotal, leading the study to address encryption methodologies and optimization processes. Power management is underscored as an essential component, with its role in extending UAV operational longevity critically discussed. The paper elaborates on the amalgamation of edge computing, artificial intelligence, and various UAV applications, including navigation and surveillance, showcasing the potential of these intersections in shaping future technological landscapes. The intricate dynamics between UAVs, advanced cellular communication, and the IoT are discussed, revealing challenges such as spectrum allocation, latency reduction, and interoperability. An overarching theme of the paper is the evident gaps in current knowledge, especially in drone-to-drone and drone-to-device communications. For instance, the need for standardized protocols, adaptive algorithms for congested networks, and solutions for real-time data transfer are highlighted. Conclusively, the survey accentuates a myriad of unresolved challenges, suggesting that UAV communications remains a fertile ground for research, ripe with open issues and future directions for exploration.

2.2 Multimedia Communication with UAVs

Expanding upon the exploration of UAV communication, attention is now turned to a fundamental aspect of this domain—multimedia communication with UAVs. Multimedia communication entails the exchange of various forms of media, including images, videos, and audio, between UAVs and other entities. As UAVs increasingly serve roles requiring real-time video transmissions, the intricacies of multimedia communication emerge as pivotal considerations. Multimedia communication for UAV deployments introduces problems and possibilities ranging from simple visual communication to the intricacies of real-time streaming, adaptive algorithms, and security considerations. This section investigates how various research projects handle these difficulties, laying the groundwork for an investigation of the link between UAVs and multimedia. With a growing need for more prosperous, more immersive experiences and the crucial nature of the data exchanged, guaranteeing the resilience, efficiency, and security of multimedia transmissions on UAV networks is essential.

In terms of video communication on UAV networks, there are numerous papers focused on distinct aspects. In [26], researchers proposed a parameter optimization mechanism for UAV intelligent video analysis. An "optimal strategy library" is designed so that the parameters for video encoding and FEC can be optimized for limited bandwidth on UAV videos on Multiple Object-Tracking (MOT) algorithms. These numbers are calculated using a data set of chosen tracking video streams and do not take changeable real-time video streams into consideration. According to their research, for MOT algorithms, the resolution of a UAV video may be more important than the frame rate. Although their recommended approach is beyond the scope of this thesis, I do investigate the changing video resolution method.

The work in [27] addresses the challenge of adaptive video streaming in UAV networks. It highlights the limitations of the IEEE 802.11 standard in UAV settings due to their highly dynamic and unpredictable network conditions. The core innovation presented is an "Adaptation Proxy" that makes real-time adjustments to video streaming quality based on network feedback, with particular emphasis on monitoring packet delay. However, a notable limitation is the reliance on a static threshold system for detecting network congestion, using fixed delay values like 1 second. While this methodology exhibits some merit, its precision is questionable, particularly in contexts where packet loss rates influence the determination of a viable threshold. The incorporation of an adaptive threshold mechanism, which intuitively modulates in response to real-time conditions, might present a more astute and efficacious avenue for enhancing video streaming fidelity within UAV networks.

In [28], researchers developed an approach to facilitate real-time video streaming on UAVs using cellular-enabled UAV technology. They specifically targeted LTE networks, optimizing both the throughput and video transmission schemes for such environments. The solution primarily focuses on buffer management, dynamically adjusting the number of frames sent per second based on network conditions to ensure continuous video transmission. However, several concerns arise regarding the paper's broader applicability. Primarily, the experiments were conducted indoors, potentially not accounting for the multifaceted challenges UAVs encounter outdoors. The approach's reliance on LTE networks restricts its utility in diverse networking scenarios, especially given the evolving nature of wireless technologies. Hardware specificity further constrains the solution's broader adoption, and unresolved challenges like antenna pattern linkage issues emphasize the need for additional refinements. Such limitations cast doubts on the approach's suitability for varied networks, suggesting that while it offers value within its specific context, its adaptability across diverse networking environments remains questionable.

In the research paper on energy-efficient secure video streaming in UAV-enabled wireless networks [29], the authors present a novel approach aimed at optimizing the balance between video quality, energy consumption, and security. At the heart of their discourse is the inception of the safe deep Q-learning network (safe-DQN). This network employs a set of safe policies, derived from the construction of a Lyapunov function, which is dynamically tuned to adhere to the constraint conditions of the constrained Markov decision process. This mechanism holistically encompasses trajectory design, video level selection, and power allocation to bolster optimal video streaming quality. Through simulations, the safe-DQN based algorithm consistently outperforms existing models in terms of energy efficiency and adaptability. A notable highlight is the algorithm's emphasis on maintaining a high secrecy rate, underlining the paper's focus on establishing a more secure connection against potential eavesdroppers. This work offers significant insights into the challenges and solutions surrounding UAV-based video streaming, making it a valuable addition to the literature on secure and efficient wireless multimedia communication on UAVs.

In the study denoted as [30], researchers evaluated both the resource allocation and the aerial trajectory design in the context of UAV-aided wireless networks that employ Dynamic Adaptive Streaming over HTTP (DASH) services. Their primary objective was to enhance the video quality, considering pivotal parameters such as bitrate, changes in bitrate, occurrences of communication outages, and timeout durations. Meanwhile, another related study, [31], introduced an energy-efficient video streaming protocol founded on the DASH methodology, specifically tailored for rotary-wing UAV systems. Their proposal emphasized the enhancement of the quality of experience for users on the ground. This was achieved by the simultaneous optimization of variables such as the UAV's transmit power, the allocation of spectrum resources, and the UAV's flight trajectory. However, it is crucial to note that DASH, given its inherent dependency on HTTP/TCP, can introduce undesirable latency. Such delays can be particularly pronounced, rendering the system less suitable for real-time streaming or scenarios demanding highly reliable Wi-Fi connections. This limitation highlights the potential advantage of exploring UDP-based streaming solutions, which tend to offer reduced latency and may be more appropriate for instantaneous, live communications.

In [32], the authors introduce a cellular-connected UAV base station that delivers real-time video via UAV user equipment to enhance fire monitoring in firefighting areas. They propose a dynamic UAV-to-UAV (U2U) communication framework to achieve live-streamed panoramic views from multiple firefighting regions. This strategy optimizes UAV positions, video clarity, and transmission strength to enhance the Quality of Experience (QoE). Using Deep Reinforcement Learning, incorporating both Deep Q Network and Actor-Critic techniques, the authors achieve these optimizations. Simulations indicate the learning method's superiority over the Greedy algorithm, resulting in improved QoE and reduced latency. However, the paper seems to neglect the energy efficiency of UAV networks and doesn't address its applicability to UAV-to-ground connections. The central emphasis on U2U limits its broader use, especially considering its design tailored for firefighting scenarios.

The "SkyEyes" research paper in [33] specifically addresses the challenges associated with adaptive video streaming from UAVs to ground base station scenarios. As UAVs equipped with high-end cameras become more prevalent among consumers, the unpredictable and fluctuating nature of wireless link capacities with UAV movement becomes a significant concern. To tackle these challenges, the SkyEyes system integrates two innovative approaches: content-based compression and video rate adaptation. The former focuses on compressing and transmitting targeted regions of interest, while the latter employs the UAV's location sensors to adapt video bitrates in accordance with the client's buffer status. Although the system showcases promise, it does not explicitly emphasize its design for real-time scenarios. This omission suggests potential latency issues or a lack of real-time processing capability, which could be viewed as a limitation in real-time video streaming applications

In the context of the security of real-time wireless multimedia transmission from UAVs, data security is essential, and [34] focuses on implementing a lightweight, real-time Advanced Encryption Standard (AES) encryption algorithm supported by onboard single-board computers. The research in [34] focuses on the design of a secure streaming application for military counter-UAV scenarios, demonstrating the effectiveness of AES encryption and decryption, even in adverse radio spectrum conditions. Furthermore, the study highlights the need for protecting sensitive multimedia data during transmission between drones and ground stations. The proposed system, integrated with AES cryptography, ensures swift and reliable encryption, safeguarding data against unauthorized access, and allowing for packet-level encryption, resilience to data loss, and resistance to passive attacks.

Other authors focus on the use of network-edge and device-edge computing to support video on UAVs. In [35], four strategies are introduced based on a combination of UAV-based processing and network-edge processing using a set of machine learning algorithms. Another use case appears in [36], where the performance boost from using a network-edge for video analysis is especially significant for longer videos. Additionally, in [37], the use of a network-edge server to offload UAV computation is analyzed. The common aspect between all of them is on balancing UAV-based and network-edge processing to conserve bandwidth, enhance scalability, and maintain result accuracy and latency. The section 3.3 contains my investigation on this area.

2.3 Error Control Methods for Real-Time Multimedia Communication

Having explored the intricacies of multimedia communication with UAVs, the challenges associated with ensuring reliable multimedia transmission have become evident. Multimedia content, especially in large volumes, is susceptible to transmission errors, which can significantly degrade user QoE if not addressed. Ensuring the integrity and reliability of this communication is a top priority. Error control methods refer to the set of techniques and protocols designed to detect, correct, and mitigate errors that occur during the transmission of data across networks. As this thesis shifts focus from the general landscape of UAV multimedia communication to specific error control methods, the need for practical, real-time error correction emerges prominently. A prevalent solution in multimedia communication is the use of Forward Error Correction (FEC) for its proven capability to meet stringent latency requirements and mitigate packet losses during network transmissions. The purpose of this section is to explore contemporary research on error control mechanisms with a focus on FEC in relation to real-time multimedia transmission.

Error control methods are pivotal in ensuring reliable data communication, especially when transmitting data over unstable or unpredictable channels. At their core, these methods strive to detect and correct errors that occur during the transmission of data packets. FEC stands out among these methods due to its proactive nature. Unlike other methods that rely on retransmitting data once an error is detected, FEC preemptively sends redundant data alongside the original data. This redundancy allows the receiver to correct a certain number of errors without requiring a retransmission, making it especially advantageous for scenarios where low latency is crucial.

In the context of UAVs transmitting a high volume of high-quality compressed video, FEC appears as an especially suitable choice. The reason lies in the inherent characteristics of UAV communications: they often operate in environments with fluctuating signal quality and might be constrained by limited bandwidth. Retransmissions, in such scenarios, can lead to significant delays and degradation in video quality. Moreover, high-quality compressed videos are particularly sensitive to packet losses, with even a single lost packet potentially resulting in noticeable visual artifacts. FEC, by mitigating the need for retransmissions, ensures that high-quality video streams are delivered more reliably and with reduced latency, preserving the fidelity and smoothness of the transmitted video, which is of paramount importance in applications such as real-time surveillance or aerial imaging.

[38] introduces R-FEC, a novel reinforcement learning-based framework designed to optimize video and FEC bitrates in video conferencing applications. While addressing the surging demand for video conferencing, it acknowledges the challenges associated with users' quality of experience and the prevalent reliance on FEC to manage latency and packet losses. Unlike prior research predominantly centered on video rate control, R-FEC considers the complex interplay between FEC and rate control, striving to maximize user QoE by dynamically adjusting bitrates based on past decisions while minimizing network congestion. Empirical evaluations showcase R-FEC's superiority, demonstrating up to a 27% improvement in video rate and a 6dB PSNR (Peak Signal-to-Noise Ratio) enhancement in video quality compared to default solutions. This innovative approach and its results offer valuable insights for optimizing QoE in video conferencing. Importantly, R-FEC is proposed for video conferencing and employs FEC for packet recovery in the data link layer. Nonetheless, its adaptability to diverse network types, such as UAVs, where adjusting video rate and FEC redundancy may prove beneficial, highlights its potential for broader applications.

Interactive streaming applications necessitate communication systems that transmit source packets with low latency and high reliability. While FEC codes offer a solution, traditional ones fall short in meeting the stringent real-time requirements. The tutorial [39] explores the evolving landscape of streaming codes designed for such applications, shedding light on their layered design through illustrative examples. Traditional FEC like RS (Reed—Solomon) codes, rateless codes, and RLC (Random Linear Convolutional) codes prove suboptimal due to their lack of consideration for varying source packet deadlines, forcing simultaneous recovery of erased packets. The tutorial introduces a novel class of codes, known as MS (Maximally Short) codes, which excel in correcting errors over burst-erasure channels by sequentially recovering erased source packets, accommodating diverse decoding deadlines. Additionally, MIDAS (MaxImum Distance And Span) codes and ERLC (Embedded RLC) codes are discussed, trading some burst-error correction for robustness in isolated-erasure channel models. The tutorial evaluates their performance across different packet-loss sequences and demonstrates their efficacy over statistical channel models and real packet traces. Future directions were introduced in the [39] include designing systems capable of dynamically selecting FEC codes based on application constraints and channel statistics, as well as tailoring FEC codes to adapt to the channel state and source stream importance. This evolving field holds great promise for interactive voice and video communication, augmented and virtual reality applications, IoT use cases, and more.

[40] explores the challenges of real-time video communication. Packet loss poses a significant threat to reconstructed video quality, detrimentally impacting users' QoE. Although common FEC techniques used in applications like Skype and Zoom are discussed as a means to mitigate this issue, the authors underscore their inefficacy in dynamic network conditions, which leads to increased bandwidth consumption. To address this, the paper introduces RL-AFEC, an adaptive FEC scheme driven by Reinforcement Learning. RL-AFEC dynamically adjusts redundancy rates for video frames, effectively reducing bandwidth usage while maintaining video quality. Additionally, it presents a packet-level Video Quality Assessment (VQA) method based on Video Multimethod Assessment Fusion for real-time video quality evaluation without the need for complete content reconstruction. Their experiments confirm RL-AFEC's superiority over conventional FEC methods, delivering commendable video quality with just a 40% increase in bandwidth consumption, making it a highly efficient solution for unreliable, bandwidth-restricted networks. The paper's contributions encompass a real-time packet-level VQA method, an adaptive RL-based FEC scheme, and exhaustive real-world evaluations. RL-AFEC's ability to adapt redundancy rates based on network conditions ensures video quality preservation while minimizing bandwidth utilization, guaranteeing commendable qual-

ity for over 95% of 1-second videos.

In [20], the authors present a novel adaptive cross-layer error control protocol (NAC) designed to enhance the reliability and efficiency of real-time multimedia streaming within Wireless Sensor Networks. The NAC protocol incorporates several key features, including an adaptive FEC algorithm at the application layer, a dynamic hybrid FEC/ARQ mechanism, and an unequal error protection mechanism within the wireless link layer. Additionally, it dynamically adjusts the level of erasure codes applied to groups of packets, guided by metrics like the mean absolute deviation of recent average round-trip times and cross-layer information such as acknowledgment packet arrivals, network traffic loads, and wireless channel conditions. By dynamically determining the appropriate redundancy for source packets based on packet loss rates in the hybrid FEC/ARQ error control algorithm at the wireless link layer, the NAC protocol offers substantial improvements over existing error control schemes while reducing the need for ARQ retransmissions. Their comprehensive simulations demonstrate that the proposed NAC protocol outperforms popular error control schemes in terms of energy efficiency, frame loss rates, frame PSNR, and PSNR under delay constraints for real-time multimedia streaming across sensor networks.

An energy-efficient framework for supporting QoE in wireless video communications was presented in [41]. The framework comprises two key components: a perceptual video quality model and an application layer energy-efficient FEC scheme. The perceptual video quality model offers real-time, low-complexity prediction of video quality, considering factors related to video content, compression, and transmission distortion. Leveraging this quality model, the proposed FEC scheme safeguards video packets against transmission losses while adhering to user-defined perceptual quality requirements. It dynamically adjusts protection levels for various video stream components, optimizing network efficiency. This paper introduces a reference-free, lightweight model for perceptual video quality prediction and advances energy-efficient, content-aware FEC, providing improved QoE in wireless video transmission while the simulation was evaluated on some short test video on 704×576 and 720×576 as resolutions. This shows that it is not suitable for sending 4K video.

In [42] and [43], extensive simulations were conducted to assess error control mechanisms in Wireless Multimedia Sensor Networks. [42] compared ARQ, FEC, and hybrid ARQ/FEC methods, finding that while FEC was energy-efficient, it struggled with higher error rates. ARQ had poor PSNR performance, and the hybrid ARQ/FEC method provided better perceived video quality but was less energy-efficient. [43] evaluated ARQ, FEC, Erasure Coding (EC), link-layer hybrid ARQ/FEC, and cross-layer hybrid schemes in terms of energy efficiency, PSNR, frame loss rate, jitter, and delay-constrained PSNR. The results showed that link-layer hybrid and cross-layer hybrid approaches improved video quality at the sink node, with the cross-layer scheme excelling in low bit error rate scenarios and link-layer hybrids in high bit error rate scenarios.

The paper in [44] introduces a novel rate control algorithm, FBRA (FEC-based Rate Adaptation), designed for conversational multimedia streams. FBRA incorporates FEC encoded RTP (Real-Time Protocol) packets alongside standard media packets to probe available bandwidth and aid in congestion control. By adjusting the FEC bit rate, the sender can conservatively or aggressively assess network capacity. Comparisons with other congestion control algorithms demonstrate that FBRA strikes a balance between capacity and packet loss rate. Real-world evaluations reveal FBRA's superior performance in terms of reduced packet delay variation and improved goodput compared to other congestion control algorithms. Moreover, FBRA's applicability on the public Internet showcases its potential. This innovative approach, utilizing FEC not only for error resilience but also for congestion control, holds promise for enhancing multimedia streaming in challenging environments and can potentially be integrated into various rate control algorithms, offering flexibility and efficiency improvements for diverse network scenarios.

In [45], an energy-efficient HTTP adaptive streaming system was presented, designed to enhance video streaming quality over SDN-enabled Wi-Fi APs. A pivotal component of this system is the use of FEC through the Luby Transform code. FEC plays a crucial role in ensuring flexible and reliable data transmission across multiple APs, particularly when channel conditions can be unpredictable. This correction method boosts the system's resilience against potential data loss, thereby elevating the streaming experience. The system heavily relies on HTTP, indicating its optimization for scenarios where a connection-oriented protocol is ideal. It's worth noting, however, that this design might not be well-suited for UDP scenarios and one AP, which are connection-less and require different optimization techniques.

