Raheeb Muzaffar

Routing and video streaming in drone networks

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Mentors
Univ.-Prof. Dr.-Ing. Christian Bettstetter
Institut of Networked and Embedded Systems
University of Klagenfurt

Prof. Andrea Cavallaro
Centre for Intelligent Sensing
Queen Mary University of London

1st Evaluator
Univ.-Prof. Dr.-Ing. Christian Bettstetter
Institut of Networked and Embedded Systems
University of Klagenfurt

2st Evaluator
Univ.-Prof. Dr.-Ing. Christian Bettstetter
Institut of Networked and Embedded Systems
University of Klagenfurt

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Abstract

Drones can be used for several civil applications including search and rescue, coverage, and aerial imaging. Newer applications like construction and delivery of goods are also emerging. Performing tasks as a team of drones is often beneficial but requires coordination through communication. In this thesis, the communication requirements of video streaming drone applications based on existing works are studied. The existing communication technologies are then analyzed to understand if the communication requirements posed by these drone applications can be met by the available technologies. The shortcomings of existing technologies with respect to drone applications are identified and potential requirements for future technologies are suggested.

The existing communication and routing protocols including ad-hoc on-demand distance vector (AODV), location-aided routing (LAR), and greedy perimeter stateless routing (GPSR) protocols are studied to identify their limitations in context to the drone networks. An application scenario where a team of drones covers multiple areas of interest is considered, where the drones follow known trajectories and transmit continuous streams of sensed traffic (images or video) to a ground station. A route switching (RS) algorithm is proposed that utilizes both the location and the trajectory information of the drones to schedule and update routes to overcome route discovery and route error overhead. Simulation results show that the RS scheme outperforms LAR and AODV by achieving higher network performance in terms of throughput and delay.

Video streaming drone applications such as search and rescue, surveillance, and disaster management, benefit from multicast wireless video streaming to transmit identical data to multiple users. Video multicast streaming using IEEE 802.11 poses challenges of reliability, performance, and fairness under tight delay bounds. Because of the mobility of the video sources and the high data-rate of the videos, the transmission rate should be adapted based on receivers' link conditions. Rate-adaptive video multicast streaming in IEEE 802.11 requires wireless link estimation as well as frequent feedback from multiple receivers. A contribution to this thesis is an application-layer rate-adaptive video multicast streaming framework using an 802.11 ad-hoc network that is applicable when both the sender and the receiver nodes are mobile. The receiver nodes of a multicast group are assigned with roles dynamically based on their link conditions. An application layer video multicast gateway (ALVM-GW) adapts the transmission rate and the video encoding rate based on the received feedback. Role switching between multiple receiver nodes (designated nodes) cater for mobility and rate adaptation addresses the challenges of performance and fairness. The reliability challenge is addressed through re-transmission of lost packets while delays under given bounds are achieved through video encoding rate adaptation. Emulation and experimental results show that the proposed approach outperforms legacy multicast in terms of packet loss and video quality.

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A special thanks to my family for their unconditioned support. They are the most important people in my world and I dedicate this thesis to them. Words cannot express how grateful I am to my parents for all their sacrifices and prayers. At the end, I would like to express appreciation to my beloved wife Ms. Sarah Raheeb who supported and encouraged me throughout this journey. To my beloved daughter Ms. Abiya Raheeb Muzaffar for being such a good girl and always cheering me up.

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List of Symbols

$\mathbb{O}$ Set of output HD video streams

$\mathbb{O}_f$ Overview video streams

B Set of best effort nodes of a multicast group G_j, $B = \{B_1, \cdots, B_n\}$

C_{R_i} Channel capacity at a particular transmission rate R_i

G_j Multicast groups where $j \in \{1, \cdots, M\}$

I Set of input HD video streams

L Length

M Number of drones

M_D Destination ground node

M_N Neighboring drone

M_S Source drone

M_{R1} Relay drone 1

M_{R2} Relay drone 2

P Primary designated node

Q_P Signal quality of primary designated node

Q_V Signal quality of a new mobile receiver node

Q_{B_i} Signal quality of a best effort node B_i

Q_{S_i} Signal quality of a of secondary designated node S_i

r_f Fixed encoding rate of overview videos

R_i IEEE 802.11 transmission rates, $R_i \in \{6, 9, 12, 18, 24, 36, 48, 54\}$ Mbit/s

r_i Video encoding rate

S Set of secondary designated nodes of G_j, $S = \{S_1, \cdots, S_n\}$

T_R Required transmission rate to multicast M video streams

$T_{\alpha-1}$ Time at step $\alpha - 1$

T_α Time at step α

V A new mobile receiver node

W Width

card(B) Cardinality of the set of best effort nodes B

card(G_j) Cardinality of multicast group G_j

card(S) Cardinality of the set of secondary designated nodes S

List of Acronyms

ACK Acknowledgement

AODV Ad-hoc on-demand distance vector

A2A Air-air

A2G Air-ground

ALVM-GW Application-layer video multicast gateway

AL-ACK Application-layer acknowledgement

ALRA Application-layer rate adaptation

ARL Army research laboratories

BGP Border gateway protocol

CORE Common open research emulator

CBR Constant bit rate

DTN Delay tolerant network

DSDV Destination-sequenced distance vector

DMS Directed multicast service

DBF Distributed Bellman-Ford

DCF Distributed coordination function

DST Distributed spanning tree

DSR Dynamic source routing

EMANE Extendable mobile ad-hoc network emulator

GMM Gaussian mixture model

GPRS General packet radio service

GPS Global positioning system

GPSR Greedy perimeter stateless routing

G2A Ground-air

GATS Group addressed transmission service

GCR Groupcast with retries

HAUS Heterogeneous unmanned aircraft system

HSPA High speed packet access

IMU Inertial measurement unit

IP Internet protocol

LM-ARF Leader-based multicast with auto rate fallback protocol

LBP Leader-based protocol

LAR Location aided routing

LTE Long-term evolution

MTU Maximum transmission unit

MAC Medium access control

MAVs Micro aerial vehicles

MANETs Mobile ad-hoc networks

NRL Naval research laboratory

NACK Negative acknowledgement

NPDUs Network protocol data units

OSPF Open shortest path first

OLSR Optimised link state routing

OSPF-MDR OSPF MANET designated routing

PSNR Peak-signal-to-noise-ratio

PPP Point-to-point protocol

QoE Quality of experience

QoS Quality of service

RW Random walk

RWP Random waypoint model

RSS Received signal strength

RACK Request for ACK

RS Route switching

RIP Routing information protocol

SAR Search and rescue

SINR Signal-to-interference-noise-ratio

SNR Signal-to-noise-ratio

SARM SNR-based auto rate for multicast

TCP Transmission control protocol

UAVs Unmanned aerial vehicles

VANETs Vehicular ad-hoc networks

WCDMA Wideband code division multiplexing access

WiSAR Wilderness Search and Rescue

WMM WiFi multimedia

WLAN Wireless local area network

WMN Wireless mesh network

ZRP Zone routing protocol

1 Introduction

1.1 Motivation

Unmanned aerial vehicles (UAVs) have been in use by the military for mission critical and warfare applications for more than two decades [WAH12]. Micro aerial vehicles (MAVs) or commonly known as drones are gaining attention both in research and commercial use. Many technological advancements related to their mechanics, design, maneuverability, capability, and sensing versatility has enabled their use in various civil applications [GMC12]. Numerous applications on aerial mapping, environmental monitoring, search and rescue (SAR), surveillance, remote sensing, and disaster management are identified [WAH12, Won01, QSB+08, FCC11] where drones can be used with reduced cost and minimal infrastructure. Newer applications such as construction [LMK11], transportation for medical assistance and consumer goods to facilitate people living in extremely remote locations and to reduce package delivery cost are emerging [Ack11, Mck13, Joh13]. Applications to provide live coverage to cultural and sports events, large gatherings, rallies, etc. are also gaining popularity.

With such diverse application categories, a vast variety of commercial drones are also available with different sizes, design features, payload capacity, and capabilities. Parrot AR Drone, AscTec Pelican and Firefly, Microdrones md4-200 and md4-1000, Draganflyer X6, Aeryon Scout micro-MAVs, Arducopter, and MarcusUAV Zephyr2 to name a few are the examples of commercially available, off-the-shelf drones being used for research and civil applications. The current research is focusing towards the design of nature inspired flapping wing drones that include drones inspired by bees, butterflies, humming birds, and bats since they provide agility with respect to maneuverability in all six directions [NCD14, BJS14, RSCH16]. Table 1.1 shows the maximum payloads capacity and wireless communication interfaces for some of the commercially available drones. The payload that the drones can carry might include the camera, global positioning system (GPS), inertial measurement unit (IMU), communication interface, and other sensors. Depending upon the application the drones might need to sense the environment and communicate with the ground stations or other drones while performing tasks as a team.