The paper [46] presents a method that focuses on optimizing QoE for video streaming by employing a neural network approach. The proposed method, ABRF, predicts network loss patterns and strategically allocates redundancy to maximize QoE using the VMAF (Video Multi-Method Assessment Fusion) metric. While this method demonstrates effectiveness in real-time video streaming over the Internet, particularly for platforms like Netflix or YouTube, its suitability for high mobility or UAV scenarios is questionable. In critical applications such as firefighting or search and rescue, the emphasis shifts from viewer perception to paramount concerns like reliability and low latency. Ensuring that vital information is transmitted without delays or distortions becomes essential. While ABRF can aid in data integrity during transmission, the QoE-optimization strategies designed for entertainment streaming may not be appropriate for high-stakes, real-time decision-making scenarios. In essence, while ABRF excels in enhancing viewer experience for entertainment platforms, its application in emergency scenarios with stringent reliability and low latency requirements remains uncertain.

The [47] underscores the significance of Application-Level Forward Error Correction (AL-FEC) in augmenting the QoE for multimedia services delivered via wireless LANs. By harnessing Reed-Solomon block codes, AL-FEC adds redundancy to data streams, enhancing their reliability without resorting to acknowledgments or retransmissions. The study illustrates a scenario where Access Points (APs) concurrently transmit video feeds to several receiving terminals via the RTP/UDP protocol, showcasing the advantages of group-casting. Yet, group-casting, despite its benefits, doesn't fit all contexts. Notably, in dynamic settings like UAV-operated areas, or in high-stakes situations such as search and rescue or firefighting, traditional group-casting may fall short, especially when there's a constraint on resources to deploy multiple APs.

The realm of error control in real-time multimedia communication is a critical aspect of ensuring data reliability and integrity, especially in the challenging environment of UAV communications. The use of FEC, mainly, has emerged as a robust strategy to tackle latency and packet loss issues, maintaining the fidelity of high-quality video streams. The contemporary research landscape has been filled with innovative solutions, ranging from adaptive redundancy in FEC frameworks to perceptual video quality models, each addressing different challenges and application scenarios. As technology continues to evolve and the demand for reliable multimedia communication grows, it is essential for the research community to continuously evaluate, adapt, and optimize these error control methods, especially in dynamic scenarios like those presented by UAVs.

After delving into the complexities of these error control methods, the following chapter will conduct a detailed literature assessment of the key study on Error Control Methods in Multimedia Communication for UAVs and additional ways for increasing reliability. This review will not only illuminate the key findings and methodologies of the thesis but will also place its contributions within the wider discourse of UAV multimedia communication, offering a comprehensive interpretation of its significance and possible influence.

Chapter 3

Literature Review

This chapter delves into the Forward Error Correction method, particularly emphasizing its prominence in addressing the low latency delivery requirements intrinsic to real-time video streaming in UAVs. The details and relevance of FEC in UAV communications are explained in subsection 3.1. Concurrently, it's imperative to acknowledge other error control mechanisms, specifically the Automatic Repeat reQuest. An analytical discourse on ARQ, its attributes, and its potential limitations in the UAV communication spectrum can be found in subsection 3.2.

As this thesis traverses through the intricacies of error control, it is also pertinent to investigate the burgeoning field of mobile edge computing. This contemporary concept, albeit in its formative stages, posits a promising avenue for enhancing the efficacy and adaptability of FEC within UAV multimedia communication frameworks. The subsequent sections provide an overview analysis of its potential implications and integration challenges.

3.1 Forward Error Correction on UAVs

FEC stands as a pivotal technique in UAV communications, particularly vital for robust real-time video streaming. A crucial aspect of FEC is the determination of redundancy levels, which directly impacts its efficacy in error mitigation. Upon diving deeper into this thesis, the initial exploration will focus on prior research. This will highlight how past innovations and challenges have shaped the current understanding and application of FEC in UAVs.

In [17], the authors present a cross-layer perspective aimed at enhancing the transmission reliability of streaming media on a cellular-connected UAV. Their proposed solution revolves around an integrated Client-Server-Ground&User framework, where they implement a series of algorithms, including a FEC mechanism. The FEC algorithm defines four distinct streaming modes, each tailored to specific network conditions based on end-to-end delay and packet loss rate parameters. However, it is noteworthy to highlight that this approach differs from our work in certain aspects. One limitation lies in the use of a predefined set of operational states and FEC, which may restrict the solution's adaptability to highly variable link conditions. Additionally, the maximum correction ability of their FEC mechanism is confined to 2% of the Packet Loss Rate (PLR), potentially limiting its effectiveness in scenarios with higher error rates. As the literature review progresses, various approaches and solutions addressing the challenges of streaming media transmission on UAVs will be explored, aiming to contribute to a more comprehensive understanding of this intricate domain.

In the study conducted in [48], the authors investigate the reliability and efficiency of employing broadcast transmissions from a UAV to multiple network access points, employing a packet-level FEC technique. Their experimental findings demonstrate that broadcast transmissions with packet-level FEC yield a significantly higher packet delivery ratio compared to unicast transmissions. Similarly, the framework proposed in [49] also utilizes broadcast transmissions from a UAV to multiple access points, aiming to enhance reliability by incorporating a FEC scheme at the application layer, eliminating the need for retransmissions. While such approaches appear attractive in theory, it is essential to consider their scalability and practicality for scenarios involving larger numbers of transmitters. Additionally, the assumption that a UAV will always remain within a range of multiple network access points may not be realistic, especially in outdoor settings.

The paper [50] introduces an adaptive error control framework for a cognitive radio-based UAV network, with the primary goal of minimizing energy consumption to extend the UAVs' operating lifespan. A key aspect of this framework involves selecting the appropriate error control mechanism, where the choice between ARQ and FEC is based on the selected radio channel. In this hop-to-hop delivery network topology, each UAV can independently choose its error coding scheme, either ARQ or one of 70 different BCH codes within the FEC category. However, it is important to note that this study does not specifically address the challenges of real-time, high-bandwidth, and high-quality video delivery in UAV networks.

The authors of [51] propose a QoE-aware adaptive mechanism to enhance video quality in UAV communication by leveraging motion vector details, FEC, and Fuzzy logic through a cross-layer adaptive video-aware approach. This mechanism seeks to optimize the video streaming experience and ensure high-quality video delivery over UAV networks. The incorporation of UAVFEC (UAV Forward Error Correction) enhances video transmissions in highly dynamic networks, maximizing QoE without unnecessary network overhead. However, the method necessitates pre-calculation of appropriate FEC redundancy based on specific scenarios, which limits its suitability for real-time video transmission in dynamic network conditions. Despite the promising potential of the adaptive video-aware mechanism in enhancing video quality, further research is needed to address the pre-calculation constraint and enhance adaptability for real-time UAV video transmission scenarios.

Table 3.1 lists publications that discuss FEC on UAVs. I could not find any publications that addressed the same objectives as this thesis and that gave me enough mathematical information and/or code to duplicate their approach for comparison.

Table 3.1: Summary of related published papers

Ref.	Year	Focus	Error control mechanism	Evaluation	Code
[19]	2023	Unicast	Comparing AL-FEC and AL-ARQ in terms of energy usage	Analysis	No
[17]	2021	Framework	AL-FEC with a predefined set and covering max 2% PLR	Testbed	No
[48]	2020	Broadcast	AL-FEC with a predefined set with 4 values	Testbed	No
[26]	2020	Tracking	AL-FEC with a predefined set with 8 values & Video encoding	Simulation	No
[50]	2019	Multiple UAVs as sender and relay	Selecting between ARQ and FEC	Analysis	No
[49]	2017	Broadcast	AL-FEC with static redundancy	Analysis	No
[51]	2014	Unicast	AL-FEC FEC with a predefined set	Simulation	No

In contrast to previously published research, this thesis focuses on a highly adaptive error control mechanism that can handle a variety of network conditions, satisfy the requirements for low-latency video delivery from UAVs, and enable real-time analysis and action by a network-edge computing aspect at a sender UAV node.

3.2 Automatic Repeat reQuest on UAVs

Despite the superior performance of FEC mechanisms in achieving high-quality video transmission on UAV communication, ARQ is also explored as an alternative solution for improving quality in this network. This section investigates the relevant papers in this area.

Another approach for enhancing QoS and controlling congestion is network coding, implemented on relay nodes in networks. Given that middle nodes in multihop routing can be bottlenecks for video streaming in flying ad-hoc networks (FANETs), network coding offers increased reliability for relay nodes.

The majority of published papers on this subject come from a research group that has focused on ARQ and network coding in UAV communication. Their initial paper examines throughput efficiencies of relaying algorithms using selective-repeat ARQ in Flying Ad hoc Networks [52]. The study evaluates three algorithms (chunk-by-chunk, fifty-fifty, and ratio-based) through Markov models and simulations involving stationary and mobile relay nodes, aiming to identify the optimal algorithm for data streaming in highly mobile UAV ad-hoc networks. Notably, this study concentrates on relay nodes and does not specifically address multimedia communication.

The study team extended their findings by simulating the application layer ARQ along with the data-link layer ARQ on relay nodes in FANETs of UAVs in their future work in [53]. They investigated how the building on the techniques suggested in [52] interacted with the 802.11n standard and the data-link ARQ algorithm on relay nodes. Using the NS-3 simulation tool, simulations were run with an emphasis on highly mobile node situations with speeds up to 50 m/s and ranges up to 560 meters. The simulation results, however, showed that they were unable to effectively resolve packet loss caused by the high mobility of nodes in a FANET despite the combination of data-link ARQ and relay-based retransmission strategies.

In another concurrent study [54], the same research group focused on evaluating network coding in various scenarios within FANETs using the NS-3 simulation tool. When the primary stream is complete, network coding, which employs the ARQ technique, may cause retransmission. The study involved comparing "copter," "fixed-wing drone," and "swarm" scenarios based on QoS metrics. The 802.11g standard was used for the data-link layer, while the AODV routing protocol was used for the network layer. The number of retransmissions in the 802.11 protocol's current ARQ technique was changed to 1, which effectively turned off the data-link layer ARQ. The study underscores the necessity for coding-aware algorithms to tackle mobility challenges and enhance network coding for relay nodes in FANETs.

Furthermore, the research group attempted to assess network coding in a real-world setting. They conducted a performance evaluation using a testbed which is introduced on [55] and suggested it as a suitable platform for future evaluations of emerging relaying and coding algorithms in FANETs.

The next paper [56] by the research group explores a version of network coding called COPE-like, which enables data compression for more efficient utilization of the wireless medium. The study discusses the application of this network coding approach in the context of UAV networks, specifically FANETs. Through a comprehensive evaluation and analysis of the results, the researchers found that network coding is a powerful tool that optimizes the use of transmission medium resources, especially in real-time wireless networks.

In the context of energy consumption in UAV networks, [19] studied comparing the performance of FEC and ARQ algorithms at the application layer. It found that FEC with adaptive redundancy demonstrates superior energy efficiency compared to ARQ in UAV networks with unstable channel quality. These results justify our research focus on implementing adaptive FEC at the application layer, with respect to relative energy consumption.

In conclusion, the research conducted so far in UAV networks has explored the utilization of ARQ in network coding approaches. However, it is evident that these studies have not specifically addressed real-time video streaming, and network coding has mainly been considered for relay nodes. Such limitations hinder the development of a comprehensive, reliable, and adaptive error control mechanism suitable for multimedia streaming in UAV networks. To achieve a truly robust solution, it is essential to design an error control mechanism that encompasses all types of nodes and scenarios, ensuring seamless and efficient transmission across the entire network. Further research and advancements in this direction are imperative to unlock the full potential of UAV networks in multimedia communication.

3.3 Mobile Edge Computing for UAV communication

Mobile Edge Computing (MEC) stands as a revolutionary paradigm, integrating the capabilities of cloud computing right at the edge of wireless networks. This transformative approach brings about a notable reduction in latency and a substantial enhancement in data processing capabilities, particularly advantageous in scenarios such as real-time video analytics on compact drones. These drones continuously generate substantial data streams, necessitating immediate analysis for a spectrum of applications spanning agriculture to surveillance. By giving drones the option to offload computationally demanding operations to nearby edge computing nodes, MEC reduces latency and makes effective real-time data processing possible [57].

There are synergistic benefits when edge computing and drone computing are combined. Small drones can locally process and analyze data, minimizing the time between data collection and useful insights. Real-time video analytics, such as object recognition and anomaly detection, are made possible while the drone is in flight thanks to this connection. This may be a novel method for delivering higher quality and lower latency for algorithms with computational components, including error-control methods. Therefore, this dissertation is attempting to mainly follow the benefits and drawbacks of the cooperative UAV-MEC offloading strategy.

Numerous papers have explored this area, but our focus has been on delving deeper into the realm of UAVs and multimedia communication. First and foremost, in their work, the researchers in [58] offer a comprehensive examination of MEC, an emerging architectural paradigm that extends cloud computing services to the network edge via mobile base stations. MEC seamlessly integrates diverse application service providers, catering to a range of stakeholders including mobile subscribers, enterprises, and various industry sectors, with particular relevance in 5G networks where low-latency requirements are paramount. Furthermore, the research underscores MEC's potential to enhance the capabilities of resource-constrained mobile devices and foster collaborative ecosystems involving multiple stakeholders. The paper also delves into the critical subjects of security and privacy concerns, proposing potential solutions and underscoring the pivotal role of MEC in shaping the future of edge technology.

On a related note, the [59] provides a comprehensive survey of the evolving field of Edge computing, with a particular focus on its significance in enabling low-latency and location-aware services, which are crucial for technologies like 5G, IoT, and augmented reality. This paper reviews the latest developments in edge computing, including Mobile Edge Computing, Cloudlet, and Fog Computing, shedding light on their diverse applications. It emphasizes the fundamental role of edge computing in scenarios where rapid response times are imperative and identifies key needs and open research challenges within this paradigm.

The article [60] formulates an optimization problem to minimize service delay and UAV energy consumption by optimizing UAV position, communication, computing resource allocation, and task splitting decisions. To tackle the complexity of this problem, the authors develop an efficient algorithm based on successive convex approximation. Numerical experiments demonstrate the superiority of the proposed collaborative UAV-EC offloading scheme compared to schemes that rely solely on either UAVs or ECs for MEC in IoT scenarios.

In [35], the research explores the potential of autonomous drones equipped with video sensors in various applications, emphasizing real-time video analysis. The study addresses challenges related to wireless bandwidth, processing power, and result accuracy. To overcome these challenges, the authors propose an adaptive computer vision system for tasks like search-and-rescue and surveillance. They introduce strategies like early discard and context-based filtering to efficiently use bandwidth. Experimental results demonstrate that this approach saves bandwidth while maintaining accuracy and speed, making it scalable for multiple drones and reducing the need for constant operator oversight.

The paper [37] investigates using UAVs in MEC networks to improve energy efficiency. It proposes an algorithm that optimizes energy use by considering factors like delay and data size. The paper also outlines the limitations of existing MEC networks, introduces a new three-layer UAV-based MEC network architecture, and discusses task offloading and data communication functions. Simulation experiments confirm the algorithm's effectiveness and suggest future research directions in UAV optimization and deep learning-based network resource prediction for MEC networks.

The [61] discusses the importance of target tracking in social security and the challenges of traditional methods involving cloud-based data processing, leading to bandwidth issues and delays. It also mentions limitations with UAV-based tracking due to flight constraints and obstacles. The study proposes a novel target-tracking model that combines UAV and ground-based tracking in edge computing. This model reduces costs, minimizes delays, and increases the likelihood of reacquiring a lost target. It demonstrates superior performance compared to traditional cloud-based surveillance systems, offering low latency, high reliability, and enhanced quality of experience.

The paper, [62], explores the symbiotic integration of UAVs with edge computing and AI. Traditional cloud-based AI systems fall short for UAVs due to latency and energy consumption concerns. The edge computing solution offers localized data processing, which improves UAV communication reliability. By bringing computation closer to data sources, UAVs achieve reduced latency, ensuring swift, dependable data processing crucial for real-time missions. This paper emphasizes "edge AI", combining AI's predictive prowess with edge computing's proximity benefits, paving the way for UAVs to adapt efficiently to changing scenarios. Furthermore, this convergence enables UAVs to undertake federated learning, which underpins both adaptability and reliability, without the necessity for consistent centralized data transfers. In essence, edge computing proves instrumental in addressing UAV communication issues, providing a reliable and flexible communication paradigm for their expanding roles.

Based on MEC perspectives, the references illustrate how UAVs and MEC can enhance real-time UAV communications. MEC reduces latency and bandwidth usage, which are vital for tasks like UAV video analytics. Strategies like early discard and context-based filtering optimize resource utilization. Studies show that collaborative UAV-EC offloading surpasses baseline methods. This highlights how UAV computing may be used to lower latency and bandwidth, opening the door for error control techniques in real-time UAV communication.

3.4 Research Challenges

Addressing the research challenges in error control for multimedia UAV communication requires innovative solutions that tackle the complexities of real-time data transmission in dynamic environments. Paramount among these challenges is the need for adaptive error control mechanisms capable of dynamically adjusting redundancy levels in response to fluctuating network conditions, ensuring optimal performance in real-time data transmission scenarios. Additionally, achieving the lowest possible latency for real-time connections is a critical objective, necessitating error control techniques that prioritize timely data delivery without compromising accuracy.

Supporting the transmission of high-resolution 4K video presents another substantial challenge, requiring the implementation of efficient error control protocols capable of managing large data volumes with minimal latency. Furthermore, the integration of UAVs with Mobile Edge Computing (MEC) offers promising avenues for enhancing real-time UAV communications by reducing latency and bandwidth usage, crucial for tasks such as UAV video analytics.

The implementation of real-time error correction mechanisms is essential to promptly mitigate transmission errors and maintain data integrity during UAV operations. Supporting time-sensitive traffic, such as emergency response or surveillance applications, requires error control strategies that prioritize critical data packets to ensure timely delivery. Finally, developing error control protocols suitable for diverse scenarios, rather than specific applications, poses a challenge, demanding adaptable and robust solutions capable of accommodating varying network conditions and operational requirements across different UAV missions.

These design objectives, rooted in established academic findings, will serve as foundational pillars as the thesis transitions to the forthcoming chapter elucidating the proposed framework.

Chapter 4

Adaptive and Reliable Forward Error Correction Method for UAV Video Transmission

The QoS requirements of real-time video streaming in UAV networks necessitate algorithms for UAV multimedia communication that are reliable, high-quality, and error-resistant. UAVs play crucial roles across numerous applications, with the precision and safety of video transmission being paramount. However, UAV networks often encounter unreliable and inconsistent communication links. Current error control techniques, particularly ARQ, have challenges including the need for a reverse channel and variable network latency. FEC systems are also used to address these issues; yet, selecting the right level of redundancy is pivotal. Moreover, while high-quality video is imperative in various UAV scenarios, it is equally vital to manage latency, especially in critical situations like search and rescue missions.

Reflecting on these challenges, the following sections present an approach that addresses these concerns. Attention is drawn to the "Design Objectives" depicted in Figure 4.1, which outline the primary goals intended to be fulfilled by the proposed method in this thesis. The figure elucidates several key targets, such as adaptive redundancy, real-time error correction, and reducing control latency. Additionally, the design aims to support high-quality 4K video, ensure compatibility with a range of scenarios and network types, and facilitate delay-sensitive traffic. Collectively, these objectives not only underscore the ambition of the proposed approach but also highlight its potential to enhance the robust-

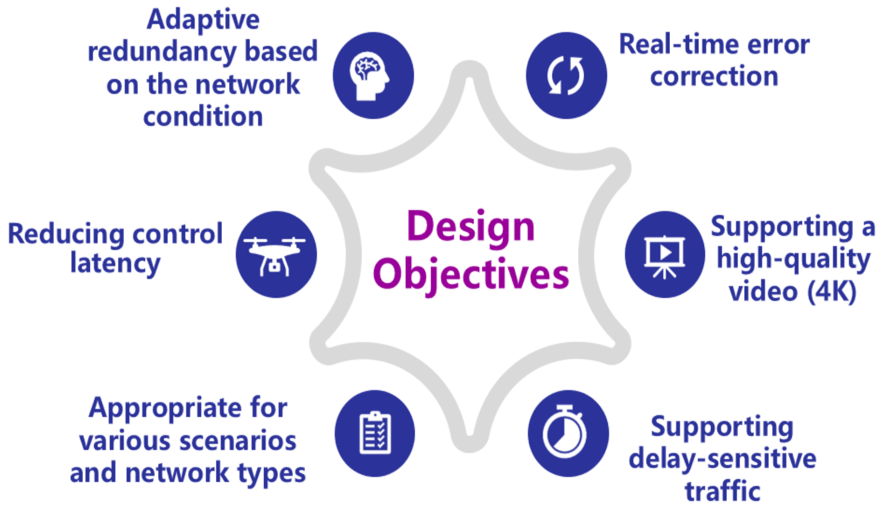


Figure 4.1: Design Objectives on AR-FEC

ness and efficiency of contemporary networked systems.

In response to these challenges, the proposed solution introduces the concept of adaptive redundancy within FEC, strategically situated at the application layer. The proposed Adaptive and Reliable Forward Error Correction (AR-FEC) approach leverages granular insights into the video's structural composition, thereby bestowing precedence upon safeguarding high-priority frames from potential errors. Furthermore, the incorporation of edge computing further amplifies the adaptive FEC algorithms' performance, effectively reducing latency and elevating the overall efficiency of UAV networks. This holistic solution signifies a substantial leap towards the realization of robust, high-quality video streaming for UAV applications, with direct implications for enhancing operational safety and efficiency across a multifaceted spectrum of domains.

4.1 AR-FEC Overview

AR-FEC is designed to reliably stream high-quality real-time video from a mobile UAV to a designated station. AR-FEC achieves this goal by adaptively changing the video quality and FEC overhead as the UAV navigates its assigned path. The adaptation decisions are based on monitored packet losses and delays for previously transmitted GoPs to estimate the network capacity and losses. Figure 4.2 shows a system block diagram of the proposed method. In this diagram, the Sender block denotes the UAV, which is responsible for capturing and transmitting the video data, while the Receiver block represents the ground sta-

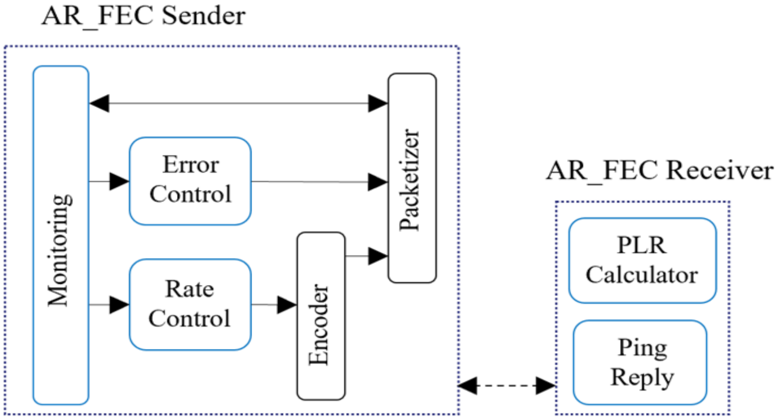


Figure 4.2: System blocks of the AR-FEC algorithm

tion, which receives and processes the video stream. The estimated parameters from the UAV are utilized to determine the appropriate FEC level and the quality of the video for the next GoP.

The AR-FEC framework, illustrated in Figure 4.2, is a composite sender-receiver system developed to optimize the reliability of real-time video transmission. At the sender's end, a "Monitoring" module diligently oversees the transmission environment, collating critical statistics to inform the "Error Control" module, which is pivotal in preserving data integrity. Concurrently, "Rate Control" collaborates with the "Encoder" to modulate the data rate adaptively, thereby optimizing video frame quality while ensuring judicious bandwidth utilization.

On the receiving end, the "PLR (Packet Loss Rate) Calculator" plays a significant role by evaluating packet loss and informing the adjustment of FEC parameters. This information is dispatched through the Real-time Control Protocol (RTCP) for real-time feedback. Complementing this, a "Ping Reply" system establishes a responsive communication channel, enabling the assessment of network latency and the detection of congestion within the network infrastructure. Such responsive communication is indispensable for adjusting FEC redundancy, thus safeguarding the video stream against the vagaries of network fluctuations.

The orchestrated functionality of these modules forges a formidable system that proactively anticipates and compensates for potential data loss. This ensures a seamless delivery of high-caliber video content to the end user, effectively elevating the viewing experience despite the challenges posed by an ever-changing network landscape.

The AR-FEC's pivotal features are detailed below:

- **On-Board Device-Edge Computing:** By integrating the FEC mechanism directly into the UAV's computing platform, AR-FEC leverages the edge of the network, minimizing latency and allowing for swift responses to fluctuating network dynamics. This close proximity to the data source affords the system an unparalleled capability to process and adjust the error correction protocols in near real-time, thus mitigating the risks associated with delayed feedback loops that can degrade video quality.
- **Unequal Error Protection for I-Frames:** AR-FEC employs a tailored Unequal Error Protection (UEP) strategy for I-frames, which are crucial for video integrity. This approach minimizes the FEC overhead while ensuring that I-frames receive the protection they need, thus preserving the overall video quality without excessive bandwidth consumption.
- **Adaptive Error Protection Ratio:** The system dynamically tunes the error protection ratio in response to the network environment. This adaptive feature allows AR-FEC to maintain a high level of error correction capability while managing bandwidth more efficiently, ensuring a balance between quality and transmission overhead.
- **Quality of Service Adjustment for Real-time Communication:** AR-FEC proactively adjusts the video quality to prevent congestion within the communication link. This quality modulation, responsive to the network's current throughput, maintains uninterrupted real-time video communication, thus avoiding the detrimental effects of network bottlenecks.
- **Real-Time Error Correction at the Control Station:** A powerful real-time error-correcting mechanism is installed on the receiving end. This component quickly corrects any data corruption that occurs during transmission, resulting in a continuous and smooth video stream for time-critical and mission-critical applications.

In summation, the AR-FEC system delivers a robust and dynamic solution for UAV-based video streaming, ensuring the consistent provision of high-quality video feeds despite the inherent volatility of mobile networking conditions.

4.2 AR-FEC Design

4.2.1 AR-FEC Network Monitoring

The robust architecture of AR-FEC is centered on its capacity to continuously monitor and analyze network performance, a process that is dependent on two critical parameters: packet loss ratio (PLR) and network delay (D). These metrics are meticulously recorded for each sent Group of Pictures (GoP), providing a picture of the network's current condition.

To facilitate a streamlined representation, we denote "t" as the index for the impending GoP to be dispatched. Consequently, PLR_t represents the anticipated PLR for this next GoP, while $PLR_{(t-1)}$ provides the actual PLR for the GoP currently being transmitted. This distinction allows for a forward-looking approach to network monitoring, where predictions and adaptations are based on the most recently gathered data.

The UAV, serving as the sending node, acquires PLR_i data via a feedback loop originating from the receiver. Upon successful reception of $GoP_{(t-1)}$'s I-frame and its accompanying FEC packets, the edge station computes the percentage of packets that are lost during transmission. This data is then relayed back to the UAV using the RTCP protocol, facilitating an iterative feedback process. The UAV retains the latest PLR figures and their associated indices, harnessing this information to adaptively forecast PLR_t for future transmissions. It's pivotal to acknowledge that the packets entrusted with carrying PLR feedback are themselves susceptible to the very channel impairments they report on, including loss and delays.

Timing is crucial in the AR-FEC system for precisely measuring network latency. At a certain moment in the GoP time-frame, the UAV transmits a PING request to the base station. The difficulty is to select a time when the PING reply may inform the succeeding GoP's transmission without being lost or delayed at the conclusion of the current GoP. Sending the PING too late in the GoP cycle may result in the UAV not getting critical timing input in time, which is vital for modifying the settings of the next GoP.

The PING request, once initiated, enters the MAC layer's queue and waits behind the ongoing video packets. Network degradation can cause this delay, limiting the AR-FEC's capacity to fine-tune its rate adaption for the following GoP. Accurately assessing network latency is thus critical; it enables the AR-FEC to adapt the video streaming rate dynamically, maintaining a seamless streaming experience in the face of fluctuating network conditions. The system's effectiveness is dependent on this precise synchronization, ensuring reliable video transmission tailored to the network's current state.

4.2.2 AR-FEC Error Protection

The AR-FEC system's error protection scheme is intricately designed to safeguard the integrity of video streaming, particularly through the careful management of I-frames and P-frames. I-frames are the foundation upon which P-frames, or predictive frames, are constructed, enabling the dynamic and real-time encoding and decoding of video sequences as they are captured and transmitted from UAVs to the receiving station. This interdependence is critical, as the loss of an I-frame due to transmission errors causes a domino effect, making the following sequence of P-frames undecipherable until a new I-frame is received. To mitigate this vulnerability, AR-FEC implements robust error protection for these key I-frame packets.

At the core of AR-FEC's error correction methodology is the implementation of the Reed-Solomon (RS) code [63, 64, 65], which has been proven to be energy-efficient [66] and highly effective in error correction—a pivotal reason for its selection in this context. The RS-FEC algorithm ingeniously transmits a set of N packets, which includes both K original I-frame packets and R supplementary repair packets, the latter serving as the FEC component. The RS code is adept at resolving up to $N - K$ packet errors, given that the locations of these errors are identified. This correction is accomplished by appending $N - K$ redundant packets to the K original packets at the application layer. Consequently, if at least K out of the N transmitted packets reach the receiver successfully, it can reconstruct the original I-frame, thereby preserving the video stream's continuity.

Incorporating more than K redundant packets into the AR-FEC system is impractical, especially given that doing so would entail securing the redundant packets themselves, which provides no concrete advantage. For example, if a total of $N = 2K$ packets are dispatched, with a doubled degree of redundancy, and then the system confronts a circumstance in which over 50% of the packets are lost owing to network conditions—signifying a packet loss ratio (PLR) greater than 50%—the system faces a predicament. To ensure successful packet recovery in such conditions, the redundancy would have to reach 50%, thereby implying that the system would be spending disproportionately in safeguarding the redundancy rather than the original data packets. This method is futile and wasteful since it increases transmission load without equivalent improvements in data integrity. This constraint highlights the need for a well-calibrated and deliberate approach to establishing the amount of redundancy required to guarantee video fidelity while not placing an undue load on network capacity.

When the receiver sends $PLR_{(t-1)}$ as part of its monitoring component, the sender would have to estimate PLR_t^e, if the RTCP feedback packet is not lost or delayed. Additionally, the sender should adjust the amount of overhead in response to changes in network conditions to avoid sending excessive FEC overhead if the network condition is improving or vice versa. In the presence of $PLR_{(t-1)}$ at the sender, PLR_t^e is calculated as:

$$PLR_t^e = \begin{cases} \frac{PLR^e_{(t\text{-}1)}}{2^\omega} & , PLR_{(t\text{-}1)} = 0\% \\ PLR_{(t\text{-}1)} & , PLR_{(t\text{-}1)} < 50\% \\ Congestion & , PLR_{(t\text{-}1)} \geq 50\% \end{cases} \tag{1}$$

This design implies using the latest captured network loss when RS-FEC can be used to recover the data. The FEC overhead is exponentially decreased when the network is error-free, signifying a potential reduction in required error correction capacity. The exponential value represents ω and is an AR-FEC parameter. If the packet loss is below 50%, the predicted PLR is maintained at the current level of packet loss, implying a stable network with manageable loss. Should the loss exceed 50%, it indicates potential congestion, necessitating an adaptive response that involves decreasing the network load. If $PLR_{(t-1)}$ is missed or delayed, AR-FEC estimates PLR_t^e using the most recently received PLR and the previously predicted PLR based on follow:

$$PLR_t^e = \begin{cases} PLR_{(t-\Delta)} + \omega & , PLR^e_{(t-1)} \leq PLR_{(t-\Delta)} \\ PLR^e_{(t-1)} + \omega & , PLR^e_{(t-1)} > PLR_{(t-\Delta)} \end{cases} \tag{2}$$

where Δ is the number of consecutive delayed ping reply packets and $PLR_{(t-\Delta)}$ shows the latest received PLR. This is a usage of the Additive Increase and Multiple Decrease (AIMD) approach on the AR-FEC algorithm to swiftly adjust and adapt to deteriorating network conditions or temporary network degradation.

PLR_t^e is further updated based on the measured D_t and its availability. Note that PLR_t^e is identified at the beginning of the GoP while D_t represents a later probe for network conditions. If D_t is not available, an Adaptive Application Threshold, denoted as λ^a, is calculated by the sender as follows:

$$\lambda^a = \lambda(1 - \alpha \times \Delta) \tag{3}$$

where λ is the max acceptable application delay threshold, α is a tunable AR-FEC parameter, and Δ represents the number of consecutive delayed ping reply packets. For example, if the last received ping reply is $D_{(t-2)}$, then $\Delta = 2$. Consequently, λ^a will adaptively decrease as network conditions deteriorate. AR-FEC compares the λ^a with the last received $D_{(t-\Delta)}$. If $D_{(t-\Delta)} > \lambda^a$, the network channel has been congested or is in the early stages of congestion. Hence, AR-FEC would enter congestion mode. Otherwise, the sender monitors the trend of the last received 5 delay samples, i.e., $D_{(t-\Delta-5)}$ to $D_{(t-\Delta)}$ and calculates their sample mean and standard deviation, denoted as μ and σ, respectively, as follow:

$$\sigma = \sqrt{\frac{\sum_{i=t-\Delta-5}^{t-\Delta} (D_i - \mu)^2}{5}} \tag{4}$$

If $D_{(t-\Delta)}$ exceeds $\mu + 2\sigma$, PLR_t^e is increased by $\omega\%$, where ω represents an AR-FEC parameter. Once the PLR_t^e is estimated, the number of FEC packets for GoP_t's I-frame is calculated as:

$$p_t^{FEC} = \frac{p_t^{\textit{I-frame}}}{1 - PLR_t^e} - p_t^{\textit{I-frame}} \tag{5}$$

where $p_t^{\textit{I-frame}}$ represents the number of packets required to send the I-frame. This approach ensures the FEC overhead is precisely tailored to the current network's performance, optimizing data transmission efficiency and reliability.

4.2.3 AR-FEC Quality adaptation

AR-FEC quality adaptation enables the algorithm to deliver high-quality video in good network conditions and switch to low quality as network conditions deteriorate. Initially, the UAV sends the GoP_1 at a low-quality and $PLR_1^e = 5\%$. This conservative approach ensures robust initial transmission and provides a baseline for adapting to network changes.

As the video stream progresses, AR-FEC assesses the effective network rate

(R_t^e) during the transmission of each GoP_t. This rate is calculated using the following expression:

$$R_t^e = \left(\frac{B_t}{T_t}\right) \tag{6}$$

where B_t represents the number of transmitted bytes for the I-frame and FEC included, and T_t represents the duration starting when the first byte of the I-frame is transmitted until the RTCP message carrying the PLR feedback is received at the sender. Noting that I-frame tends to be large in size, their transmission is considered a good probe for the network throughput.

The algorithm proactively adjusts the video quality of the upcoming GoP_t based on the observed throughput. If the calculated R_t^e falls below the product of a predefined safety factor (β) and the previously estimated network rate for $GoP_{(t-1)}$, AR-FEC will consider lowering the video quality:

$$R_t^e \leq \beta \cdot R_{t-1}^e, \quad \beta = \frac{D_{t-2}}{D_{t-1}} \tag{7}$$

where β is a safety factor that is an AR-FEC parameter, and its default value is 1. AR-FEC will downgrade the video quality from high to low if:

- The system is identified as in congestion when PLR_t^e or D_t are deemed high as explained above. In this mode, AR-FEC will also set PLR_t^e to 50%. This means that we send low-quality video with high correction ability.
- AR-FEC expects a link layer buffer overflow. The overflow condition is defined as $queue\ capacity < queue\ occupancy + p_t^{GoP}$. Note that AR-FEC would also adjust the PLR_t^e if the packets of GoP_t at low-quality will cause the buffer overflow. The update value is determined by the max value for PLR_t^e that avoids the overflow.