A team of drones is often beneficial for performing tasks efficiently since a single drone system is limited with its payload capacity, capability, endurance, and flight time [CS15]. However, working as a team requires coordination and communication among the fellow drones and the base station. Thus, communication remains an essential element to enable team behavior, coordination, and cooperation in a drone network. Drone networks differ from mobile ad-hoc networks (MANETs) and vehicular ad-hoc networks

Table 1.1: Maximum Payload and Communication Interface of some drone Platforms

Platform	Maximum Payload	Communication Interface
Parrot AR. Drone	-	802.11b, g, n, ac
AscTec Pelican	650 g	Xbee Pro, 802.11a, b, g, n, ac / Mini PCI Slot
AscTec Firefly	600 g	Xbee Pro, 802.11a, b, g, n, ac / Mini PCI Slot
Microdrones md4 - 200	250 g	RC transmitter, video downlink
Microdrones md4 - 1000	1200 g	RC transmitter, video downlink
Draganflyer X6	500 g	802.11n
Aeryon Scout	400 g	802.11b, g
MarcusUAV Zephyr2	1000 g	RC transmitter, video downlink

(VANETs) in terms of node mobility, node density, frequency of topology change, mobility pattern, radio propagation, and communication links [BST13]. Unlike MANET and VANET, nodes in a drone network form air-air (A2A), air-ground (A2G), and ground-air (G2A) links for communication to coordinate as a team and to fulfill tasks for a given application.

This thesis focuses on identifying communication requirements for video streaming applications in drone networks that are challenging due to frequent fluctuations in link conditions caused by the high mobility of drones and communication in three-dimensional space. We further discuss existing routing protocols and their applicability with drone networks and propose a routing protocol that considers trajectory and location information to calculate routing paths in advance. Moreover, an application-layer multicast video streaming framework applicable over IEEE 802.11 ad-hoc network is proposed that multicast video streams from teams of drones without any modification in the medium access control (MAC) layer to achieve reliability and smooth video playback.

1.2 Problem formulation

A team of drones can be beneficial to perform tasks faster and efficiently through coordination but require strong wireless networking and communication capabilities in three-dimensional space [YKB13]. In addition, Quality of Service (QoS) requirements are to be met to support multimedia applications. The question arises if the existing widely accepted routing algorithms are sufficient to fulfill the requirements for a mission-oriented network of drones [BST13]? A mission can be defined as a SAR scenario, surveillance or an event coverage where the drones are mobile and may require relaying data to the ground station or receiver nodes.

Consider a constrained area of $(L \times W)$ and M drones e.g., (1000×1000) m^2 area and four drones with some areas of interest marked in red as shown in Figure 1.1. These areas of interest are to be captured using drones in the form of multimedia traffic to provide coverage of an event or area surveillance. A limited fleet of drones is available

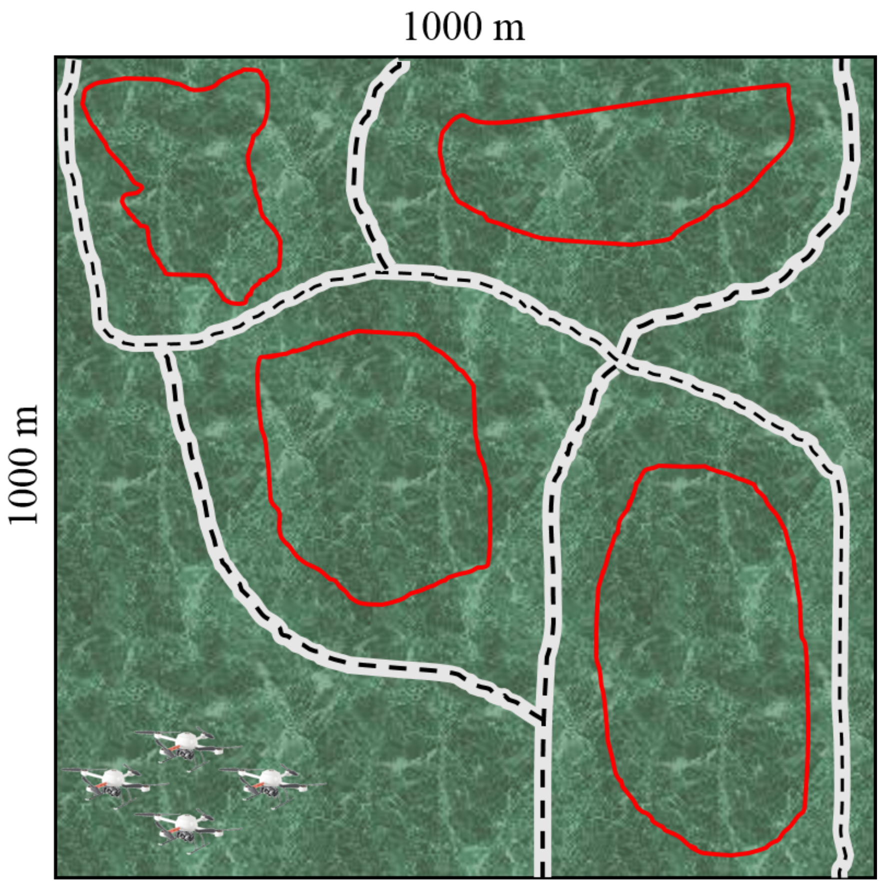


Figure 1.1: Example mission scenario where the areas of interest marked in red are to be captured with a fleet of drones.

to capture marked areas that may require data relaying to maintain connectivity. This depends on how far these areas of interest are from the ground node and what available number of drones can be used to provide the service. Requests can be received from users who can connect to the ground node or to the drones directly and receive their desired multimedia transmission. A reliable communication link between the drones and the ground station is thus imminent for such a scenario that requires a routing mechanism for a highly mobile environment. Routing is the process to find the path of data delivery from a source to a destination node. Because of the limited transmission range and high mobility of nodes in a network of drones and ground nodes the routing paths are to be discovered frequently. This causes loss of data packets and decreases an overall network throughput. A routing protocol for such a network is required since extremely limited packet loss and packet delay is bearable for live video streaming applications [LKPG11].

Streaming videos from drones can be used for SAR, surveillance, remote sensing, and post-disaster operations [WAH12, CS15, GMC12, Won01, QSB+08]. Videos of different observed areas can be streamed simultaneously using multiple drones to be viewed by multiple first responders on their mobile devices in a multipoint-to-multipoint fashion

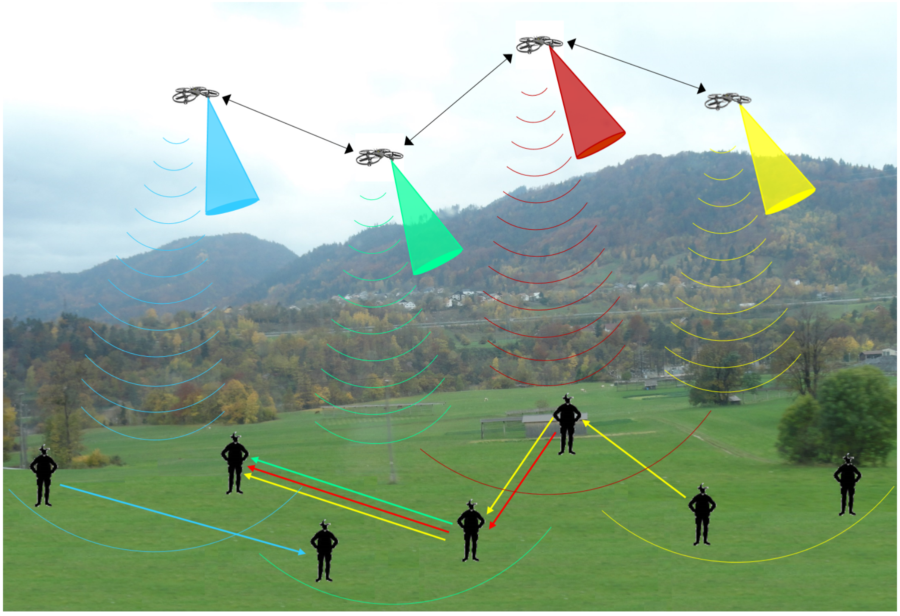


Figure 1.2: Multipoint video streaming from a fleet of drones to multipoint recipients. Drones receive video traffic from neighboring drones and transmit to recipients in their communication range. Recipient nodes also share received traffic streams among their neighbors.

to gain large-scale situational awareness. The scenario is illustrated in Figure 1.2. The drones move around a given bounded area at defined paths, capture videos, and stream them to the viewers. Viewers shall be able to receive at least *overview* (low definition) videos from multiple drones observing different areas. Viewers shall then be able to select a video from a particular drone and receive its high-quality stream when needed. The selection of a particular video stream by a first responder shall be communicated to the drone in the range or to the neighboring viewer node to form a video multicast group.

Multicasting is an efficient way to transmit identical data to multiple users since it saves network resources compared to unicasting [JR05], [dMCGA03]. IEEE 802.11 is the protocol of choice as it is supported by several drone platforms [BST13], is low-cost, widely available, standardized, and operates in the licence-free spectrum [FMZ07]. Multicast frames in IEEE 802.11 are addressed to a group of hosts and are not acknowledged. Since a source has no knowledge of the lost packets or the link condition of the receiver nodes, it cannot retransmit the lost packets or adapt the link transmission rate.