By adjusting video streaming parameters dynamically to meet real-time network capabilities, AR-FEC optimizes the viewer's experience even when network circumstances change. This intelligent adaption mechanism allows AR-FEC to balance network efficiency with video quality.

4.3 Visual Overview of AR-FEC Flowchart

As illustrated in Figure 4.3, the AR-FEC algorithm's flowchart provides a visual and systematic guide to the decision-making process that dynamically adjusts the video streaming quality and error correction strategies in response

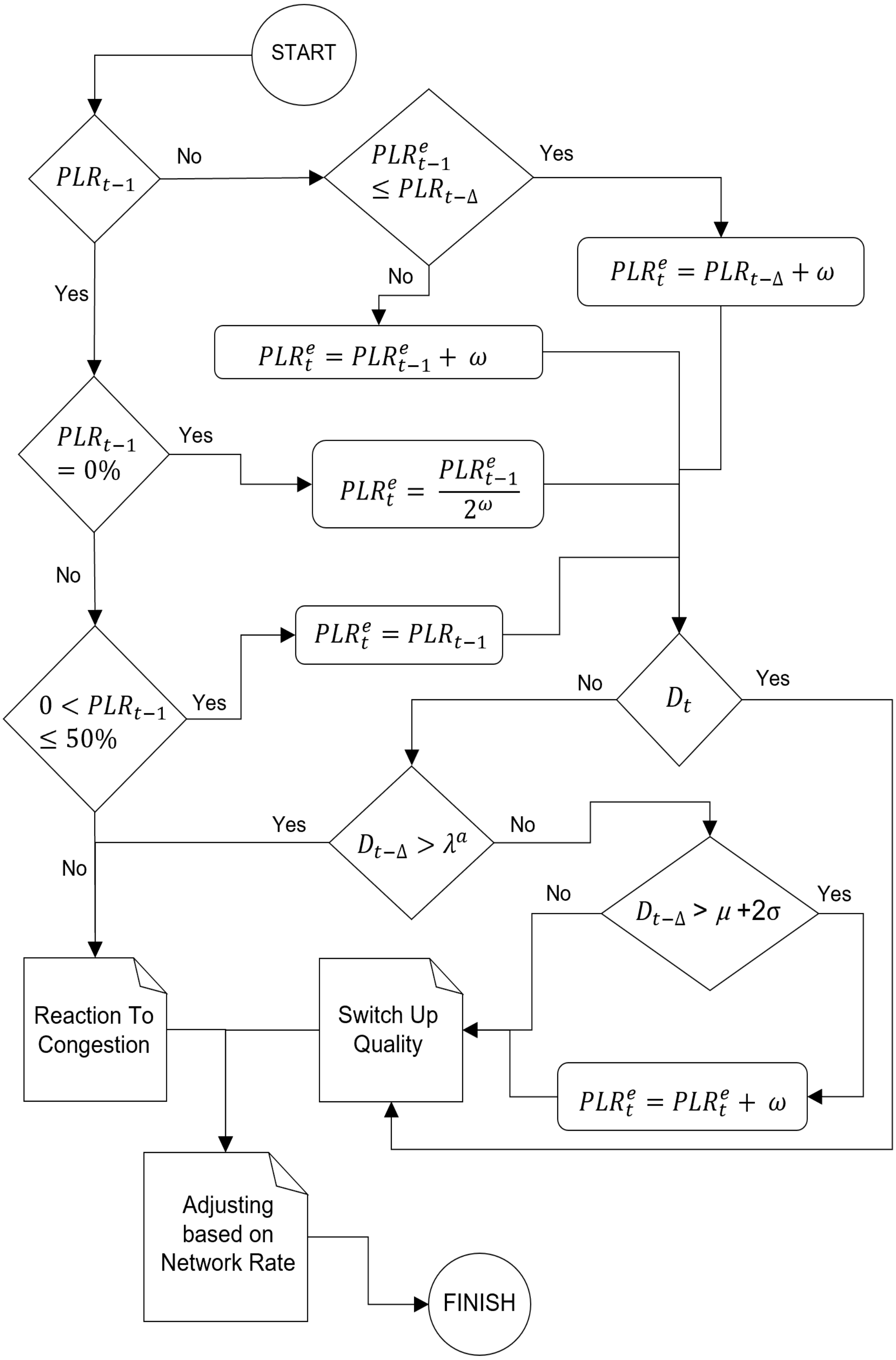


Figure 4.3: AR-FEC Algorithm

to varying network conditions, a concept elaborated in the previous subsections. This subsection aims to elucidate the algorithm's functionality through its primary modules, ensuring a clear understanding of its operational flow. Table 4.1 presents a comprehensive compilation of symbols representing AR-FEC parameters, facilitating a deeper understanding of the algorithm's complexities.

Table 4.1: Symbols for AR-FEC System

Symbol	Definition
t	Index for the upcoming GoP
$(t-1)$	Index for the transmitted GoP
PLR_t	Actual PLR for the upcoming GoP
$PLR_{(t-1)}$	Actual PLR for the transmitted GoP
PLR_t^e	Estimated PLR for the upcoming GoP
ω	Exponential value representing a parameter in the AR-FEC system
Δ	Number of consecutive delayed ping reply packets
$PLR_{(t-\Delta)}$	The latest received PLR
D_t	Network delay for the upcoming GoP
λ^a	Adaptive application threshold
λ	Maximum acceptable application threshold
α	Tunable AR-FEC parameter
μ	Mean of network delay
σ	Standard deviation of network delay
$p_t^{I-frame}$	Number of packets required to send the I-frame of GoP
p_t^{FEC}	Number of FEC packets for the I-frame of GoP
R_t^e	Effective network rate for the upcoming GoP
β	Predefined safety factor for determining quality upgrades

4.3.1 Reaction to Congestion

The "Reaction to Congestion" component, as depicted in Figure 4.4 and previously discussed in subsection 4.2.2 on AR-FEC Error Protection, serves as the foundational response strategy of the algorithm to detect and address network congestion. This module actively monitors the network's PLR to estimate the extent of congestion. Upon detecting that the PLR has hit or exceeded the critical threshold of 50%, which signals significant network congestion, the AR-

FEC algorithm proactively degrades the video output to a lower quality. This strategic downgrade is implemented as a resource-conserving measure to alleviate the strain on the congested network and maintain the integrity of video transmission.

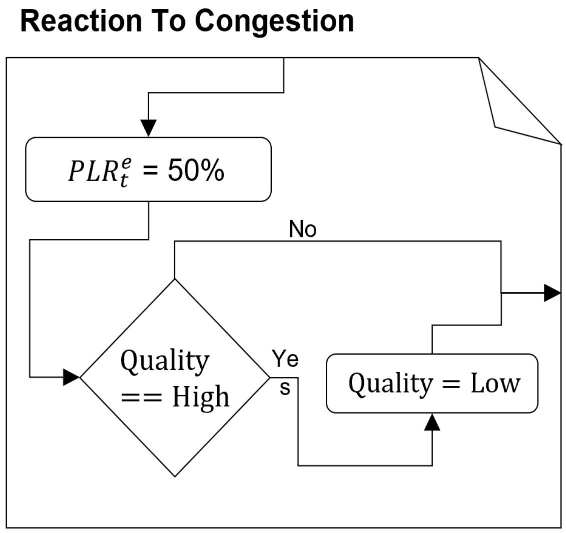


Figure 4.4: Reaction to congestion module

4.3.2 Switch Up Quality

In scenarios where the latency history of GoP transmission indicates a substantial improvement in network conditions, the 'Switch Up Quality' module is activated, as illustrated in Figure 4.5 and alluded to in Equation (5). This component of the AR-FEC system is tasked with determining the opportune moments to upgrade the video quality, taking care not to compromise network reliability. To this end, it utilizes a predefined safety factor, which has been detailed earlier, to make informed decisions about enhancing the video streaming experience. This decision-making process is informed by real-time analysis of network throughput, as delineated in subsection 4.2.3, ensuring that quality improvements are both timely and prudent.

4.3.3 Adjusting Based on Network Rate

Figure 4.6 illustrates the AR-FEC algorithm's capabilities to prevent link layer buffer overflows, a critical aspect of maintaining uninterrupted video streaming. It operates on the principle $queuecapacity < queueoccupancy + p_t^{GoP}$, adjusting the PLR_t^e to the highest feasible value that prevents overflow, thereby

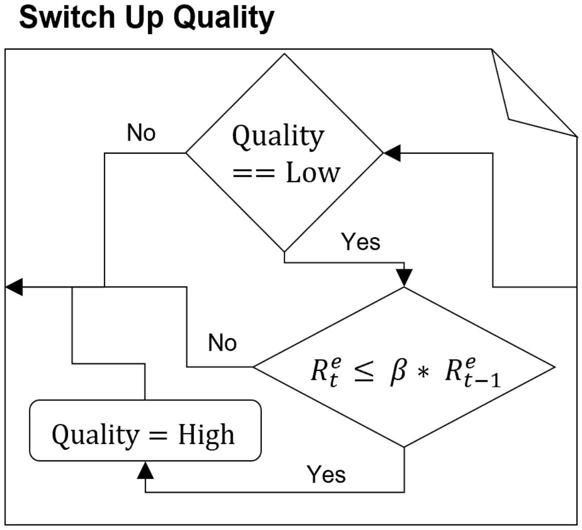


Figure 4.5: Switch Up Quality module

ensuring the video stream remains stable. This module is a culmination of the principles set forth in previous discussions, notably the harmonization of transmission quality with network capacity. It highlights the algorithm's nimbleness in adapting to varying network conditions and underscores its commitment to delivering an optimal balance between maintaining high-quality video and efficient bandwidth use, as introduced in earlier subsections on quality adaptation and error protection.

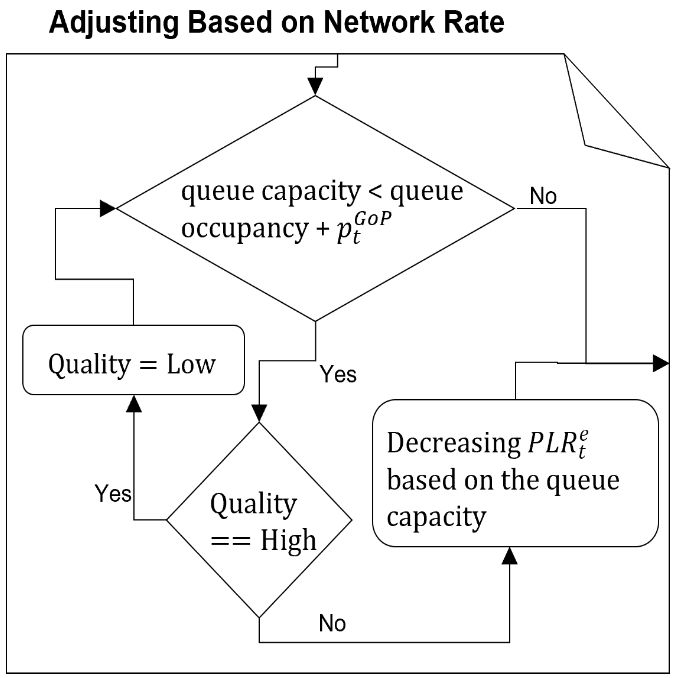


Figure 4.6: Adjusting Based on Network Rate module

4.4 Analyzing Complexity Factors in AR-FEC

The complexity analysis of the AR-FEC method proposed in this thesis reveals its efficiency in real-time operation. Unlike many other techniques, AR-FEC does not engage in iterative processes, searches, or complex operations for decision-making regarding overhead or quality settings. Its computational load primarily stems from the addition of overhead to I frames based on observed metrics, ensuring streamlined and expedited processing without compromising on performance.

4.5 Conclusion of the AR-FEC

In conclusion, in this chapter, we have explored the intricacies of the AR-FEC method, a sophisticated approach devised to maintain high-quality and reliable video streaming from UAVs to ground stations, even in the face of variable network conditions. The AR-FEC strategy adeptly employs adaptive FEC redundancy at the application layer and proactively adjusts to congestion, quality shifts, and buffer constraints to uphold a high standard of video transmission. This adaptive and anticipatory mechanism is crucial for ensuring a consistent and dependable connection, which is vital for UAV operations. Moving forward, the subsequent chapter will delve into a simulation-based evaluation of AR-FEC, aiming to substantiate its efficacy in sustaining high-quality aerial video communication within environments that are both resource-limited and latency-sensitive.

Chapter 5

Simulation Environment

This chapter presents a thorough analysis of the simulation environment and performance metrics that are important in assessing the AR-FEC approach in UAV networks. Utilizing the NS3 framework, the simulation setup, encompassing network topology and various operational scenarios, is detailed. Key performance metrics such as number of decodable frames, frame latency, and throughput are defined, serving as the basis for assessing the effectiveness of the AR-FEC method. Additionally, various evaluation schemes are discussed, providing a comprehensive analysis of AR-FEC under realistic UAV operating conditions. The aim is to succinctly demonstrate the capabilities of the AR-FEC algorithm in enhancing UAV network communications.

5.1 Network Simulator Selection for Thesis Evaluation

In the pursuit of identifying the most suitable network simulator for effectively evaluating the AR-FEC method in UAV video transmission scenarios, this study undertakes a meticulous examination of various simulators. The selection process is anchored in a comprehensive set of criteria that are pivotal for ensuring the simulator's alignment with the specific requirements of UAV communication systems and AR-FEC method efficacy. These criteria encompass:

- **Support for IEEE 802.11 Network Protocols**: Given the prevalence of IEEE 802.11 standards in UAV communications, the simulator's ability to accurately model these protocols is crucial.

- **Realistic Mobility Models**: Essential for simulating the dynamic movement patterns of UAVs, thereby impacting network performance and the effectiveness of AR-FEC methods.
- **Realistic Physical Radio Models**: To accurately reflect the complexities of wireless communication in UAV scenarios, including factors like signal propagation, interference, and fading.
- **Support for Video Transmission and Metrics**: Considering the focus on video data transmission in UAV applications, the simulator must adeptly handle video streaming and provide relevant quality metrics.
- **Open-Source Availability**: An open-source simulator offers flexibility and adaptability, crucial for academic research and customization for specific UAV network scenarios.
- **Commercial vs. Academic Use**: The choice between commercially licensed and freely available academic tools hinges on available resources and the need for specialized features.

This rigorous evaluation not only ensures that the selected simulator is technically capable of replicating the complex environment required for AR-FEC in UAV-based video transmission but also aligns with the practical constraints and objectives of academic research. The subsequent subsections offer a detailed comparative analysis of several prominent network simulators, scrutinizing each against these vital criteria to determine their suitability for this specialized application.

5.1.1 Overview of Network Simulator Tools

The landscape of network simulation is rich and varied, featuring a wide array of tools each designed to meet specific simulation needs in the realm of network modeling and evaluation. This overview explores some of the most significant simulators, examining their capabilities and suitability against the established criteria for AR-FEC method evaluation in UAV video transmission scenarios.

5.1.1.1 NS2 and NS3

NS2 [67], a foundational tool in network research, has paved the way for its more advanced successor, NS3. NS3 [68] stands out for its comprehensive support for IEEE 802.11 protocols, making it ideal for UAV communications. It excels in simulating realistic mobility patterns of UAVs and includes advanced physical radio models, essential for authentic wireless communication simulations. Furthermore, NS3's capabilities in handling video transmission and providing relevant quality metrics render it a top choice for UAV-based AR-FEC research. The open-source nature of NS3 further enhances its appeal for academic research, offering a platform for extensive customization and experimentation.

5.1.1.2 OPNET (Riverbed Modeler)

OPNET, now Riverbed Modeler, is renowned in the industry for its extensive network modeling capabilities [69]. It robustly supports various network protocols, including IEEE 802.11, and offers advanced features for simulating realistic radio environments and analyzing video transmission metrics. However, its proprietary nature and licensing requirements might pose challenges for academic researchers with limited budgets, despite its extensive feature set and detailed simulation abilities.

5.1.1.3 GNS3 (Graphical Network Simulator-3)

GNS3 is highly regarded for its ability to simulate complex network architectures, integrating both virtual and real network devices [70]. It supports IEEE 802.11 devices and is particularly useful for practical network configuration and topology simulations. However, GNS3's focus on real-device integration, while beneficial for training and certification preparation, may not offer the depth required for intricate UAV communication simulations and the specific nuances of AR-FEC methods.

5.1.1.4 OMNeT++

OMNeT++ [71] is a flexible and modular simulation framework that can be tailored for detailed network simulations, including those involving IEEE 802.11 protocols, with the integration of additional modules like the INET Framework. While inherently adaptable, setting up OMNeT++ for specific UAV communication scenarios, particularly those requiring realistic mobility and physical radio models, may necessitate additional customization and module integration.

5.1.1.5 Mininet

A specialized tool designed to simulate Software Defined Networking (SDN) systems and wired network topologies is called Mininet [72]. It is less suitable for UAV-based wireless network simulations since its main strength is in virtual network emulation on single workstations. Mininet's emphasis on wired networks and SDN limits its capacity to simulate actual UAV communication scenarios, particularly those involving video transmission.

5.1.1.6 ArduPilot

ArduPilot [73], while primarily a software suite for unmanned vehicle control, holds relevance in the context of UAV network simulations. It does not inherently provide network simulation capabilities but could offer valuable insights when integrated with network simulators for comprehensive UAV system simulations. However, its focus is on vehicle control, and it lacks direct features for simulating network protocols or communication metrics.

5.1.1.7 Simbeeotic

Simbeeotic is specifically designed for simulating UAV swarm communications [74]. While it may possess some capabilities in wireless communication simulation, its specific support for IEEE 802.11 standards, detailed physical radio models, and video transmission metrics is not as extensive as more network-centric simulators like NS3. Its focus on UAV swarms provides unique insights but may fall short in the detailed simulation of network protocols and AR-FEC methods.

5.1.1.8 Other Tools

Additional tools such as SPIRENT, MOSIMTEC, X-Plane, and UTSim serve specialized sectors. SPIRENT and MOSIMTEC are more aligned with industrial applications, offering robust solutions for commercial needs [75, 76], while X-Plane is dedicated to aeronautical simulation, excelling in flight dynamics modeling [77]. UTSim, although not extensively documented, seems to offer more limited capabilities in network simulation [78]. These tools, while proficient in their respective domains, may not fully meet the specific requirements of UAV-based network simulation for AR-FEC method evaluation.

5.1.2 Conclusion: Choosing NS3 for UAV Network Simulation

This study's evaluation of network simulators underscores NS3 as the optimal choice for AR-FEC methods in UAV networks, surpassing others like OPNET, GNS3, and Mininet, which lack specialized features for dynamic 3D mobility in drones. OMNeT++, though adaptable, requires significant modifications for drone networks. Simbeeotic and ArduPilot, more attuned to UAV dynamics, fall short in overall network simulation.

NS3 excels with its comprehensive support for network protocols and capability to simulate complex UAV networks, making it ideal for this research. Its open-source nature enhances flexibility and adaptability, which are crucial for academic environments. NS3 accurately models UAV communication complexities, rendering it perfect for AR-FEC method evaluation.

The tool's widespread academic use brings a robust community offering extensive knowledge, resources, and support, essential for effective, efficient simulation studies. NS3's rich documentation and user-contributed modules foster deeper research insights in UAV network communication.

In summary, NS3's blend of detailed simulation features, suitability for UAV network requirements, and strong academic community backing make it the premier choice for this thesis. Its selection promises precise, realistic simulations and fosters an environment conducive to academic advancement in UAV network communication.

5.2 Evaluation Setup

With the rapid expansion of UAV technologies and the growing significance of their applications, the demand for reliable video communication systems is more pressing than ever. This section of the thesis delves into the evaluation setup designed to rigorously test the AR-FEC method, a forward error correction mechanism tailored for real-time video delivery from UAVs. Through meticulous simulation and comprehensive parameter tuning, this research aims to shed light on the capabilities and limitations of AR-FEC, paving the way for advancements in UAV-based video communications.

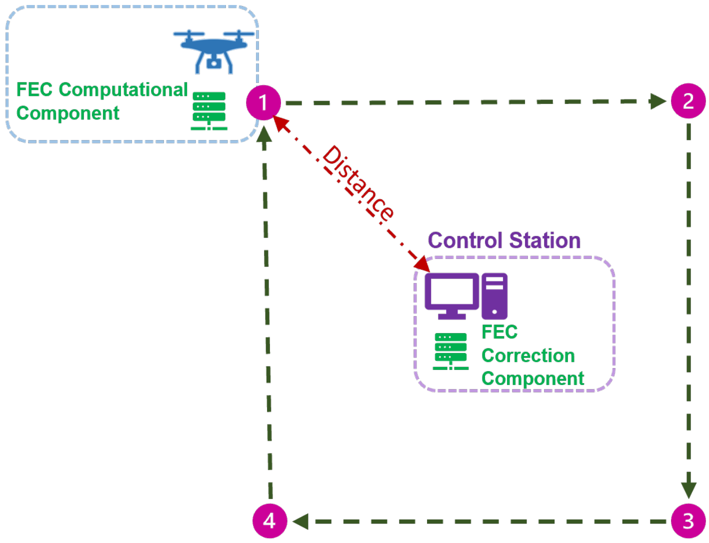


Figure 5.1: Evaluation topology

5.2.1 Simulation Topology and Setup

In UAV communication research, the authenticity of the simulation environment is critical. This section provides a detailed overview of the network configuration and the UAV's flight model, essential components of our thorough evaluation framework. The evaluation topology, depicted in Figure 5.1, is a visual guide to the complex relationship between the UAVs and the ground station.

Displayed prominently in this figure is the UAV's precise route, defined by a series of waypoints that enforce a fixed square trajectory. These waypoints ensure that the UAV's flight is accurately simulated, reflecting the exact movement patterns required for the evaluation. The ground station is more than a passive receiver; it is a crucial entity that measures the UAV's signal strength and the reliability of data transmission, providing a robust assessment of the AR-FEC method's performance in various conditions.

The waypoints not only plot the UAV's course but also serve as test points for the AR-FEC mechanism's adaptability to changing distances and orientations. The figure, with its detailed representation of communication ranges and environmental challenges, is pivotal for simulating the complexities of real-world UAV operations. The following sections will explore the rationale behind the chosen simulation parameters and their effect on signal propagation, data integrity, and the efficacy of the AR-FEC method within UAV network simulations.

5.2.1.1 3D Mobility Model on UAV Simulation

The NS3 framework, integrated with the WaypointMobilityModel, is crucial in the simulation, accurately depicting UAV flight in a three-dimensional space. This model is highly regarded for its precision in replicating UAV trajectories, critical for an effective assessment of the AR-FEC method under realistic conditions. Its capability to customize waypoints enables the simulation of diverse and complex flight paths, vital for a comprehensive evaluation of UAV communication systems.

Key attributes that make the WaypointMobilityModel ideal for UAV simulations include its capability to dynamically represent changes in speed and direction, critical for mimicking real-world UAV behavior. Additionally, its seamless integration with NS3's wireless communication models ensures a holistic approach to simulating UAV networks. This model is particularly effective in complex aerial environments, where accurate replication of varied altitudes and navigational challenges is required. Figure 5.1 showcases the UAV's path around a stationary ground station, underlining the model's effectiveness in capturing the nuanced interplay between UAV mobility and communication performance. Such detailed simulation is crucial for validating the adaptability and efficacy of the AR-FEC method in dynamic operational scenarios.

5.2.1.2 Wireless Standard and Video Traffic

The simulation employs the IEEE 802.11n wireless standard, which operates on a 2.4 GHz frequency, for its communication needs. This standard is specifically chosen due to its proven extended range capabilities, especially in outdoor environments, making it highly suitable for UAV operations as highlighted in the comparative analysis by [12]. Another significant advantage of the 802.11n standard is its high data throughput capacity, which is essential for transmitting high-resolution video—a common requirement in UAV applications. Furthermore, its backward compatibility feature ensures that the UAV communication system can seamlessly integrate with existing network infrastructures. These combined attributes of the 802.11n standard make it an ideal choice for effectively managing the transmission of video traffic in UAV networks.

5.2.1.3 Video Encoding and Input Video

The simulation utilizes real video traffic patterns obtained from authentic drone footage [79], ensuring that the evaluation reflects realistic operational conditions. This footage is processed by using FFmpeg [80], a powerful multimedia framework that can decode, encode, transcode, and stream media content. The processing involves stripping the audio from the footage and encoding the video into two different quality formats: 4K and 720p resolution, both at a frame rate of 30 frames per second (fps) and a GoP of 30 frames using the H.264 video compression standard, known for its high compression rates and excellent quality. As long as frame rate and GoP have the same number, AR-FEC determines the number of redundancies and the quality of video per second.

5.2.1.4 Adaptive Real-Time Streaming Through Evalvid Add-on

To simulate the transmission of these video frames over a network, the Evalvid-ns3 framework is employed and further extended in this study. Evalvid is a toolset that enables the study of the effects of network protocols and configurations on video streaming quality. This is particularly useful when researching areas such as Quality of Service (QoS), congestion control, and video streaming over various network conditions which are crucial for applications like streaming drone footage where quality and real-time performance are paramount.

The Evalvid-ns3 extension developed for this research includes support for RTCP (Real-Time Control Protocol) feedback mechanisms, which enable the monitoring and control of streaming media quality by providing information about packet delivery and network congestion. Additionally, RTP (Real-Time Protocol) header functionalities are integrated to ensure proper format and delivery of streaming data.

RTP (Real-Time Protocol) and RTCP (Real-Time Control Protocol) are integral components of Internet Protocol-based multimedia communication systems [81]. RTP is designed for end-to-end, real-time transfer of streaming media. It facilitates the delivery of audio and video over networks and is highly utilized in communication and entertainment systems that require streaming media, such as video conferencing and online video services. RTP does not inherently provide any mechanism for ensuring timely delivery or quality-of-service guarantees; it relies on underlying network mechanisms to do so. It is typically run over User Datagram Protocol (UDP) to allow for the speedy transmission required for live data.

RTCP works in conjunction with RTP by providing out-of-band control information about the media stream. It supports the monitoring of data delivery and provides minimal control and identification functionalities. RTCP regularly sends control packets to all participants in the session, offering feedback on the quality of the data distribution. This feedback includes statistics like packet count, packet loss, jitter, and round-trip delay, which are essential for adaptive streaming techniques. These statistics help maintain the quality of service, which is especially important for UAV scenarios where network conditions can significantly impact the quality of the video received.

5.2.1.5 Optimizing Link Layer Performance with MinstrelHtWifiManager

In the NS3 simulation, the MinstrelHtWifiManager module is employed to enhance the performance of the link layer. This module is a rate control algorithm designed to optimize the transmission speed of wireless networks. It works by dynamically adjusting the data rate based on current network conditions, aiming to achieve the best throughput while minimizing data loss. This adaptability is crucial in maintaining network efficiency, especially important for real-time applications like video transmission.

MinstrelHtWifiManager is particularly adept at handling high-throughput (HT) scenarios, as commonly encountered in modern wireless communication standards like IEEE 802.11n. It continuously monitors and analyzes the success rates of different transmission rates, adapting its choices in real-time to ensure optimal performance. This feature is invaluable in UAV video streaming contexts, where varying distances and environmental conditions can significantly impact network performance.

By combining the dynamic rate control of MinstrelHtWifiManager with the speed and simplicity of UDP, the simulation aims to create a link layer environment that is both efficient and responsive to the needs of real-time video transmission

5.2.1.6 Implementation of the AR-FEC Algorithm

The effectiveness of the AR-FEC method in this simulation is anchored on the effective coordination of FEC and quality adaptation mechanisms. Central to this approach is the enhancement of the algorithm's real-time correction capabilities, which are critical for ensuring the continuous delivery of high-quality video streams.

Table 5.1: Simulation Parameters

Parameters	Value
Distance	400m - 600m - 800m
Max Acceptable Application Threshold	0.5s - 1s -1.5s
Mobility Model	WaypointMobilityModel
Error Rate Model	TableBasedErrorRateModel
Video Quality	720p and 4K
Frame Rate	30 fps
Number of frames for each GoP	30 frames
Codec	H.264
Propagation Loss Model	FriisPropagationLossModel
Propagation Delay Model	ConstantSpeedPropagationDelayModel
Wireless Standard	802.11n - 2.4 GHz
Transport Layer	UDP
Rate Control Algorithms	MinstrelHtWifiManager

A key feature of the AR-FEC method is its focus on sender-side prediction for redundancy. This aspect of the algorithm is designed to respond swiftly to feedback received from the receiver, allowing for dynamic adjustments to the transmission based on current network conditions. Such immediate adaptation is essential for maintaining video quality, especially in scenarios where network performance may fluctuate rapidly.

In essence, this simulation framework is crafted to provide a realistic environment for validating the AR-FEC method's ability to deliver high-quality video over UAV networks. It integrates practical UAV mobility patterns, advanced wireless communication standards, and real-time adaptive streaming techniques, all of which are pivotal for ensuring the relevance and applicability of the research outcomes.

5.2.2 Simulation Parameters

The specific parameters utilized in the simulations are detailed in Table 5.1. This extensive setup is aimed at thoroughly evaluating the efficacy of the proposed AR-FEC method under various realistic UAV operating conditions.

The significance of the research is underscored by a notable gap in existing literature, as highlighted in Chapter 3. This gap is characterized by the scarcity of scholarly works explicitly focused on error correction algorithms tailored for multimedia communications in UAV contexts, a deficiency that has inevitably limited the breadth of the comparative analysis. Despite an exhaustive literature search, no studies were found that align closely with the research objectives and provide the necessary algorithmic details or source code, which are crucial for ensuring repeatability and enabling a thorough comparative evaluation.

In response to this challenge, an in-depth performance analysis was conducted, focusing on the core tenets of the proposed AR-FEC algorithm, particularly its adaptability in video quality and redundancy of FEC. The research primarily revolves around assessing the efficacy of the AR-FEC algorithm, and its effectiveness was ascertained by comparing it against various alternatives. These included:

1. **No-FEC-Quality Schemes:** These schemes involve transmitting video at a constant quality without employing Forward Error Correction. They are designated as No-FEC-720p and No-FEC-4K, corresponding to their respective video quality levels.

2. **AR-FEC-Quality Schemes:** In contrast to the No-FEC variants, these approaches transmit video at a fixed quality while incorporating adaptive FEC for enhanced reliability. These are referred to as AR-FEC-720p and AR-FEC-4K, again indicating the quality of video transmission.

By exploring these different schemes, this study aims to provide a comprehensive assessment of the AR-FEC algorithm's performance in various UAV-operating scenarios. This approach not only tests the effectiveness of the proposed algorithm under varying conditions but also contributes valuable insights to the field of UAV-based multimedia communication, particularly in areas where existing research is limited.

5.3 Performance Metrics

A range of application and network metrics is carefully examined to assess the performance of the AR-FEC approach, presenting a comprehensive picture of its efficacy, including:

1. **Number of decodable frames for every quality at the receiver:** This refers to the number of frames that can be successfully decoded at the receiver for each quality level. A frame is considered undecodable if any of its packets are lost and cannot be recovered, or if it is received after its designated playout time.

2. **Frame latency:** This measures the time taken to transmit and receive

an entire frame. It represents the delay experienced from the moment a frame is sent until it is fully received.

3. **Throughput:** This is the rate at which useful packets are received during the entire simulation duration. It excludes lost and delayed packets from the calculation, providing a measure of the actual data transfer rate.

The parameters in AR-FEC are strategically chosen to align with specific scenario requirements, ensuring optimal performance across diverse operational contexts. Each parameter undergoes scrutiny through the selection of three distinct values, allowing for a comprehensive investigation into their influence on system performance. For instance, in the context of evaluating the AR-FEC method's efficacy in UAV communication, the distance between the UAV and the receiving station serves as a pivotal variable, with tests conducted at 400 m, 600 m, and 800 m. Furthermore, the analysis extends to the application threshold (λ), with values set at intervals of 0.5 s, 1 s, and 1.5 s, thereby enabling a detailed examination of streaming performance, particularly emphasizing scenarios where the distance between the UAV and the receiving station is 800 meters. This meticulous approach to parameter selection ensures a thorough exploration of AR-FEC's adaptability and effectiveness across various operational scenarios.

To fine-tune the AR-FEC algorithm, specific parameters were set, with α=0.8 and a uniform increase (ω) of 2 for PLR_t^e. Each simulation runs for a duration of 72 seconds, with results aggregated from 10 iterations per configuration, ensuring statistical reliability. The timing of Ping packets, sent in the middle of each GoP, is adjusted to optimize the performance outcomes.

For these simulations, NS3, a C++ based network simulator, serves as the backbone, enabling the implementation and rigorous testing of the proposed algorithm. The comprehensive log files generated during simulations were critical for evaluating AR-FEC's performance. Python, known for its versatility, was utilized to process these logs and analyze the received data for post-processing tasks.

For researchers and practitioners interested in exploring the proposed algorithm further, the NS3 code and detailed evaluation setup for the AR-FEC algorithm are available at the following URL: `https://github.com/BatoulSarvi/AR-FEC`. This repository provides an open platform for replicating this study, facilitating further research and development in this domain.

In summary, this chapter establishes a detailed simulation environment using NS3 for assessing the Adaptive and Reliable Forward Error Correction (AR-FEC) method in UAV networks. Key performance metrics and varied operational scenarios have been methodically outlined, setting a foundation for a comprehensive evaluation. The upcoming chapter will delve into the results derived from this simulation setup, providing an in-depth analysis of the AR-FEC method's performance and effectiveness in UAV multimedia communication.

Chapter 6

Evaluation

In this chapter, an assessment of the newly developed adaptive and reliable forward error control mechanism for UAV video transmission, AR-FEC, is undertaken. The assessment is designed to systematically investigate the algorithm's performance over a range of operational factors, with a particular emphasis on the effects of different application threshold settings and distances. The aim of this analytical investigation is to get a comprehensive understanding of the capabilities and constraints of AR-FEC in various UAV operating conditions, providing insights into its overall efficacy and possible areas for improvement in order to improve the quality of UAV-based video transmission.

6.1 Impact of Operating Distance

In this section, an in-depth examination is conducted to assess how varying operating distances influence the performance of the schemes under consideration. Specifically, the focus is on understanding the efficacy of the AR-FEC approach across a range of distances, a critical factor in UAV network communications. For this purpose, the evaluation is structured with the application threshold (λ) consistently set at 1 second. This approach allows for a detailed observation of the algorithm's responsiveness and reliability in different spatial scenarios, providing vital insights into the distance-related dynamics of AR-FEC in practical UAV applications.

6.1.1 Number of decodable frames

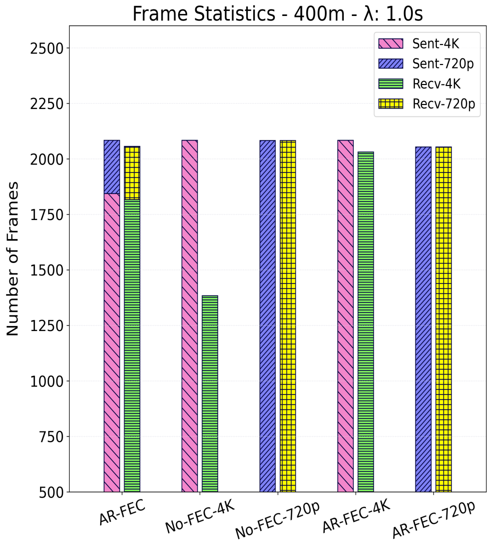
Figure 6.1(a-c) demonstrates a comparative analysis of the transmission efficacy, highlighting the transmitted and received frame counts and their respective quality across varying UAV operational distances of 400m, 600m, and 800m, respectively. These graphs underscore the proficiency of AR-FEC in achieving the right balance between the quality of streaming content and the robustness of the transmission. The video streamed at low quality exhibits no loss for 400m and 600m, but a minimal loss of 9 frames is encountered in the 800m case on No-FEC-720p, which is rectified when using FEC (AR-FEC-720p).