When not all drones are in the range of the viewers, videos must be relayed [CHKV07, BDH$^+$10] among drones or between viewers (Figure 1.2). This solution involves multi-hop multicast video streaming, for example using tree driven approaches [WZ07], [ARM06]. These approaches require routing, channel access, and high bandwidth when both source and destination points are mobile. Information pertaining to multicast nodes entering and exiting multicast groups needs to be maintained in a decentralized manner to obtain regular transmission feedback from the multicast group members and to regulate the transmission rate based on their link conditions.

Existing schemes [CCS+07, PSC+06, PKBV09, PFGC13, AKWP10] that address the feedback problem for multicast traffic and adapt the transmission rate require modifications in the medium access control (MAC) layer. The MAC layer of each node joining a multicast group shall be tailored to the requirements of the scheme being used. The node selected amongst the multicast group to provide feedback shall be dynamically elected with changing link conditions due to mobility and shall be made responsive (i.e. be able to provide feedback considering packet reception by all members of the group). Moreover, existing schemes are not designed for highly mobile networks like those formed with drones. A multicast video streaming framework for drone networks that addresses these shortcomings is required.

1.3 Challenges

In this section, potential communication challenges over IEEE 802.11, challenges in three-dimensional wireless communication, multicasting over 802.11, and video multicast streaming are highlighted. A list of these challenges is given in Table 1.2.

Table 1.2: IEEE 802.11 communication challenges in drone networks

Category	**Challenges**
Wireless communication	Interference
	Signal fading
	Variable bandwidth
	Limited transmisson range
	Multi-hop communication
	Environmental changes
Communication in three-dimentional space	Dynamic topology
	Terrain changes
	Obstacles in space
	Antenna orientation
	Radiation pattern
Multicasting	Reliability
	Performance
	Fairness
Video streaming	Strict delay bounds
	Quality of experience

1.3.1 Wireless communication and routing challenges for drone ad-hoc networks

Wireless communication is prone to fading and interference with other wireless devices. A wireless signal can fade in time, space, and phase causing temporal link failures and packet losses. Fading along with signal attenuation in mobile wireless environment renders reduced and variable bandwidth compared to wired networks [SSB+16].

The networking and communication constraints associated to an ad-hoc network of drones include *limited transmission range*, *high mobility of nodes* and *frequent topology change* that may require route changes and multi-hop communication. The terrain, environmental changes, and obstacles in space can cause higher and bursty bit errors [BST13, SSB+16]. Similarly, antenna orientation, radiation pattern, and other antenna characteristics can influence on the communication link quality [AKJ11].

Because of *limited transmission range*, a direct communication link between the drones and destination ground nodes may not always be possible. Even if a direct communication link is available the achieved throughput may not be sufficient for an acceptable quality of multimedia transmission. In such a case some drones might be required as relay nodes to provide connectivity and to increase the communication range.

High mobility is another constraint to be considered. High mobility makes the network topology change frequently. Connectivity between the source drone and the destination node may not be maintained due to a change in the network topology. If the connection is lost, drones cannot coordinate as a system and the mission objectives might be jeopardized. It is, therefore, important that the communication link between the drones and the ground node remains established until the mission is complete.

Legacy routing algorithms [AY05, CWKS97, TMB01, BST13] do not cater for high mobility and communication in three-dimensional space. If a relay node gets out of the radio range, a new route discovery is initiated. Establishing a new route might take enough time resulting in packet loss and disruption to the multimedia transmission. Jointly, these characteristics of wireless communication and drone networks can be the cause of higher jitter, delay, packet loss, and frequent link failures [LKPG11].

1.3.2 Issues with multicast video streaming in mobile ad-hoc networks

In addition to limited *transmission range* in wireless networks and *network topology changes* in mobile networks requiring path discovery and routing [CWKS97, TMB01], challenges with multicasting over IEEE 802.11 include reliability, fairness, performance, and delay [CCS+07, VZ13, ZLCP04, Naf07].

The 802.11 protocol multicasts data packets using the broadcast address. A packet with a broadcast/multicast address shall be decoded by all recipients of a multicast group. If all members acknowledge (ACK) the receipt of the packet, the ACK packets will collide and so the source will keep on re-transmitting the same packet for several times. The *reliability* problem stems from the lack of a mechanism that acknowledges reception of multicast packets or retransmissions of lost packets [DT06]. The challenge is how to make multicasting reliable such that lost packets are retransmitted to the desired recipients.

Since there exists no feedback mechanism in 802.11 multicasting, a source cannot adapt the transmission rate when the receivers link conditions vary. Thus, a receiver node can suffer network congestion due to a bad link condition or it can waste available network resources when it could afford higher bit rates. The objective is to achieve *fairness* through rate adaptation such that the source transmission rate is controlled based on the reception conditions of the members of the multicast group.

The distance, location and reception condition of the wireless members of the multicast group may vary. The reception conditions vary in time and space, and therefore the achievable throughput vary for different members of the multicast group. 802.11 uses the lowest bit rate (1, 2 or 6 Mbit/s) for multicast traffic. This poses *performance* degradation for the nodes that can afford better bit rates. Ideally, members of the multicast group would receive video data at an individual transmission rate supported by each member, similarly to unicast. However, since this is not possible for multicast traffic, a higher performance can be achieved by transmitting at a rate affordable for all members of the multicast group rather than using the lowest transmission rate as in 802.11 multicasting.

Finally, adhering to strict *delay* bounds between packet transmission and reception, and QoS support for live video multicast streaming is affected by fading, interference, and signal attenuation due to mobility [ZLCP04, Naf07]. For example, delays higher than 250 ms are not acceptable for live video streaming but can be experienced when a receiver is three hops away from the source [LKPG11].

1.4 Contributions

In this thesis, we list applications that can be beneficial by drones working as a team. As the characteristics of drone networks differ from other mobile networks, the communication requirements for drone applications also vary due to communication in three-dimensional space and high mobility of nodes. We focus on identifying communication needs for applications that benefit from video streaming. In addition, we study existing communication technologies to understand if the communication requirements posed by the drone applications can be fulfilled by the available communication technologies. We then highlight the shortcomings in the existing technologies that might be essential for drone applications requiring video streaming.

Furthermore, we discuss the existing routing protocols to understand their applicability in drone networks. Considering that in most applications the trajectories that the drones follow are pre-defined, we propose a routing protocol that utilizes location and trajectory information of the drones for calculating routing paths to avoid route error and route discovery overhead.

Lastly, we propose an application-layer approach applicable over ad-hoc networks for multicast video streaming from teams of drones. The contribution of the proposed solution includes the adaptation of *video encoding rate*, *frame rate*, and *link transmission* *rate* based on the feedback from multiple receivers of the multicast groups. The nodes sending the feedback are dynamically elected based on the receivers' link conditions. The proposed framework is evaluated using emulation and further validated on a testbed setup.

1.5 Organization of the thesis

Chapter 2 gives a background to video streaming applications in drone networks and discusses their communication requirements and related issues. Chapter 3 details upon related work on existing routing protocols and the proposed route switching (RS) algorithm. The simulation setup and evaluation of the RS algorithm is presented. In chapter 4, we discuss the legacy multicast approach in 802.11 and existing works. The application-layer multicast video streaming approach is proposed and is validated through emulation and testbed setup. Chapter 5 concludes this thesis.

1.6 Summary

In this chapter, an introduction to drones applications and available platforms is presented. The problem of routing and video streaming is formulated. Challenges to routing and video streaming are also highlighted. Finally, contributions of the thesis are listed.

2 Networking of drones and video streaming communication demands

In this chapter, a background on the characteristics of drone networks is presented and potential multicast video streaming applications are highlighted. We identify the communication requirements for video streaming applications and study existing wireless communication technologies to understand if the communication demands of video streaming applications can be met by the existing wireless technologies. Since in drone networks mobility in three-dimensional space is of a concern, the mobility models that are used while designing communication protocols are studied. Suitability of these mobility models with respect to different drone applications is also discussed. An introduction to the simulation and emulation platforms used in our study is presented along with the rationale for their selection for our work is discussed. Open research issues that need further investigation related to networking and communication of drones in particular to video streaming applications are also identified.

Parts of this chapter are taken from [HYM16] which is published in cooperation with Samira Hayat and Evşen Yanmaz.

2.1 Drone networks and their applications

Small-scale drones, especially the multi-rotors drones ([Asc, Par, Mic] has gained considerable attention for use in civil applications due to their high maneuverability. The rotors of a multi-rotor drone control its movement (yaw, pitch, roll and throttle) and provide higher maneuverability compared to the fixed wing drones. Because drones have little payload carrying capacity Table 1.1, they can be equipped with different sensors like IMU, range sensors (ultrasonic, infrared, laser), barometer, magnetometer, GPS, cameras, and visual systems based on the application they are being used for [GMC12]. The use of a multi-drone system over a single drone system for distributed processing is advocated in [CS15]. Cooperative teams of drones can be useful for application including but are not limited to *object detection*, where multiple UAVs search for a target and share the information with each other, *tracking* detected objects, e.g., a moving target, *surveillance*, *sensor data collection*, *monitoring* (environmental, fire detection, irrigation system, water management), *construction*, and *delivery of goods*. Distributed processing is considered as a future research direction for applications involving multiple drones.

Several research studies related to single-drone system [CHJ+10, XAD+04, DDLW09] are carried out, however, intensive investigation on communication and coordination for a multi-drone system is still in progress. The SUAAVE project [CHJ+10] primarily concerns with investigating the safety aspects of multiple drones that communicate and collaborate in performing tasks autonomously and to respond to node failures and report their findings to the base station. SUAAVE project implements several safety and control procedures that are performed before and during the flight, landing and returning to the base station triggers are implemented to ensure safe operations. So far the activities within SUAAVE focused on getting single vehicles airborne in a safe manner while a further extension for a multi-drone system is yet to be implemented.

AUGNet [XAD+04] considers an ad-hoc network consisting of stationary ground nodes and aerial nodes. Aerial nodes are used to extend the communication range. The goal is to test the communication performance with and without mobility, with and without the drone for one to five hops of varied lengths. Multiple experiments are performed to calculate throughput, connectivity, congestion, network performance, node failure, and range. It is observed that drone-supported network generates shorter routes with other ground nodes and provide better throughput. Similarly, increased connectivity range is observed when drones are used as relays.

The UAVNet framework [MBZ+12] is developed to provide an adaptable, mobile, scalable, and robust communication infrastructure for flying wireless mesh network (WMN). The mesh nodes also act as an access point to connect clients such as notebooks, smart phones, and tablets via IEEE 802.11g. UAVNet supports airborne relay scenarios such that one or two drones autonomously position themselves between the two end systems to establish a communication link. Results show that the flying wireless mesh nodes result in an up to 6.3 times higher throughput compared to the ground link.

The AirShield remote sensing project [DDLW09] aims for a multi-drone communication system targeting quick and efficient response in a disaster situation. The communication systems constitute A2A links for relaying and routing data to the ground station, A2G links to transmit measurements and telemetry data, and backend network topology that processes received measurements and formulates operational commands for the mission. A use case of the system architecture that supports services of geographic information sensing, decision support, and communication is defined. Route planning implementation is to be on board to avoid collisions and integration as a swarm of drones. Various communication technologies such as WiMAX, General Packet Radio Service (GPRS), Wideband Code Division Multiplexing Access (WCDMA), High Speed Packet Access (HSPA), and IEEE 802.11g are considered for the system. Further work on the integration of the sensor network and communication system is underway.

The heterogeneous unmanned aircraft system (HAUS) [FB08] is developed to study multi-drone communication networks and multi-vehicle cooperative control. Experiments conducted for G2G and A2G communication demonstrate the feasibility of mesh network on highly mobile nodes, however, it is discovered that the network could not distinguish if the packet loss is due to mobility or is due to the network congestion. This motivates the need for delay tolerant network (DTN) protocols . However, DTN protocols are required to be designed to cope with communication challenges in three-dimensional space and account for times when the DTN becomes unavailable.

Considering the above studies perusing to use a swarm of drones for various applications it can be stated that there still remains many open research questions that need to be investigated for a fully autonomous network of drones. Open research issues on routing protocols, communication and networking in drone networks are identified in [Sah14]. Communication and networking specific open issues, include: antenna design and radio propagation models fitting three-dimensional communication; the development of physical layer protocols for movement aware rate adaptation to improve communication efficiency; the development of MAC layer protocols to cater for high link fluctuations and to minimize latency variations caused by high mobility and varying distances between nodes; the design of routing protocols that allow adaptability with the change in network density, topology and location of nodes and that consider node failures and admittance in a multi-drone environment; development of transport layer protocols to address the reliability, congestion control, and flow control issues due to high bit error rates and link outages caused by frequent topology changes; and the design of protocols to support multimedia applications considering delay bounds, minimum packet loss, and high bandwidth demands and to support diverse traffic types including real-time, periodic, and delay tolerant.

2.1.1 Applications for video streaming

We now consider applications particular to video streaming and their communication demands in terms of connectivity, range, and traffic demands. Applications requiring video streaming from drones can be classified as *monitoring and surveillance* [CDO07, SLS+04, BG11, BDL13], *search and rescue* [GMG+08, CG] and *post-disaster assessment* [WD00]. Examples of monitoring applications include monitoring of oil and gas pipelines, nuclear installations, natural disasters, floods, volcanic eruptions, agricultural area, and fire scenes. Examples of surveillance applications include surveillance for border control, traffic, forests, large gatherings and events, fisheries, coastal surveillance, and operations against poachers. SAR operations could be in the case of a natural disaster, terrorist activity, and search for missing persons in e.g. a forest area. The post-disaster assessment application is to assess the damage caused by a disaster and prepare for the response activities accordingly. While we define the applications requiring video streaming, a reliable means of communication is vital to meet the QoS demands for these applications. Infrastructure based technologies may be used for some situations that may meet the QoS demands posed by these applications but in situations where an infrastructure-based technology is unavailable infrastructure-less technologies are to be used. A comparison of the existing technologies is given in Table 2.1 of Section 2.2 to identify technologies that can support the communication demands for video streaming applications from drones.

2.1.2 Communication needs for video streaming in drone networks

Transmission of videos streams in real-time poses stringent bandwidth, delay, and loss requirements to guarantee continuous video playback [WHZ+01, SYZ+05]. Because of the high encoding rate of the videos, a continuous video playback can be guaranteed if the required throughput remains under the available network capacity. A high packet loss or large delays in the video packet reception can cause distortion or frequent pause in the video playback. We now discuss existing examples of video streaming using drones for various applications.

A real-time aerial traffic surveillance systems using camera-mounted drones is studied in [CDO07]. A relay based network architecture for streaming a video from a drone is used. The drone streams video to a ground station (laptop) using the analog transmission, the ground station relays the video stream over the internet using the mobile broadband cellular network, assuming its availability in close proximity. The end users can then stream videos posted over the internet in near real-time. The problem, however, is the network congestion and wireless link fluctuation that does not guarantee a dedicated amount of bandwidth allowing only a low-quality video stream. Field experiments suggest that without the use of a storage server a smooth video could only be streamed at an encoding rate of 45 kbit/s with a frame rate of 15 frames/s and a screen resolution of 160×120. While a storage server is used, that streams and also stores the video from the internet, an increase in the encoding rate to 109 kbit/s is affordable.

Video streaming using AR Drones over an 802.11 ad hoc network is studied with the motivation of monitoring an agricultural area [BDL13] that may require enough time and manpower, otherwise. The designed control software allows estimating the communication range and video transfer rate. The tests conducted to stream a video when the distance is varied between 40 m and 74 m results on average a video stream of 700 bit/s while in a two-hop scenario (up to 200 m) the average throughput is of 612 bit/s. The authors suggest, an improvement in the video quality can be possible using a cross-layer solution and routing protocol with QoS support in a multi-hop scenario.

Wilderness Search and Rescue (WiSAR) [GMG+08] uses small-size drones having a wingspan of 42 - 50 in for visual-based aerial search. A 900 MHz transceiver is used for data communication while an analog 2.4 GHz transmitter is used for video streaming. To search for the missing person the signs including the point last seen and the direction of travel are considered. The video image is digitized at 640×480 resolution. It is found that the detection of unusual colors of clothing and man-made objects is possible if the operational height of the drone remains between 60 m and 40 m. The field tests indicate a requirement in the improvement of the video quality since distractive jittery motions, disorienting rotations, noisy and distorted images adds difficulty in the search and detection process. Computer vision algorithms are used to enhanced the stability and temporal locality of video features.

Disaster situations such as fire, flood, hurricane, earthquake require post-disaster assessment, planning, and response [WD00]. In such situations, drones can be helpful in providing safe, timely, and critical information to disaster managers for planning relief operations. To transfer imagery data 65 kbit/s downlink is required [WD00], while streaming an H.264 or MPEG-2 video over an ad-hoc WLAN requires an encoding rate of about 2 Mbit/s [DLBMF10].

Although not many real-world examples for video streaming from drones is available, however, based on the existing examples a good quality video stream requires an encoding rate of 2 Mbit/s. Apart from the video stream requirement, control and telemetry communication data varies from an application to other. Considering the existing technologies, it can be stated that the current unlicensed technologies may not cope with the requirements of diverse video streaming applications in situations where large communication range is required and broadband license-based technology is not available.

2.2 Wireless communication technologies

In this section, we compare existing wireless communication technologies and their suitability for drone applications. We categorize the wireless communication technologies based on the spectrum type (licensed/unlicensed), mobility support, communication range, theoretical maximum physical data rate, and latency (Table 2.1). Although the unlicensed technologies are more prone to interference and do not provide a secure communication means but they are easy to setup and can support many applications. Factors including mobility support, communication range, and data rate are important in understanding if the communication requirements of a drone application can be fulfilled by the technology of choice.

The quality of a video stream depends on the compression mechanism, encoding rate, resolution, and frame rate. While streaming a video wirelessly for a particular drone application the choice of technology is essential considering its range, throughput, and spectrum type. The video streaming throughput requirements as per the existing studies range from a few kbit/s to 2 Mbit/s, but a high-quality video stream requiring 20-40 Mbit/s [LG91] is still not possible. Using 802.11, a video stream for traffic surveillance encoded high than 109 kbit/s gets distorted [CDO07].