In contrast, when video is streamed at high quality, frame losses occur at all distances. These losses reached 72% at 800m without FEC, while using FEC reduced this loss to 56%. Notably, when AR-FEC is employed, there is a significant decrease in frame loss. At 800m, the frame loss on AR-FEC is reduced to 1% and 7% for low-quality and high-quality videos, respectively. The critical point is that the adaptation component of AR-FEC significantly enhances the number of high-quality frames compared to AR-FEC-4K. Additionally, at distances of 600m and 800m, it results in an 8% and 5% increase in high-quality frames, respectively.

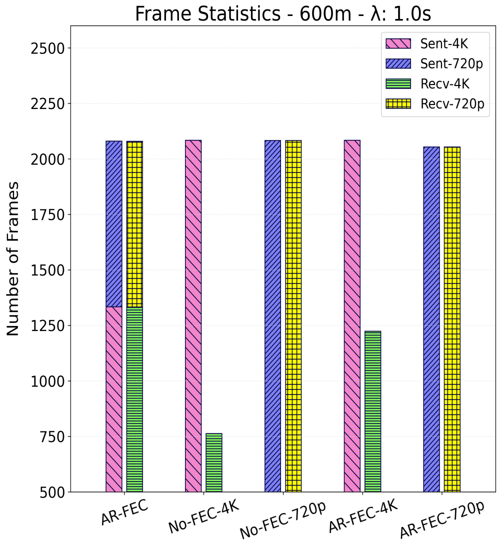
This adaptability is paramount, as it not only preserves the integrity of the video quality over greater distances but also suggests a scalability potential of AR-FEC in varied operational contexts, potentially accommodating even greater distances or more challenging conditions while maintaining high-quality video transmission standards.

6.1.2 Throughput

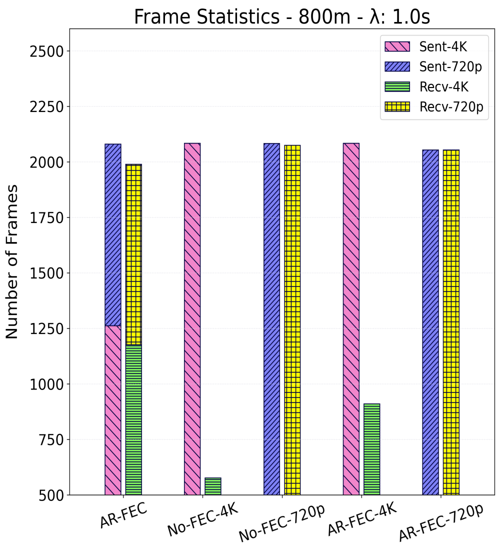
Figure 6.2 illustrates the throughput of compared transmission schemes at increasing distances for UAV video transmission. At a distance of 400m, the AR-FEC-4K setup is shown to be superior, achieving the highest throughput, which correlates with the delivery of the most high-quality video frames (as detailed in Figure 6.1a). However, in the other two distances, AR-FEC exhibits the highest throughput by delivering a large number of frames, particularly high-quality frames. This is indicative of AR-FEC's robust performance, which is achieved with a relatively low overhead, enhancing its practical application in UAV operations. Regarding the lower-quality methods, No-FEC-720p and AR-FEC-720p both sustain consistent throughput at various distances. This congruent perfor-



(a) Distance = 400m



(b) Distance = 600m



(c) Distance = 800m

Figure 6.1: Received frame quality for different distances

mance results from sending a constant amount of frames to the recipient, as Figure 6.1 explains.

The efficiency of the FEC application is further quantified in Table 6.1, showing the FEC packet ratios for different configurations at the specified distances. AR-FEC's packet ratio remains consistently lower than that of the AR-FEC-4K at extended distances, denoting a more efficient error correction that does not

Table 6.1: FEC packet ratio (%) at different distances – $\lambda = 1.0s$

Algorithm	**400m**	**600m**	**800m**
AR-FEC	0.54	0.68	1.26
AR-FEC-720p	1.45	1.45	1.45
AR-FEC-4K	1.02	15.68	18.56

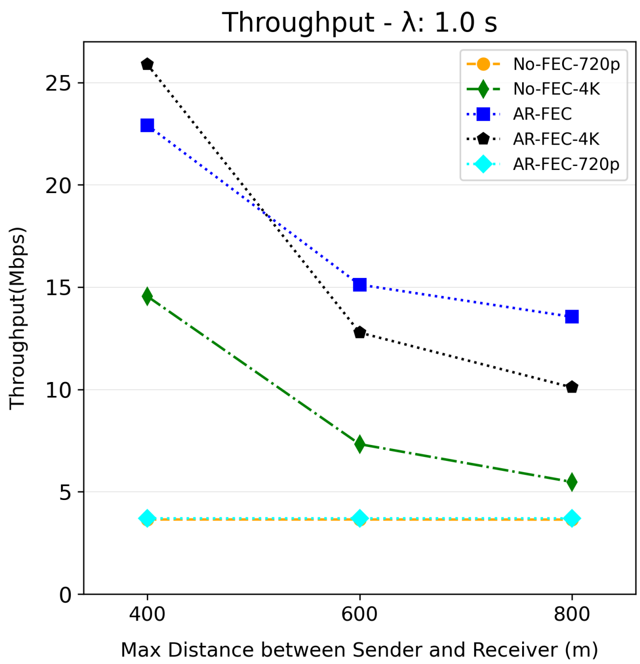


Figure 6.2: Throughput on different distances at λ=1.0s

unnecessarily consume bandwidth. This efficiency becomes particularly salient at 800m, where AR-FEC maintains less than 5% frame loss while delivering over 56% high-quality frames, with the FEC packet ratio accounting for a mere 1.26% of total traffic.

The throughput trends captured in the figure highlight AR-FEC's adeptness at preserving high-quality video transmission over greater distances with minimal loss and bandwidth expenditure. These characteristics are vital in UAV applications, where the optimization of bandwidth is critical. The throughput data reinforces the premise that AR-FEC stands out as a leading solution for ensuring reliable, high-definition video streaming in UAV communications, particularly when operating over long ranges and demanding minimal throughput degradation. This capability of AR-FEC to maintain superior throughput with efficient bandwidth usage is pivotal for UAV video transmissions, potentially enhancing a wide array of applications from surveillance to broadcast.

6.1.3 Frame latency

Figure 6.3 provides a detailed visualization of average frame latency for various transmission schemes across distances of 400m, 600m, and 800m. The latency, especially for high-quality video transmissions, tends to increase with distance. However, the AR-FEC mechanism exhibits a consistently lower latency compared to both No-FEC-4K and AR-FEC-4K across these distances. This trend is most pronounced at the 800m mark, where AR-FEC showcases an average latency of just 0.074 seconds, significantly lower than the 0.154 seconds observed for AR-FEC-4K, and substantially lower than the 0.217 seconds for No-FEC-4K.

This comparative latency analysis suggests that AR-FEC's lower latency is not solely due to error correction but also to its adaptability, which dynamically adjusts video quality in response to changing network conditions, thus avoiding the build-up of delays in the transmission queue. This adaptability is crucial for maintaining the continuity and real-time aspect of video streams, particularly in applications where delays can impact operational effectiveness, such as in time-sensitive UAV monitoring tasks.

Moreover, the graph indicates that the variance in latency also diminishes with AR-FEC, implying that not only is the average latency lower, but the consistency of frame delivery is also improved. This reduction in latency variance is vital for applications that require a predictable and reliable video stream.

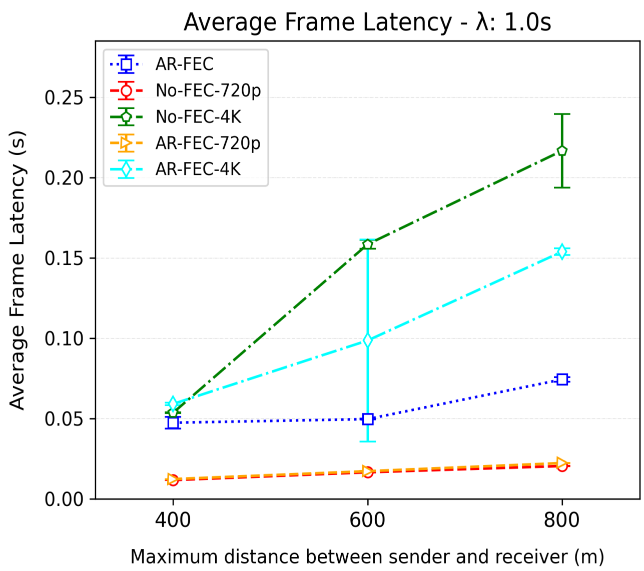


Figure 6.3: Average Frame Latency on different distances at λ=1.0s

6.2 Impact of Application Threshold

The role of the application threshold (λ) is essential in UAV video transmission, especially when considering long-range scenarios such as an 800m distance between sender and receiver. It is important to note that λ affects both the decisions made by the sender and the perception of lost frames by the receiver. If an error control mechanism does not consider the delay constraint parameter, decreasing the maximum application threshold can have a detrimental impact on the quality of the received video.

At a reduced λ, which implies a tighter delay constraint, the system may experience an increased packet loss rate due to packets that arrive later than the threshold allowance. This is a crucial consideration for an error control mechanism, as delayed packets, beyond the threshold, are effectively equivalent to lost packets, adversely affecting the video quality. In high-stakes UAV applications such as search and rescue or precision agriculture, where every frame can carry critical information, maintaining a consistent frame delivery within the set λ is non-negotiable.

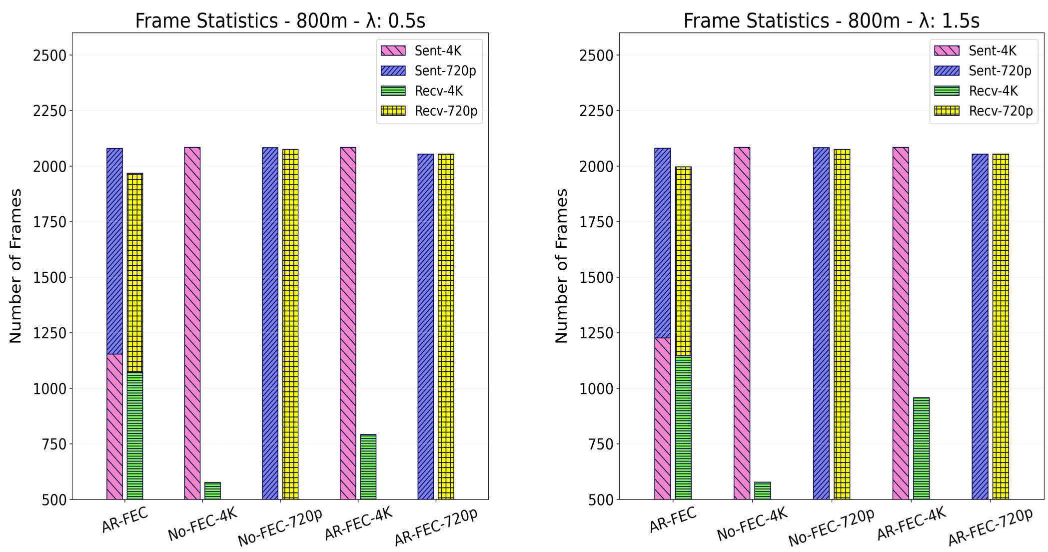
If an error control algorithm exhibits inconsistencies in frame delivery across different λ settings, its reliability for time-sensitive applications comes into question. The ability of an algorithm to adapt to the threshold parameter and mitigate the effects of delayed packets is a testament to its sophistication and suitability for real-time video streaming over considerable distances.

For UAV systems, the capability to fine-tune λ and still achieve optimal video quality is indicative of a robust and resilient transmission system. This adaptability is particularly valuable when dealing with varying network conditions and when striving to meet the stringent demands of latency-sensitive video communication. Therefore, investigating the impact of λ at the 800m mark provides valuable insights into the adaptability and reliability of the error control mechanism under evaluation, with significant implications for the practical deployment of UAV video transmission systems.

6.2.1 Number of decodable frames

Figure 6.4(a-b) demonstrates the interplay between the application threshold (λ) and the video frame deliverability, showcasing the number of decodable frames at different λ settings of 0.5s and 1.5s. In scenarios using AR-FEC-4K, a decrease in λ from 1.5s to 0.5s leads to a 9% drop in the number of received frames. This decline is attributed to the stringent requirement to deliver high-quality frames with reduced delay, which becomes increasingly challenging at higher bit error rates without the implementation of quality adaptation measures. Conversely, the same reduction in λ results in a negligible decrease of less than 1% for AR-FEC, underscoring the system's ability to maintain consistent frame delivery through adaptive mechanisms.

Furthermore, the data presented in Figure 6.4 indicates that while AR-FEC does experience a minor decrement in the number of frames delivered at the more restrictive threshold of 0.5s, it still successfully delivers over 94% of the frames. Impressively, within this subset, more than 52% of the frames are of high quality. These statistics underscore the pivotal role that video quality adaptation plays in the robustness of video transmission.



(a) λ = 0.5s (b) λ = 1.5s

Figure 6.4: Received frame quality on different λ at 800m as distance

By adjusting the video quality in real-time to align with network conditions and threshold constraints, AR-FEC ensures that the integrity of the video stream is not compromised, even under tight latency requirements. The ability of AR-FEC to dynamically modulate video quality in response to varying λ values is critical in applications where delay and quality are both vital parameters. This flexibility demonstrates the effectiveness of AR-FEC in delivering a high proportion of usable, high-quality frames, even when operating under severe temporal constraints, thus enhancing the reliability of UAV-based video communications.

6.2.2 Throughput

Figure 6.5 demonstrates the throughput performance of transmission algorithms across a challenging 800m UAV communication link, measured at various application thresholds. AR-FEC stands out, achieving a stable throughput of 12.4 Mbps at the stringent threshold of 0.5 seconds and 13.3 Mbps as the threshold extends to 1.5 seconds. These results reflect AR-FEC's capacity to maintain performance despite stringent delay constraints, outperforming AR-FEC-4K which records a throughput increase from 8 Mbps to 10.8 Mbps with the threshold relaxation. This increase aligns with a 9% rise in high-quality frame delivery, as elaborated in Figure 6.4. AR-FEC's capability to sustain the highest throughput, surpassing that of AR-FEC-4K without accruing significant overhead, emphasizes its suitability for UAV video streaming services. The throughput metrics at both the lower and upper bounds of λ demonstrate AR-FEC's effectiveness in delivering quality service without compromising efficiency, which is consequential for real-time UAV applications.

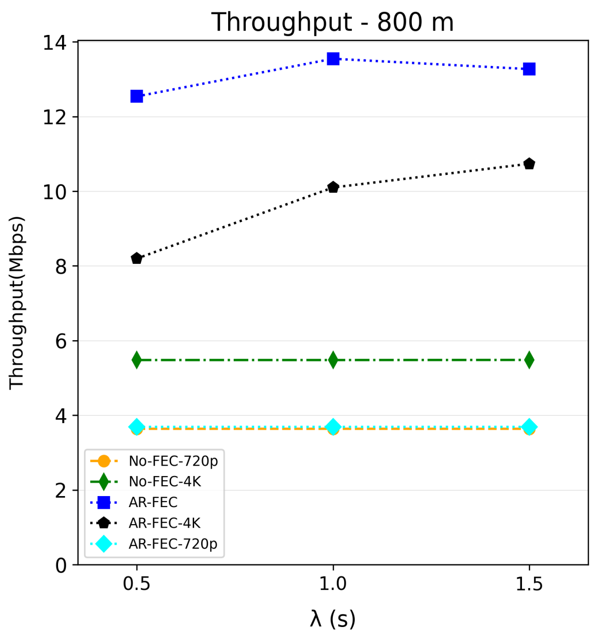


Figure 6.5: Throughput on different λ at 800m as distance

Table 6.2 displays the FEC packet ratios for different approaches employing FEC mechanisms at various application thresholds. Generally, there should be a decreasing overhead when we have an increase in the maximum application threshold. This stems from a decrease in PLR because of delayed packets. In contrast, the table reveals a consistent overhead in AR-FEC-720p as all frames have low-quality and there are no losses/delayed I-frame packets that can be recovered by the 1% FEC packets (as a minimum value) for each GoP. Additionally, AR-FEC-720p has a lower number of total packets compared to AR-FEC, resulting in a higher FEC packet ratio for AR-FEC-720p. AR-FEC achieves the highest throughput with the lowest redundancies. On the other hand, AR-FEC-4K exhibits the highest FEC ratio, resulting in approximately 19% overhead while achieving around 8 Mbps throughput at a 0.5s application threshold. Moreover, the FEC packet ratio shows a mere 2% difference between λ=0.5s and λ=1.5s in the case of AR-FEC-4K. However, Figure 6.5 illustrates a significant difference of around 3 Mbps in throughput for this scheme. This further emphasizes the importance of the adaptive quality module in AR-FEC, as it plays a significant role in achieving optimal performance.

Table 6.2: FEC packet ratio (%) at different λ – Distance=800m

Algorithm	**0.5s**	**1.0s**	**1.5s**
AR-FEC	1.33	1.26	1.22
AR-FEC-720p	1.45	1.45	1.45
AR-FEC-4K	19.54	18.56	17.94

6.2.3 Frame latency

Figure 6.6 presents a detailed analysis of average frame latency, showcasing how different transmission schemes fare over an 800m distance when subjected to varying application thresholds (λ). The AR-FEC scheme distinguishes itself with the lowest latency readings, indicating its superior handling of video frames under tight delay constraints. Notably, AR-FEC's average latency slightly decreases from 0.074 seconds at a restrictive threshold of 0.5 seconds to an even lower 0.054 seconds as the threshold is relaxed to 1.5 seconds. This minor variance in latency underscores the efficiency of AR-FEC, particularly when contrasted with the larger latency reductions observed in AR-FEC-4K, which drops from a higher 0.217 seconds to 0.063 seconds between the same λ values.