While monitoring, SAR, and post-disaster relief operations require communication range for small, medium and large areas [HYM16], the available technologies cannot support high-quality video streams in real-time for such applications. Nevertheless, if low data rate video streaming fulfills the requirement, Wi-Fi, WAVE, WiMAX, UMTS and LTE technologies can be considered depending on the area size and density of drones. If, however, the coverage area is large and multi-hop 802.11 is unable to support the required throughput demands, licensed spectrum technologies like WiMAX, GPRS, EDGE, UMTS and LTE may be more suitable. However, these technologies require an existing infrastructure. Areas, where such infrastructure based licensed technologies, are not available or in disaster-struck areas, communication coverage for medium and large areas sizes may not be possible until alternate technologies for such situations are devised.

2.3 Mobility models for drone applications

Mobility is a major concern in a multi-drone system over the design of communication protocols. Mobility model defines the position, path and speed variation of the drones in a mission scenario. The network performance evaluation of developed protocols requires the use of correct mobility models for particular applications, considering the fact that field tests are expensive and restricted to specifically designed settings [XWK+14]. The

Table 2.1: Comparison of Wireless Technologies

Technology	Standard	Spectrum Type	Device Mobility	Comm. Range	Maximum PHY Rate	Latency	Network Topology	References
Bluetooth v4	802.15.1	Unlicensed	Yes	150 m	1 Mbit/s (gross air data rate), up to 3 Mbit/s (with Enhanced Data Rate)	3 ms	Ad hoc piconets	[Dec14a], [Dec14b]
Zigbee	802.15.4	Unlicensed	Yes	10 - 100 m	250 kbit/s	Channel access: 15 ms	Ad hoc, star, mesh, hybrid	
Wi-Fi	802.11a	Unlicensed	Yes	35 - 120 m	54 Mbit/s	Slot time: 9 μs SFIS: 16 μs DIFS: 34 μs Propagation Delay: 1 μs	-	[LSS07], [KR13], [LMT04], [LBON14], [Gas13]
	802.1b	Unlicensed	Yes	38 - 140 m	11 Mbit/s	Slot time: 20 μs SFIS: 10 μs DIFS: 50 μs Propagation Delay: 1 μs	-	
	802.11n	Unlicensed	Yes	70 - 250 m	600 Mbit/s	Slot time: 9 μs SFIS: 16 μs DIFS: 34 μs Propagation Delay: 1 μs	-	
	802.11ac	Unlicensed	Yes	-	6933 Mbit/s	-	-	
WAVE	802.11p	Licensed	Yes	1000 m	27 Mbit/s	≈100 ms	Ad hoc	[MDvWH12]
WiMAX	802.16	Unlicensed	No (Line of Sight)	48 km	32 - 134 Mbit/s	-	Single last hop	[Ome]
	802.16a	Licensed	No	48 km	75 Mbit/s	-	access network, wireless back-haul network	
	802.16e	Licensed	Yes (Limited)	1 - 5 km	15 Mbit/s	-	Mesh	
GPRS	GPRS	Licensed	Yes	-	115 kbit/s	≈500 ms	-	[JG03], [GW], [FMMO99], [Ibr02], [BEG+], [HWB00], [BP07], [MKM11], [DJFJ+09], [AGEBCR14]
EDGE	EDGE	Licensed	Yes	-	384 kbit/s	≈300 ms	-	
UMTS/ WCDMA	UTRA	Licensed	Yes	-	2 Mbit/s	≈280 ms	-	
UMTS/ HSPA	HSUPA, HSDPA	Licensed	Yes	-	14.4 Mbit/s	≈38 ms	-	
LTE	LTE	Licensed	Yes	-	DL: 300 Mbit/s	User Plane: 5 ms	-	
LTE Advanced	LTE Advanced	Licensed	Yes	-	DL: 1 Gbps	User Plane: 10 ms	-	

existing mobility models are classified as random, temporal dependent, spatial dependent, models with geographical constraints, and hybrid. These categorized models are evaluated based on their adaptability for multi-drone systems, networking performance, and ability to realistically capture the attributes for multi-drone systems.

A node using the random way point mobility model moves at a random speed and chooses a random destination point without any mobility coordination with other nodes in the network. Random models are unrealistic since randomly chosen points ignore the temporal and spatial correlation and do not mimic aerodynamic constraints of aerial nodes.

The Gauss-Markov mobility mode is a memory-based model where each node is initialized with a random speed and direction [BJ10]. In fixed intervals of time, the node updates its speed and direction considering previous speeds and directions. A tuning parameter determines the degree of dependency on the previous values and reflects the randomness of the Gauss-Markov process. The Gauss-Markov mobility models are more realistic since they take temporal correlation into account, however, they do not appropriately model the turn behavior of aerial nodes and do not consider safety requirements.

The existing mobility models for drones include semi-random circular movement model, three-way random model, pheromone repel mobility model, and Smooth turn mobility model [XWK+14]. The semi-random circular movement model [WGWW10] allows the drones to move in a circle around a fixed center point with variable radii. Once a drone completes its circular trip, it chooses the next round movement by randomly selecting the radius with the same center point. The model can typically be used for SAR applications considering the center point as the last known location. The three-way random mobility model [Kui] has three state selection criteria to either turn left, turn right or go straight. A drone chooses its next destination point after a fixed time interval but the probability of the next direction is based upon the direction in the previous time step. This reflects a smooth turn behavior which is suitable to reflect drone movements. As the drone gets closer to the boundary, it turns away such that the angle between the heading direction and the normal line to the boundary is randomly in between a defined parametric value. The pheromone repel mobility mode guides the drones to areas not recently visited by other drones. The drones create pheromone maps by dividing the area into a grid and marking each sector of the grid with a timestamp that they visit. The map information is shared through a broadcast with which each drone updates its local pheromone map. The merged pheromone maps produce a measure called pheromone smell that gives higher weights to most recent visited places. Drones plan their next move based on the aggregated pheromone smells. In case the pheromone smell of all the sectors i.e. the one in straight ahead, on the left and on the right is equal, the drone uses the basic three-way random model to choose its next mobility point. The three-way random and pheromone repel mobility model possess spatial correlation properties and are suitable for coverage applications.

The smooth turn mobility model [WNZF13] is a memory-less model that selects a point in the space along the line perpendicular to its heading direction and circles around it until the vehicle chooses another turning center. The perpendicular point chosen in space ensures smooth turn trajectories. It is memory-less since the next point the drone chooses is independent of the previous point. Thus it naturally captures the random trajectory pattern of drones with large and smooth turn behavior and constant speed. Smooth turn mobility model captures spatiotemporal correlation of accelerations that are reflective of aerodynamics and captures frequent network topology changes and are more suitable for patrolling and reconnaissance applications [XWK+14].

The flight plan mobility model depicts pre-defined flight plans and captures aerodynamics, high mobility and safety constraints. The flight plan mobility model is good for cargo and transportation scenarios where flight dimensions are known before hand. Although there exists a number of mobility models that are suitable for modeling mobility scenarios for different applications, none of them comprehensively consider safety requirements such as collision avoidance.

2.4 Simulation and emulation platforms

The design and architecture of new or improved system models and protocols require validation and performance evaluation. Experimental validation and evaluation process is expensive and time-consuming. Simulation and emulation platforms are used to predict the performance of a system model in a real-world scenario. Performing extensive simulations also help improve the design of the system model to achieve better performance.

Many simulation and emulation platforms exist and are updated with new features but not all may be suitable for any kind of simulation work. To evaluate a new model, a careful choice of the simulation or emulation platform is required by exploring the capabilities of the platform and the requirements of the proposed design. In this section, we discuss some available open-source simulation and emulation platforms and argue the ones' we selected for our work.

2.4.1 Comparative analysis of open source network simulation tools

Network Simulator version 3 (NS-3) and Objective Modular Network Testbed in C++ (OMNeT++) are the two well developed, widely used, open source network simulation tools. NS-3 is a C++ based open sourced discrete event network simulator. Users of NS-3 can construct simulations of computer networks using models of traffic generators, protocols such as transmission control protocol / internet protocol (TCP/IP), and devices and channels such as Wi-Fi, and analyze or visualize the results, however, NS-3 is not backward compatible with NS-2. This means that models from NS-2 needs to be ported to NS-3 in a manual way [SGB12, WvLW09]. Since most of the networking modules are developed in NS-2, porting them to NS-3 is a time-consuming process.

Main features of NS-3 includes modular, documented core, C++ programs and python scripting, alignment with real systems, software integration, virtualization and test bed integration [PJ08]. NS-3 modules includes TCP; IPv4, IPv6 support; MANET routing: Optimized Link State Routing Protocol (OSLR), Ad-hoc On-Demand Distance Vector (AODV) Routing, Destination-Sequenced Distance Vector Routing (DSDV), Dynamic Source Routing (DSR); IEEE 802.11 and variants, WIMAX, Long-Term Evolution (LTE), Point-to-Point Protocol (PPP); Mobility Models: Random direction, Random Walk (RW), Random waypoint model (RWP), and Gaussian mixture model (GMM).

NS-3 features libraries for basic wireless local area network (WLAN) modules and realistic environment (IP and MAC addresses, real packets, BSD-like sockets, multiple interfaces per node, etc.). NS-3 allows simulation of popular wireless technologies including Wi-Fi and WiMax with a possibility to modify the operation of any module from the library. A notable feature of NS-3 is its ability to cooperate with the real devices and applications. Packets sent in NS-3 has the same format as packets sent in real networks. This allows the NS-3 simulation to send data on a real network. Therefore NS-3 can be easily integrated into the testbed and virtual machines.

Omnet++ is a C++ based discrete event simulator for modeling communication networks, multiprocessors and other distributed or parallel systems. It is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators but it is also used for queuing network simulations and other areas as well [SGB12]. Omnet++ simulations consist of modules and multiple simple modules can be linked together to form a compound module. Omnet++ provides a rich graphical user interface (GUI) and an abstract modeling language [WvLW09].

Table 2.2: Comparison between NS-3 and Omnet++ Network Simulators

	NS-3	Omnet++
Simulator Type	Discrete Event	Discrete Event
Language	C++ and Python	C++ and NED
GUI	No	Yes
Performance (Simulation run time, memory usage)	Good	Slightly Inferior
Support	Fewer users (manual portability from NS-2)	High user support
Ease of Use	Complex	Easy
Wireless Network Implementation	Yes (IEEE 802.11 and variants, WIMAX, LTE, PPP)	Yes (INET Framework for wired and wireless networking protocols, including UDP, TCP, SCTP, IP, IPv6, Ethernet, PPP, 802.11, MPLS, OSPF, and many others)
Wireless Mobility	Yes (Mobility Models - RW, RWP, GMM)	Yes (BonnMotion, Constant Speed, Gauss Markov, Linear, Mass, Random, etc.)
3D Network Support	Can be modeled but not existent	3D networks can be modeled

The Omnet++ features include graphical network editor, GUI for simulation execution, links into simulation executable, a command-line user interface for simulation execution, graphical output vector plotting tool, documentation along with sample simulation examples. Several open source simulation models have been published in the field of network simulations such as IP, IPv6, multiprotocol label switching (MPLS), mobility and ad-hoc networks [PJ08].

There is a tradeoff between NS-3 and Omnet++ considering the need to simulate three-dimensional ad-hoc networks. Both NS-3 and Omnet++ are powerful tools that can be used for wireless and mobile networks. INET support for Omnet++ provides a rich framework for mobile, wireless and 3D networks. A basic comparison of the two simulators is formulated in Table 2.2. Considering Omnet++ strong GUI features and existent wireless and three-dimensional mobility support, it is considered a viable option to use as our simulation platform.

2.4.2 Network emulators

The Common Open Research Emulator (CORE) is a real-time network emulator capable of emulating routers, switches, Hubs, PCs, and hosts through virtualization with an extension to support wireless networks [ADHK08]. CORE is developed by the network technology research group that is part of the Boeing Research and Technology division. The U.S. Naval Research Laboratory (NRL) is supporting further development of this open source project [COR]. CORE supports for mobility scripting, IPSec, VPN, distributed emulation over multiple machines and GUI. CORE provides emulation for network and higher layers, however, it can be configured with Extendable Mobile Adhoc Network Emulator (EMANE) to emulate data link and physical layer. The Quagga routing suite can also be configured with CORE for wired routing protocol like Open Shortest Path First (OSPF), OLSR, Border Gateway Protocol (BGP), Routing Information Protocol (RIP), etc. For wireless routing, OSPF MANET Designated Routing (OSPF-MDR) is also available in Quagga routing suite. Since CORE emulator runs in real time, real machines and network equipment can be connected to interact with the virtual networks designed on CORE.

EMANE is a framework for modeling mobile network systems in real-time [EMA]. EMANE is being developed by the U.S. NRL in cooperation with the U.S. Army Research Laboratories (ARL). EMANE provides a flexible modular environment for designing and testing simple and complex wireless network architectures. EMANE emulates data link and the physical layer for mobile and wireless networks. Since EMANE can be configured with CORE [AGA11], data link and physical layer parameters can be managed using CORE GUI. EMANE parameters and services can also be configured through XML files. EMANE supports 802.11abg radio models along with Distributed coordination function (DCF) channel access function. It also supports Wi-Fi multimedia (WMM) capabilities that prioritize traffic in four different traffic classes namely, background, best effort, video and voice. On the physical layer, implementation for free space and two-ray propagation model is available in EMANE.

Other platforms of interest include QualNet [DLB07, qua] and Simbeeotic [KWDW]. Similar to CORE and EMANE QualNet also supports to set up terrain, network connections, subnets, mobility patterns of wireless users, and other functional parameters of network nodes. QualNet also has GUI support and provides high fidelity on all layers of the communication stack. However, QualNet is not an open source platform like CORE and EMANE.

Simbeeotic supports modeling swarm of MAVs [KWDW]. Simbeeotic enables MAV prototype development that can model MAV kinematics including collision avoidance and supports to the actuation, sensing, and communication functions. Since our work focuses on video multicast streaming that does not require MAV prototype modeling, we choose to use the combination of CORE and EMANE platforms to model our framework.

2.5 Open research issues and challenges

Considering drone applications and a multi-drone system, many open research issues needs further investigation. Because of the fluid network topology, wireless link fluctuations, and diverse application requirements in drone networks, enhancements in all layer of the communication protocol stack is required [HYM16, BST13, Sah14]. The diverse drone applications have different traffic demands and bandwidth requirements[HYM16]. Applications requiring video streaming demand high bandwidth and possibly high communication range. Although many real-world experimental findings use technologies like IEEE 802.11, however, a study on a dense network of drones and on an autonomous multi-drone system is required to understand the feasibility of available technologies with respect to the application requirements. Licensed-based technologies may be beneficial for applications requiring long range communication, however, in disaster situations, these technologies may not be available. A multi-hop communication in unlicensed technologies like 802.11 may not be able to cope with the bandwidth, jitter, and packet loss requirements.

Issues related to security and privacy for different drone applications also needs to be addressed. In the case of an autonomous multi-drone system, high priority communication intercepts shall be designed to cater the needs of safety and security. Unprecedented events like obstructions caused by a flock of birds or similar may occur during the course of a mission that requires immediate action either autonomously or through a control center. Possibly an application layer intercepts to communicate such an event allowing the mission to be adaptable in such situations needs investigation.

2.6 Summary

In this chapter, we give examples of drone applications and existing works on the development for a multi-drone network. We discuss the usage and approaches of autonomous multi-drone networks and identify open research issues on networking and communication for such systems. Applications that benefit from video streaming using drones are also identified. Information from existing real-world examples is collected on the requirements of video streaming and the technologies used. We study existing wireless communication technologies and identify their suitability and their shortcomings for video streaming applications. Moreover, mobility models used for diverse drone applications with respect to their suitability to different drone applications are presented. Open research issues that need further investigation related to networking and communication of drone applications are also identified.

3 Trajectory-aware ad-hoc routing protocol for drone networks

3.1 Introduction

A multi-drone system has advantages over a single drone system with respect to economic benefits, coverage flexibility, time efficiency, mission resilience, and sustainability [THA15]. The installation and maintenance cost of multiple small drones is less compared to a large drone [CCC07]. Multiple drones can provide coverage to different areas simultaneously, are resilient and mission sustainable in case of failure or malfunction of a drone. Multiple drones can complete a mission quicker than using a single drone system. However, to enable participation of multiple drones for a mission, several communication design challenges for an ad-hoc network of drones need to be addressed. These challenges include a high degree of mobility causing link fluctuations and signal attenuation, frequent topology change requiring route discovery, connectivity for coordination and collaboration with peer nodes, varying distances and limited transmission range causing bandwidth instability, diverse traffic types, and traffic frequency desiring sundry communication demands [BST13, Sah14, HYM16]. A routing protocol enables a source to find a path to route data packets from the source to the destination. In drone networks route discovery is frequently required to enable the nodes in the network to communicate in a multi-hop fashion.

The results in this chapter are achieved in cooperation with Evşen Yanmaz and are published in [MY14]. Parts of this chapter are taken from [MY14].

In this chapter, we give an overview of common routing protocols for ad-hoc networks and their limitations in the context of drone networks. We consider a network of drones, where each drone is equipped with a GPS module and an 802.11a wireless transceiver and is continuously streaming traffic to a ground station while following defined path in three-dimensional space. We propose a scheme that schedules routing by exploiting the location and trajectory information of the drones participating in the mission to improve the overall network performance. We investigate the network performance in terms of achieved throughput to evaluate the behavior of existing routing protocols namely the ad-hoc on-demand distance vector (AODV) routing and location aided routing (LAR) in a mission scenario and analyze if the proposed route switching (RS) scheme can help in achieving better network performance and can provide better support to fulfill QoS requirements for drone applications.