The latency performance of AR-FEC is even more remarkable given the context provided by Figure 6.4a, which reveals a stark contrast in the delivery of 4K frames between AR-FEC, the No-FEC-4K, and AR-FEC-4K schemes at the 0.5-second threshold. Despite the challenges of streaming at high resolution and under stringent delay constraints, AR-FEC not only maintains but also improves its latency, showcasing its robustness against the high error rates often encountered in real-time UAV video streams.

These observations collectively suggest that AR-FEC not only excels in managing latency across various thresholds but also demonstrates an exceptional capacity to deliver high-quality video content reliably in error-prone conditions. This resilience to delay sensitivity, coupled with a consistent quality of service, positions AR-FEC as an optimal solution for UAV video streaming applications that demand real-time data transmission with minimal compromise in video quality, even in the most challenging environments.

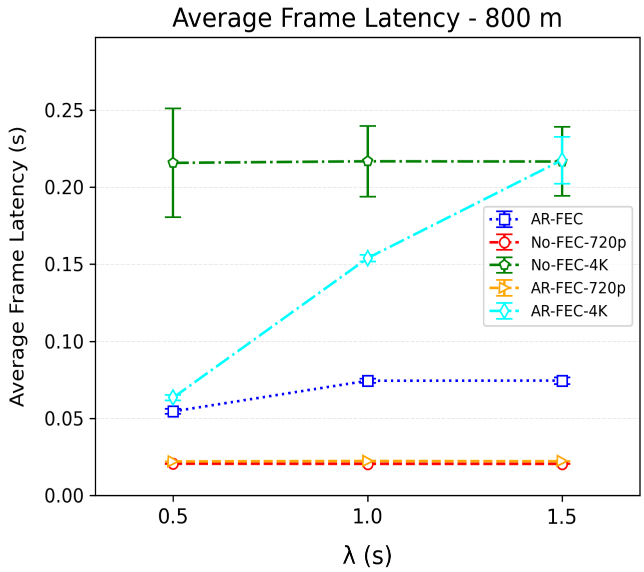


Figure 6.6: Average Frame Latency on different λ at 800m as distance

In a scenario with one drone as the sender, AR-FEC's performance in UAV video transmission was thoroughly evaluated, showcasing its ability to significantly reduce frame loss, maintain high throughput, and ensure low latency over distances up to 800m. These results, particularly notable at the farthest range, highlight AR-FEC's adaptability and robust error correction in a relatively controlled environment. As the study progresses to a more complex scenario involving two drones as senders, it will explore AR-FEC's functionality amid increased noise and error rates characteristic of a congested airspace. This next phase aims to assess the scalability of AR-FEC in an environment that closely simulates the challenges of real-world UAV operations with multiple active senders.

6.3 Impact of two UAVs as senders

In this section, we extend our investigation to assess the dynamics of AR-FEC performance in a dual-sender scenario, simulating a more complex UAV communication network. This setup, depicted in Figure 6.7, features two drones acting as senders, each equipped with an FEC computational component, to understand the implications of multiple simultaneous transmissions on key performance metrics over varied distances. The second UAV, known as Node2 below, is introduced to the system, and embarks from point 3, charting a clockwise trajectory around a predefined square route. The control station, positioned centrally, integrates an FEC correction component, symbolizing the nexus of data reception and error correction. Maintaining an application threshold (λ) of 1 second, consistent with the single-sender analyses, this configuration allows for a direct performance comparison while introducing the complexities of additional aerial traffic and potential interference. The evaluation will closely monitor how the interplay between the two drones influences the efficacy of the AR-FEC algorithm, particularly focusing on its capacity to uphold communication integrity in an environment with augmented noise and error rates.

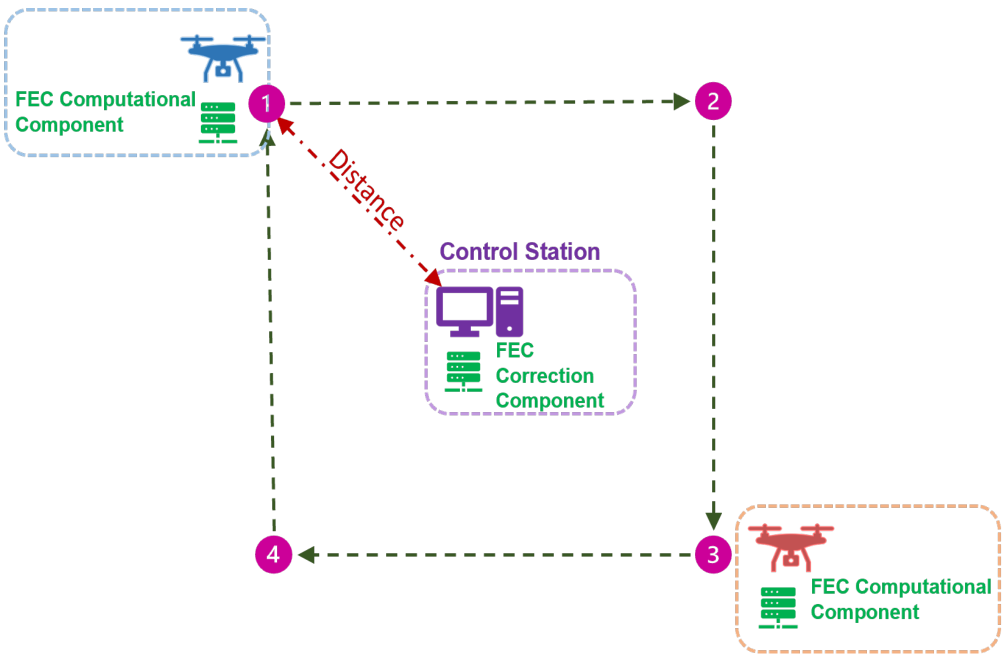


Figure 6.7: Evaluation topology for two drones as sender

6.3.1 Number of decodable frames

Figures 6.8, 6.9, and 6.10 illustrate the influence of dual-sender traffic on the reception and quality of video frames across distances of 400m, 600m, and 800m, respectively, under a fixed application threshold (λ) of 1 second. These depictions confirm that the AR-FEC algorithm effectively balances streaming reliability with quality. Notably, low-resolution streams (No-FEC-720p and AR-FEC-720p) maintain integrity without frame loss across all distances, with a minimal loss occurring only at 800m for Node2, which is corrected by employing FEC.

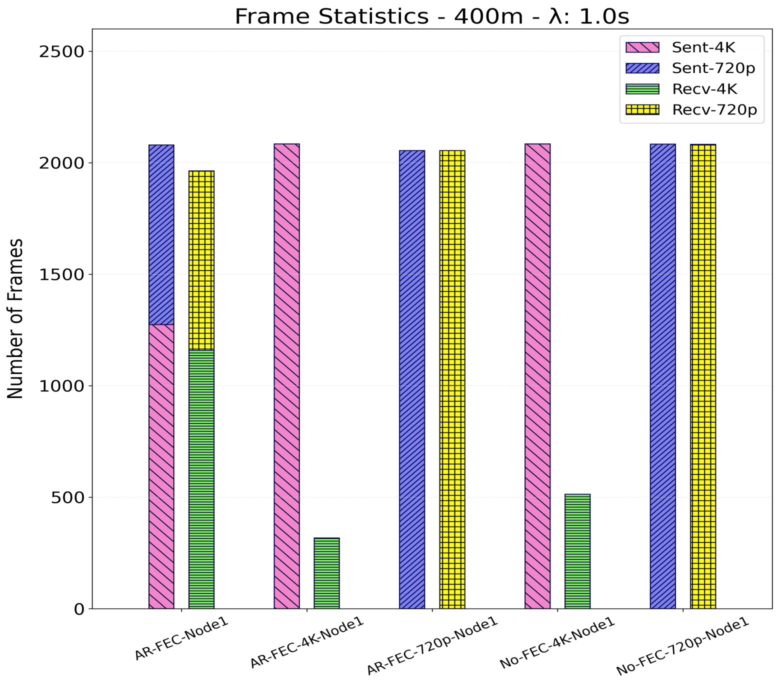
400m Distance Analysis:

At the 400m mark, Figure 6.8 showcases the impact of increased traffic with two drones serving as senders on the quality and reliability of video transmission at a fixed application threshold (λ) of 1 second. The performance of AR-FEC is commendable, as it consistently delivers a significant majority of frames with minimal loss, maintaining high-quality video transmission despite the added complexity of a second sender. Especially, in the low-resolution video streams (720p), the AR-FEC-720p scheme experiences no frame loss, indicating robustness in less demanding transmission conditions. In stark contrast, high-resolution streams (4K) suffer considerable frame loss, which is markedly reduced by the AR-FEC mechanism, demonstrating its effectiveness in enhancing video stream reliability.

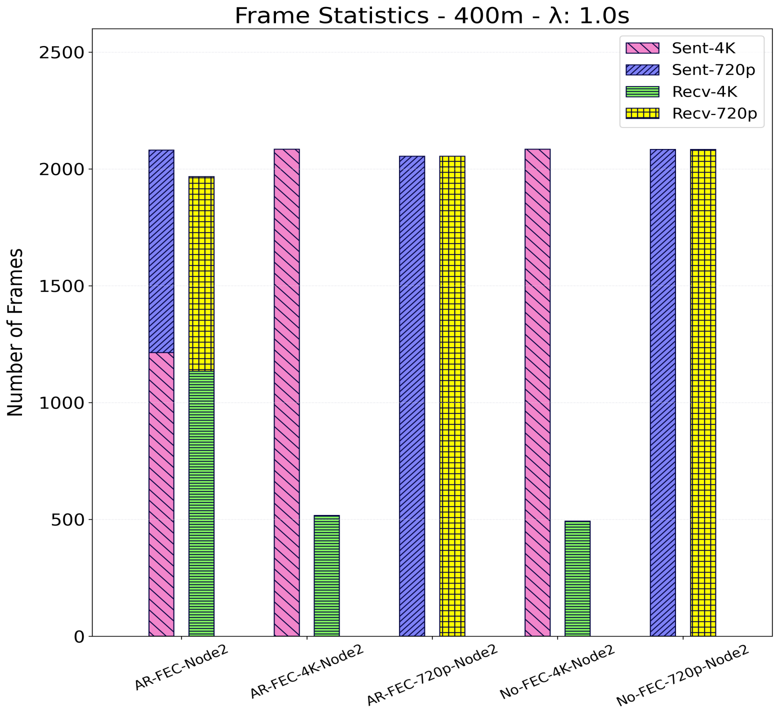
Comparative analysis on 400m reveals that while AR-FEC's performance is resilient at shorter distances, the introduction of an additional sender increases the challenge, as evidenced by Node1 and Node2 recording losses of 116 and 113 frames, respectively. This is a clear increase from the single-sender scenario where AR-FEC's frame loss was significantly lower, as shown in Figure 6.1a. The AR-FEC-4K, when faced with the added sender, incurs over a 75% loss rate, a drastic shift from the 3% loss observed in a single sender setup. These outcomes underscore the necessity of AR-FEC's adaptive capabilities and FEC's redundancy to combat the rise in network traffic and ensure the delivery of a reliable and high-quality video stream, even in scenarios of close proximity UAV operations characterized by increased noise and potential interference.

600m Distance Analysis:

Moving to the 600m distance, Figure 6.9 provides the frame statistics afford insight into the dynamics of transmission efficiency within a dual-drone



(a) Distance=400m - Node 1



(b) Distance=400m - Node 2

Figure 6.8: Frame quality on 400m with 2 nodes as sender

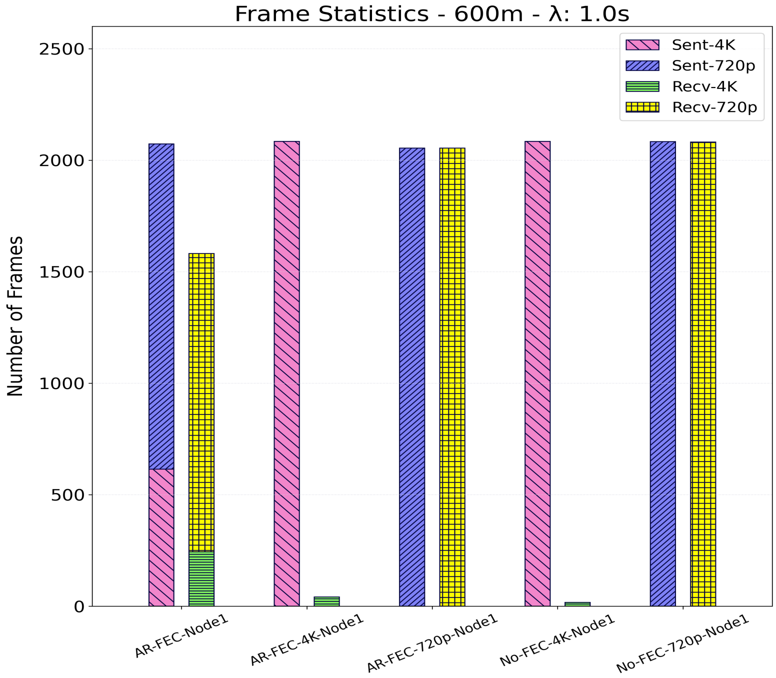
configuration. When employing two UAVs as transmission sources, the AR-FEC protocol sustains the integrity of 720p video streams, achieving no frame loss. This level of reliability is consistent with that of a single-sender model. In stark contrast, the high-resolution 4K video streams processed under the AR-FEC-4K protocol experience a significant reduction in the number of frames successfully received, highlighting the challenges posed by managing larger volumes of high-quality data in an environment with increased signal traffic.

The AR-FEC scheme reports a frame loss of 25%, whereas the AR-FEC-4K and No-FEC-4K configurations encounter frame losses exceeding 98%. Comparatively, in scenarios featuring a single drone, as illustrated in Figure 6.1b, the frame loss for AR-FEC-4K and No-FEC-4K are recorded at 45% and 65%, respectively. This marked increase in frame loss with the addition of a second UAV underscores the complexities of transmitting high-fidelity video streams, thereby emphasizing the critical necessity for robust error-correction mechanisms such as AR-FEC to maintain reliable communication across multi-drone networks

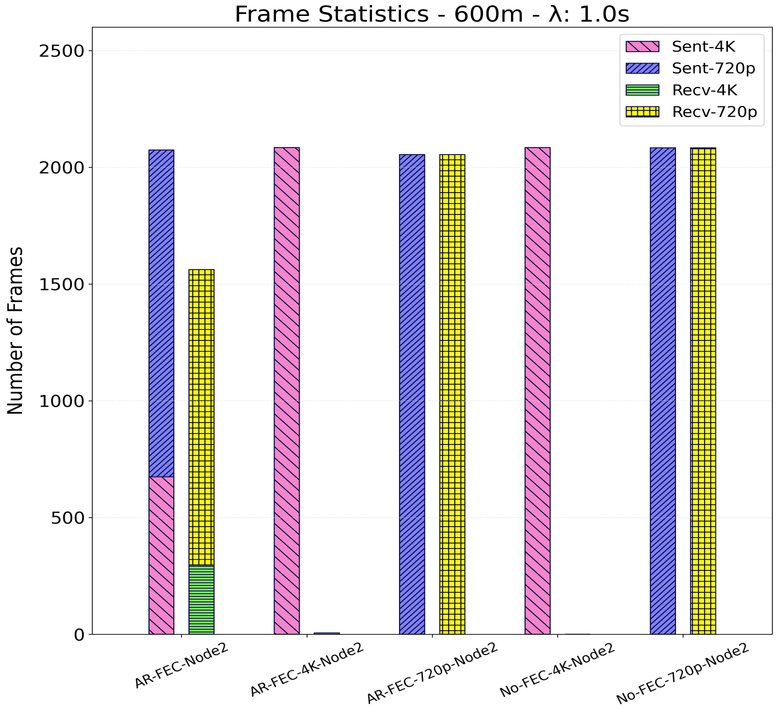
800m Distance Analysis:

When comparing the performance of different methods for delivering 4K video at a distance of 800 meters, a clear difference is observed between using one drone as a sender (as shown in Figure 6.1c) and using two drones (Figure 6.10). The adaptive algorithm in the AR-FEC system demonstrates remarkable resilience, maintaining high frame delivery rates despite challenging conditions. This technology appears to prioritize maintaining a stable connection, adapting in real-time to high error rates and noise, and potentially sacrificing quality to keep the stream going.

On the other hand, when two drones are used as senders, both the AR-FEC-4K and No-FEC-4K methods exhibit a significant drop in performance, with a drastic loss of frames noted in Figure 6.10. This severe frame loss at the maximum operational range indicates a struggle to handle the combined challenges of increased traffic, higher resolution, and longer distance. The high loss rates for both AR-FEC-4K and No-FEC-4K highlight the importance of AR-FEC's adaptive features in managing data transmission under tough conditions. The data suggests that without such adaptability, delivering high-quality video streams becomes highly unstable, underscoring the value of AR-FEC's ability to dynamically adjust transmission quality to ensure the best possible outcome.