3.2 Routing protocols for drone networks

Routing protocols can generally be classified as proactive, reactive, and hybrid protocols [AWD04]. The proactive protocols maintain and regularly update the routing information to every other node in the network. The routing information is stored in tables and periodically updated. The advantage of proactive protocols is that they do not require route discovery when data transmission is required. However, regular updates of the routing tables require a frequent exchange of messages consuming network bandwidth. Examples of proactive protocols include destination sequenced distance vector (DSDV) [PB94] and optimised link state routing (OLSR) [JMC+01].

Reactive routing is an on-demand routing process. The route discovery process starts when a source requires sending data packets to a destination in the network. Route discovery usually occurs with flooding the route request packet through the network. Route reply is sent back to the source when the destination receives the route request packet. In contrast to proactive routing, reactive routing protocols reduce the overhead of maintaining and updating the routing information. Examples of reactive routing protocols include AODV [PR99], dynamic source routing (DSR) [JM96], LAR [KV00], and greedy perimeter stateless routing (GPSR) [KK00].

Hybrid protocols are the combination of reactive and proactive routing protocols. Hybrid protocols maintain routing information of close by nodes while route discovery for far away nodes is done using the route discovery process. Examples of hybrid protocols include zone routing protocol (ZRP) [HPS02] and distributed spanning trees based routing protocol (DST) [RRS+99]. In this section, we discuss some of the commonly used proactive and reactive ad-hoc network routing protocols.

3.2.1 Destination-sequenced distance vector routing

The DSDV [PB94] routing protocol is a modification of Distributed Bellman-Ford (DBF) algorithm that finds the shortest route from a source to destination. DSDV overcomes the problem of routing loops in DBF by introducing an incremental destination sequence numbers parameter included in the routing packet updates. Routing packets are transmitted as broadcast as soon a node detects a topological change in the network. The routing packet includes the destinations address, the number of hops required to reach the destination, and the sequence number. The DSDV protocol uses full dump and incremental routing update packets to disseminate the routing information. A full dump update may span over many network protocol data units (NPDUs) and contains complete routing table entries of a node. Incremental updates contain entries altered after the previous full dump update. Full dump updates are common if the network topology changes frequently. If multiple routes to a destination exist, a node chooses a route with the highest destination sequence number rather than the shortest path. Although DSDV reduces the latency for route discovery and guarantees loop-free paths but has a large overhead of control messages utilizing the network bandwidth [AWD04]. It is not suitable for drone networks since the network topology changes frequently requiring destination of full dump messages that will consume extra network bandwidth.

3.2.2 Optimised link state routing

The OSLR [JMC⁺01] is a proactive protocol that employs periodic exchange of link-state messages to maintain the network topology information at each node. Nodes periodically broadcast link-state messages through HELLO packets to its neighbors. However, flooding is controlled through a set of neighbor nodes called the multipoint relays (MRPs) that can retransmit the broadcast messages. Non-MRPs do not retransmit the HELLO messages but can update their neighbor tables with the link-state information. This way each node can maintain link-state information of two-hop neighbors and the MRPs selected by the neighbor nodes. Using this information, nodes selects the set of its MRPs but with the condition that the next hop neighbor must have a bi-directional link. Thus the route to all destinations from a node is a sequence of MRPs to the destination build using the topology control messages forwarded through MPR nodes. The drawback of OLSR protocol is the periodic flooding of control messages from each node to its neighbor nodes, although retransmission is controlled through the MRPs [AYJ15]. OSLR is better suited for large and dense networks that may not be the case with drone networks.

3.2.3 Ad-hoc on-demand distance vector routing

The AODV routing protocol [PR99] uses an on-demand route discovery mechanism. The route discovery process starts when a node has to send data to a destination and it does not have a route to the destination. The source node broadcasts route request packets in the network to find the path to the destination. When an intermediate node receives a route request, it either broadcasts it to its neighbors or sends a route reply to the source node if it has a valid route to the destination. If an intermediate node receives a duplicate copy of the route request packet i.e. with the same broadcast ID, it discards the packet. Moreover, if an intermediate node does not have the route, it forwards the route request packet to its neighbors. As the route request packet travels from a source to various nodes, it automatically sets up the reverse path entries back to the source. When an intermediate node who has the route to the destination or the destination node itself receives the route request packet, it sends the route reply to the source using the reverse path. Reverse path route entries are maintained for at least enough time to traverse the network and produce a reply to the sender. A sender node may experience delays using the AODV protocol during the route construction process. Also, delays can be experienced due to link failures in which case route re-discovery process is initiated.

3.2.4 Location aided routing

LAR [KV00] is an approach to improve the flooding based route discovery mechanism in mobile ad-hoc networks. LAR uses the location information (x, y coordinates) e.g. through GPS along with the flooding based scheme for route discovery to a destination node. It assumes that a source node knows the location of the destination at a certain time and the average speed at which the destination node is moving. When at a later time the source node has to find the route to the destination node its sends the route request packet in the direction of the expected zone based on the previous location information of the destination node. Thus in all route request and route reply packets location information of the node is included. This scheme reduces the number of packets required for route discovery since it only sends the route request packet in the direction of destination's expected zone. However, there might be a possibility that the destination node is no more present in the expected zone. In such a case, if time to live for the route request packet expires, the source node flood the request packet in the entire network as in the case of AODV [PR99], increasing the latency for route discovery.

In another variant of the LAR scheme, the source node includes the distance between the source and destination in the route request packet since it already has the destination node's location information. Now when a neighboring node receives the route request packets, it calculates the distance between the destination node and itself. If the calculated distance is less than that of the distance sent by the source node, the neighboring node forward the request to its neighbors otherwise drops the packet. The remaining mechanism of route reply remains the same as in flooding based route discovery schemes.

3.2.5 Greedy perimeter stateless routing

The GPSR [KK00] algorithm uses location information of the destination node to route data packets. It assumes that all nodes know their own position and builds knowledge of their immediate neighbors. Beacon signals are used to continuously update the neighbor information, this way location information of each node travels in the network. Data packets sent are marked with the destination location. A source node sends data to the destination by forwarding packets to its closest neighbor in the direction of the destination. This way data packets are routed from neighbor to neighbor referred as the greedy algorithm. Nevertheless, there exist a possibility that the neighboring node closer to the destination is out of the communication range. In such a scenario where greedy forwarding is not possible the node shifts to perimeter forwarding mode and sends data to its neighbor using the planner graph traversal. The planner graph traversal uses the right-hand rule i.e. the next node traversed is the one present nearest to the destination in the counterclockwise direction of the source. A node using perimeter forwarding mode shifts back to the greedy mode whenever possible. Combining the greedy and planar perimeter modes gives the full GPSR algorithm which incorporates the greedy forwarding algorithm on the full network graph while perimeter forwarding on the planarized network graph when greedy forwarding is not possible.

3.2.6 Limitations of routing protocols in context to drone networks

The existing routing protocols, may it be proactive, reactive or hybrid are not sufficient for drone network since they are either not fault tolerant or provide limited communication resources and are not designed for peer-to-peer mobile ad-hoc networking between the drones and the ground stations. In a multi-drone environment the network topology changes frequently due to mobility and because of the changes in the orientation (pitch, roll, and yaw) of the drones the link conditions changes influencing the network performance. To cater for the changing network topology there is a need to design a routing and communication protocol for such a setup. The above mentioned protocols are not designed for such a setup [BST13, THA15] since the change in the network topology may lead to route disconnection from source to destination as a relay node move out of the communication range. Subsequently, a route error message is sent to the source which then broadcasts a new route discovery message to find the new route to the destination. This consumes additional network bandwidth along with the delay in the traffic from the source to the destination. In addition, applications with strict QoS requirements on bandwidth, jitter, and packet loss suffer from route disconnections and delays caused by the route discovery process. These limitations in the existing protocols lead to investigate and design a communication mechanism for a multi-drone system.

We propose a route switching scheme, explained in the next section that exploits the location and trajectory information to schedule routes from source to destination. In other words, the route from the source to destination is calculated before the source loses its route to the destination due to a change in the network topology.

3.3 Route Switching

A trajectory-aware route switching mechanism is proposed to overcome the route error and the route discovery overhead of the existing ad-hoc routing protocols. The idea is to maintain information about the available routes from source to destination and switch to an alternate route when it is likely that the current route is going to break. We utilize prior knowledge on the position and mobility of nodes participating in the mission to switch to an alternate route.

The drones participating in the mission might need multiple hops to transmit their multimedia traffic to the destination. Since all drones are mobile, the established route being used to route packets to the destination may get disconnected. When this happens, AODV or LAR will send a route error message to the source to which the source will initiate a new route request. However, using the prior knowledge of path information it can be predicted when a next hop drone is going to go out of the communication route from a source to the destination.

In such a case, the time for route error and thereafter a new route discovery can be avoided by switching to an alternate route. This is illustrated in Figure 3.1 where M_S is the source drone, M_D is the destination ground node, M_{R1} and M_{R2} are potential drones that can relay from source to destination, and M_N are other source neighboring drones. Here at time $T_{\alpha-1}$, the route from a source to the destination is established via M_{R1}. We know that at time T_α, M_{R1} would no longer be in M_S radio range. Therefore, before time T_α the route from M_S to M_D can be switched via M_{R2} to avoid the time required for a new route discovery. In other words, a new route can be established using the neighbor, location, trajectory, and time information. This way the time for a new route discovery can be avoided as the communication link between M_S and M_D will remain established as long as an alternate neighbor drone to relay is available.