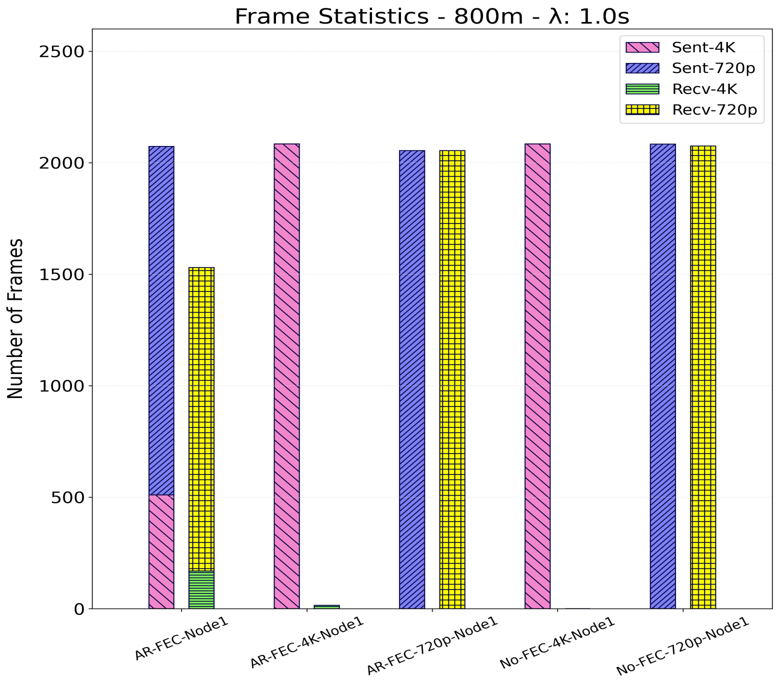


(a) Distance=600m - Node 1

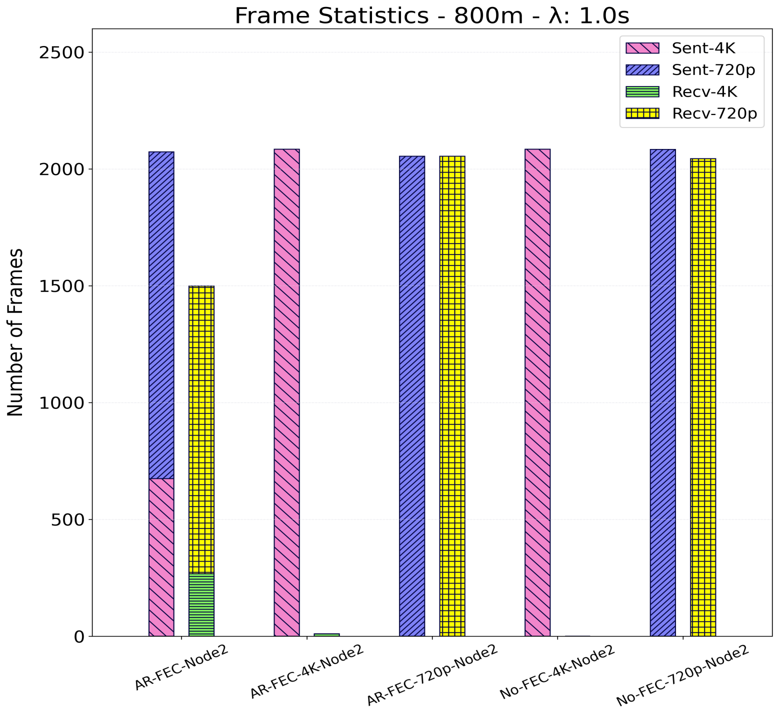


(b) Distance=600m - Node 2

Figure 6.9: Frame quality on 600m with 2 nodes as sender



(a) Distance=800m - Node 1



(b) Distance=800m - Node 2

Figure 6.10: Frame quality on 800m with 2 nodes as sender

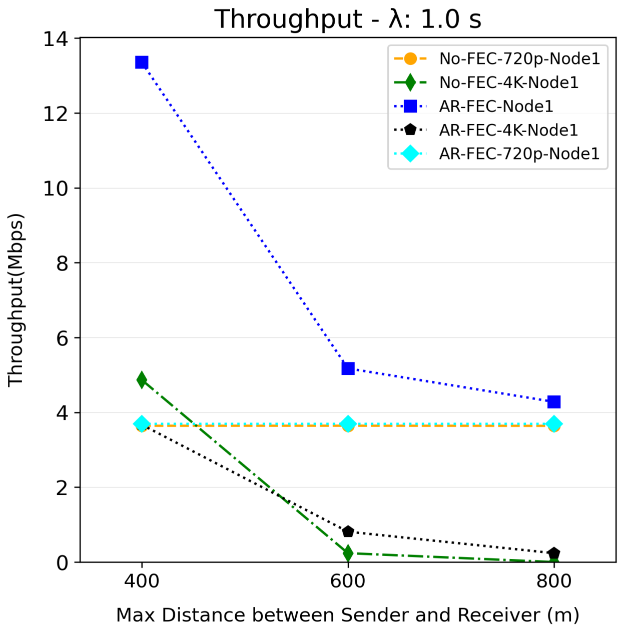
6.3.2 Throughput

An in-depth analysis of throughput for two-drone sender scenarios is depicted in Figure 6.11, revealing the performance of the examined schemes over a range of distances. At the outset, at 400 meters, the AR-FEC algorithm excels on both nodes, delivering a superior throughput. This is evident in Figure 6.8, where AR-FEC not only achieves the highest throughput but also demonstrates exceptional resilience in maintaining it as distances increase to 600 and 800 meters in Figure 6.9 and 6.10, respectively. Despite a relative decline at these extended ranges, AR-FEC's performance persists above other methods, indicating its robust adaptability in challenging conditions.

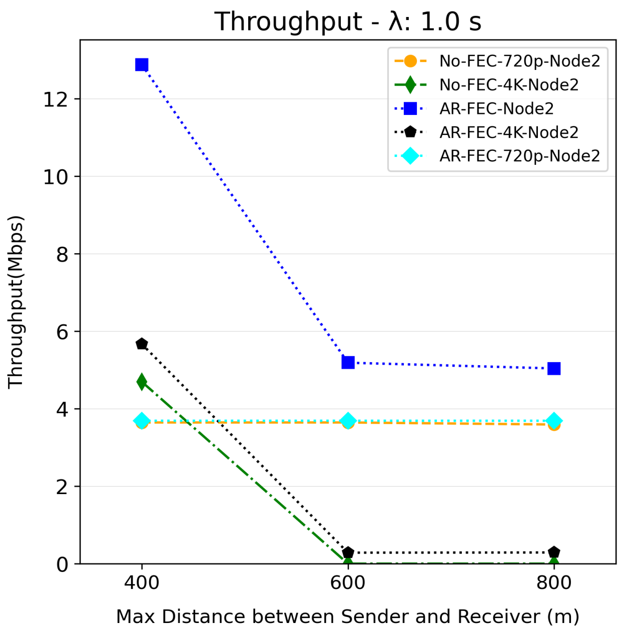
Conversely, the high-resolution AR-FEC-4K and No-FEC-4K schemes, while initially comparable at shorter distances, exhibit a pronounced decrease in throughput as they contend with the compounded stress of additional traffic and extended range, culminating in an almost negligible throughput at 800 meters. This trend is markedly illustrated in the corresponding figures, showcasing the limitations of these schemes when network demands escalate.

Table 6.3 provides a granular view of the FEC packet ratios for the employed schemes across various distances. The AR-FEC approach consistently maintains the lowest FEC packet ratios, with an exceptional sub-1% ratio at 400 meters for node 1 and marginally higher for node 2, as the distance reaches 800 meters. This contrasts with the AR-FEC-4K's FEC ratios, which indicate a significant increase, reflecting a higher overhead and subsequent frame loss, with node 1 peaking at nearly 26.14% at 800 meters.

The AR-FEC's adeptness at ensuring a substantial proportion of high-quality frames is further substantiated by the throughput graphs (Figs. 6.8, 6.9, and 6.10). Here, AR-FEC not only keeps frame loss consistently below 28% across all examined distances but does so with minimal FEC overhead—demonstrably under 5%. In sharp divergence, AR-FEC-4K struggles with a steep increase in FEC packet ratio correlating with a drastic spike in frame loss, reaching 75% at 400 meters and a complete loss at 800 meters, emphasizing the adaptive strength of AR-FEC when managing transmission quality and network traffic in long-range drone communications.



(a) Node 1



(b) Node 2

Figure 6.11: Throughput on different distances at λ=1.0s for 2 nodes as sender

Table 6.3: FEC packet ratio (%) at different distances – $\lambda = 1.0s$ - Two senders

Algorithm	**400m**	**600m**	**800m**
AR-FEC-node1	0.82	4.44	3.72
AR-FEC-node2	0.96	7.57	5.56
AR-FEC-720p-node1	1.45	1.45	1.45
AR-FEC-720p-node2	1.45	1.45	1.45
AR-FEC-4K-node1	23.99	25.96	26.14
AR-FEC-4K-node2	21.98	26.14	26.13

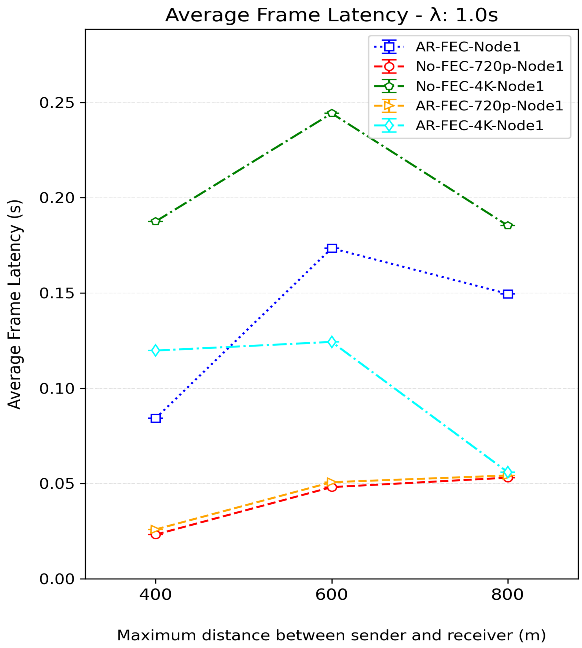
6.3.3 Frame Latency

Delving into frame latency, Figure 6.12 showcases the impact of increasing distances on the performance of different video transmission schemes with two drones as senders. It is evident that high-resolution video transmission tends to be associated with greater latencies. Within this context, the AR-FEC algorithm distinguishes itself, maintaining lower latency levels across distances, which suggests an efficient handling of data packets even in extended-range operations.

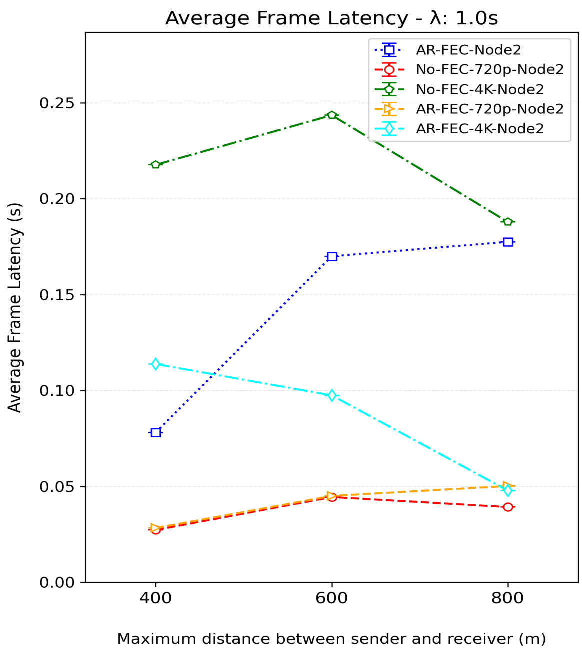
The results show that AR-FEC has a complex behavior; Figure 6.12 shows that AR-FEC has a somewhat higher latency at 600 and 800 m distances than AR-FEC-4K. This is because, as Figs. 6.9 and 6.10 illustrate, the high-resolution AR-FEC-4K struggles greatly, delivering only 2% of frames at these difficult distances, while the AR-FEC guarantees the delivery of a substantial majority of frames—72%.

At the critical range of 800 meters, the average latency for AR-FEC hovers at 0.15 seconds for Node 1 and 0.17 seconds for Node 2, demonstrating a stable latency performance despite the increased distance. In comparison, the latency for AR-FEC-4K is lower at 0.05 seconds; however, this comes at the cost of a drastic reduction in high-quality frame delivery, as evidenced by the high-quality frame delivery percentages. No-FEC-4K shows the highest latency of 0.188 seconds, reflecting the absence of any latency management mechanism. The contrast is more pronounced when considering the one-drone scenario (Figure 6.3), where AR-FEC achieves a consistent latency of 0.074 seconds, indicating its superior management of latency irrespective of traffic load.

In conclusion, the analysis of the two-drone case shows a distinct difference in performance across the evaluated parameters. The AR-FEC method has demonstrated a constant superiority in maintaining high throughput, quality, and low latency, especially when compared to the No-FEC alternatives. Al-



(a) Node 1



(b) Node 2

Figure 6.12: Frame latency on different distances with 2 nodes as sender

though adding a second drone increases complexity and increases the possibility of interference, these issues are substantially mitigated by AR-FEC's capacity to adapt to network circumstances. The findings suggest that the ability of AR-FEC to preserve video quality increases with increasing distance. In multi-drone communication systems, adaptive error correction plays a crucial role in providing dependable and effective video transmission, even as operating demands increase. The data presented in this section clearly illustrates this point.

6.4 Summary of the Evaluation

In this evaluation chapter, a comprehensive assessment of the AR-FEC mechanism in the context of UAV video transmission was conducted. Through systematic analyses of varying operational factors, including operating distances and application threshold settings, insights into AR-FEC's performance under diverse UAV operating conditions were sought.

Firstly, the impact of operating distance on AR-FEC's performance was investigated. Across distances ranging from 400m to 800m, an assessment was made of AR-FEC's ability to balance video streaming quality and transmission robustness. Superior frame delivery rates, reduced frame losses, and enhanced throughput compared to non-FEC alternatives were observed, suggesting AR-FEC's effectiveness in mitigating the effects of network congestion and maintaining high-quality video transmission.

Next, the influence of the application threshold (λ) on AR-FEC's performance was examined. By varying λ settings from 0.5s to 1.5s, the capacity of AR-FEC to adjust video quality in response to latency constraints dynamically was observed. Even under stringent delay requirements, a high proportion of usable, high-quality frames was consistently delivered by AR-FEC, indicating its robustness in latency-sensitive UAV applications.

Furthermore, an analysis was extended to a scenario involving two UAVs as senders, simulating a complex UAV communication network. Despite the added complexity and potential for interference, AR-FEC demonstrated resilience in maintaining high throughput, quality, and low latency. The adaptability of AR-FEC appeared crucial in mitigating the impact of increased aerial traffic, suggesting reliable video transmission even in environments with heightened operational demands.

In conclusion, the evaluation suggests AR-FEC's potential as a critical component of UAV video transmission systems. AR-FEC's adaptive error correction mechanisms enable it to effectively navigate varying network conditions, ensuring reliable and high-quality video transmission across different operating scenarios. The findings presented in this chapter provide insights into AR-FEC's suitability for real-world UAV applications, indicating potential enhancements in communication capabilities for UAV operations.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

In this thesis, an innovative adaptive FEC mechanism tailored for robust, high-quality multimedia communication via UAVs, increasingly prevalent in various applications, has been developed and meticulously examined. The exploration commenced with the proposal of an adaptive cross-layer FEC scheme. This scheme, residing within the application layer, intelligently adjusts FEC redundancy levels in real-time, responding to the immediate packet loss rate and projected network traffic conditions. A dynamic module that finely tunes the quality of video frames was then introduced. This tuning is informed by the current state of the wireless link channel, and the queuing data predicted at the lower layers, embodying a true cross-layer optimization approach.

The next advance was the application of an unequal error protection strategy to video packets. This strategy intelligently allocates resources to different types of video frames, thereby significantly enhancing transmission efficiency and the quality of video as received at the control station. Anchored in the principles of edge computing, this method leverages real-time video analytics at the network edge, allowing for prompt and intelligent adaptations at the device-edge interface.

The simulation results presented in the evaluation section of this work underscore the effectiveness of the proposed AR-FEC method. When juxtaposed with scenarios bereft of FEC, and those with non-adaptive FEC strategies, AR-FEC's superiority was evident across various performance metrics — including frame delivery, average latency, and throughput. In scenarios involving two drones, AR-FEC demonstrated commendable adaptability and resilience, maintaining service quality despite the added complexity and potential for increased interference.

In terms of latency, a critical metric for real-time applications, AR-FEC maintained consistent performance, thereby validating its design as latency-sensitive and suitable for time-critical UAV communication tasks. It showcased an exceptional ability to mitigate the latency introduced by dual-sender scenarios, underscoring its potential for scalable deployment in complex operational environments. The throughput results further attested to AR-FEC's robustness, where even under the strain of increased distances and network demands, the algorithm sustained a level of throughput that ensures a steady stream of high-quality video.

7.2 Future Work

Building on the robust foundation laid by this thesis, the pathway to future research is rich with potential. The exploration of advanced queue management strategies opens a realm of possibilities for optimizing data traffic. Envision a system where priority queues are not just for I-frame and P/B-frame packets but are dynamically adjusted based on real-time analytics and traffic predictions, ensuring seamless video delivery even during network fluctuations.

Machine learning techniques, particularly those harnessing the power of deep learning and neural networks, could revolutionize the proposed approach to FEC redundancy. By training models on vast datasets encompassing various network scenarios, these intelligent systems could anticipate and react to changes in network health, preemptively adjusting FEC parameters before packet loss escalates.

Beyond performance indicators, the sustainability of UAV multimedia systems is paramount. A comprehensive study into the energy consumption of the proposed adaptive system could lead to breakthroughs in energy-efficient UAV operations. One could imagine UAVs that adjust their communication protocols, not only based on the data requirements, but also on energy constraints, extending their operational lifespan and reducing their environmental impact.

Integrating these elements, future UAV systems could feature an ecosystem of smart, adaptive communication protocols, machine learning-driven traffic management, and energy-aware operations. This would pave the way for UAVs to be deployed in more complex and mission-critical applications, from environmental monitoring to emergency response, where reliability, efficiency, and autonomy are not just desired but essential. As UAVs become increasingly integrated into the fabric of our society, the work presented in this thesis will contribute to the development of the next generation of UAV communication systems.

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