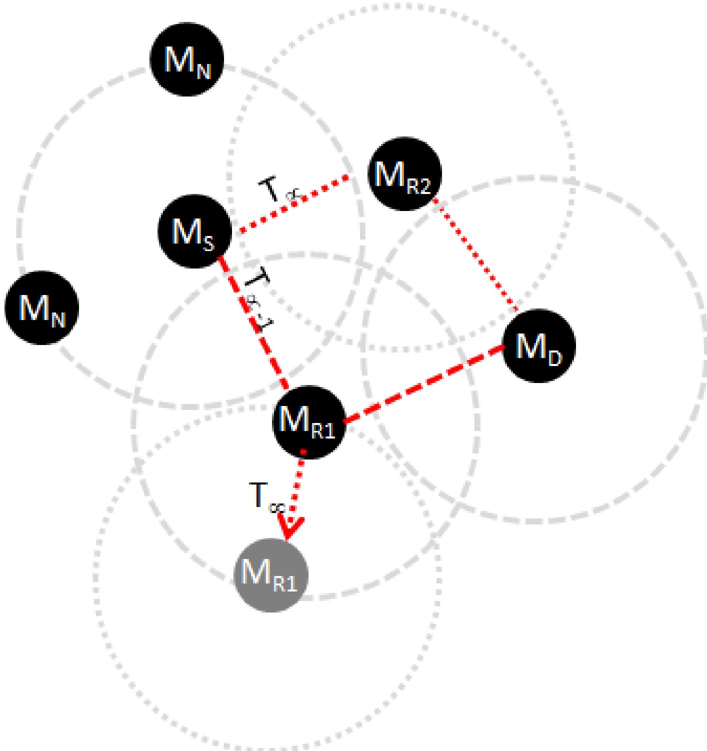


Figure 3.1: Transmission range and routes of drones in a network. M_S is the source drone, M_D is the destination ground node, M_{R1} and M_{R2} are potential relay drones from source to destination, and M_N are neighboring drones. The dashed and dotted circles and lines are the current and next transmission ranges and routes respectively.

3.3.1 Assumptions

1. Destination node is stationary on ground, all other nodes are moving in three-dimensional space.

2. The duration of the mission is defined and is known in advance to all nodes in the network.

3. All nodes in the network have some storage capacity and processing power to calculate the routes from the source to destination.

4. In mission-oriented networks, where the team of drones operate together to achieve a goal, e.g., to continuously cover a known area, optimum defined paths can be used [MF12]. Therefore, we assume that at any time instant of the mission, the source knows the location and trajectory of any node in the network through defined path information.

3.3.2 Trajectory-aware routing protocol

To find the route from the source to the destination, each source node first gains knowledge of its multi-hop neighbor nodes. The source then locates the destination node to find out if it can directly connect to the destination at any time instant during the mission. This is done using the trajectory information of the source and the destination. If so, the source directly connects to the destination to transmit its data whenever possible and seeks the help of relay nodes, otherwise. If a direct connectivity is not possible i.e., the destination is out of source communication range a multi-hop path has to be established. To do so, the source looks for its n^{th} hop neighbors that are connected to the destination. The n^{th} hop neighbors are sorted based on connectivity time with the destination. To select the n^{th} hop neighbor, the algorithm finds the $(n-1)^{th}$ hop neighbors that are connected with n^{th} hop neighbors and so on until $(n-m)^{th}$ hop is the source itself. The connectivity time of all intermediate relay nodes is sorted. The calculated route is the one that provides the maximum connectivity time from the source to the destination. Thus multiple routes are calculated but the route that has the maximum connectivity time is selected. However, since the source nodes are mobile, the calculated route can disconnect and so a new route must be calculated before the source experiences a disconnection. The algorithm thus calculates a new route as many times a disconnection is expected. The RS routing approach is summarized in Algorithm 1.

Algorithm 1: Trajectory-aware routing protocol

---

1 Input parameters: node trajectory and timing information, transmission range, channel model, source location

1. Source acquires knowledge of its multi-hop neighbors
2. Source checks if it will directly connect to the destination at any time instant during the mission
3. Source routes its packets to destination directly whenever connected
4. Otherwise, finds the n^{th} hop source neighbors that are connected to destination
5. Sort connectivity time of the n^{th} hop neighbor with the destination and the $(n-1)^{th}$ hop neighbor, select the most connected one
6. Decrement n and repeat steps 4 - 6 until route is found
7. Send packets to destination through the calculated route

The proposed scheme benefits by providing an alternate route from the source to the destination during the mission; i.e., when a moving relay node gets out of the communication range of the source an alternate route without a new route discovery can be established to maintain connectivity. Considering a mission, the expected delay in the multimedia transmission can be reduced through this scheme since the route error and route discovery overhead is avoided. Nevertheless, it also comes with a cost

Table 3.1: Simulation parameters

Parameters	**Values**
Radio Interface	802.11a
Carrier Frequency	5 GHz
Number of Channels	1
Bit Rate	54 Mbit/s
Rate Adaptation	Adaptive Auto Rate Fallback
Mode	Ad-hoc
Channel Propagation	Free Space, Rayleigh
Transmission Power	7 dBm
Thermal Noise	-95 dBm
Radio Sensitivity	-90 dBm
Path Loss Alpha	2
Area bound	1000 m $\times$ 1000 m $\times$ 50 m
Simulation Time	900 s

of maintaining the knowledge of alternate routes. Routes are calculated based on the trajectories of the drones participating in the mission. The computation can be done centrally at the base station, which can then send the route information to each drone or in a distributed way, where each drone maintains trajectory information of all the nodes in the network and calculates its own route accordingly. In either way, some storage capacity is required to maintain the trajectory information of the drones. The storage requirement can increase if the mission time is extended or more drones are added to participate in the mission.

Also, the computational cost to check when a relay node is going to get out of the range and when to shift to an alternate route is involved. More computational power is required to compute the routes as the network size increases or as the number of hops from the source to destination increase or both.

3.4 Simulation setup

Unless otherwise stated, the parameters used in the simulations are given in Table 3.1. These parameters are chosen in accordance with our platforms and experimental work [YHSB14]. We used Omnet++ as our simulation platform. A number of source drones chosen in the network are 1, 3, 6, and 9 respectively. Each source drone continuously sends UDP traffic to the ground station at a rate of 54 Mbit/s such that the maximum channel capacity is utilized. The UDP packet size is set to 1480 bytes.

We investigate the performance of the proposed protocol for two mobility scenarios. First, we consider random mobility scenario where each node initially places itself randomly over the constrained area. Nodes then choose their destination randomly with random speed and direction. We then consider trajectories from a real coverage mission scenario of a disaster rescue operation [SIN]. The scenario considered, is to provide live coverage through multimedia streams to multiple areas of interest where some sports events e.g., a marathon or a cycle race are taking place.

3.5 Results and Discussion

The simulation results of the proposed RS algorithm using the random mobility scenario and the mission scenario are presented in this section.

3.5.1 Random mobility scenario

The random mobility scenario uses the random waypoint mobility model where a node moves by randomly changing its speed, acceleration, and direction after a random time interval. The random mobility model is popular due to its simplicity and is widely used to simulate ad-hoc networks. To test the RS algorithm, we generated random trajectories shown in Figure 3.2 to create a scenario for random mobility. We consider these generated trajectories as the area of interest for the drones to follow and transmit traffic to the ground station. To generate these random trajectories, a mobile host changes its direction uniformly randomly between $0° - 360°$, speed from 2 m/s − 5 m/s after a random interval of 5 s − 10 s. The destination node (FixedHost) denoted by ★ (Figure 3.2) is kept stationary and all other nodes transmit while they move randomly. Nodes move without any pause at any location. Three stationary relay nodes denoted by ♦ are also placed randomly to help route the traffic to the destination node. Stationary nodes are important since without them some source nodes e.g., M0, M6, and M8 are unable to form a route to the destination at many time instances during the mission time. The mobility of drones is constrained to an area of 1000 m × 1000 m × 50 m.

We calculate achieved network throughput based on the number of data packets received during the mission time. The number of packets sent is more than the number of packets received since the source continuously transmits at a consistent rate of 54 Mbit/s while there may not be an available route to the destination. Packets not received due to broken or inaccessible link are dropped. The destination node is able to receive packets if the source is within its communication range or if there is a route available through the relay nodes. Figure 3.3 shows the achieved network throughput as the number of transmitting source nodes are increased from 1 − 9. We chose M0 as the source node when 1 node is transmitting, M0, M1, and M2 when 3 nodes transmit, and so on (Figure 3.2). Free space channel propagation model is used for this simulation. We observe that RS outperforms LAR and achieves approx. 10 % higher network throughput since it utilizes the trajectory information to calculate the route from source to destination. This means that whenever a source gets a disconnection a new route (if available) is

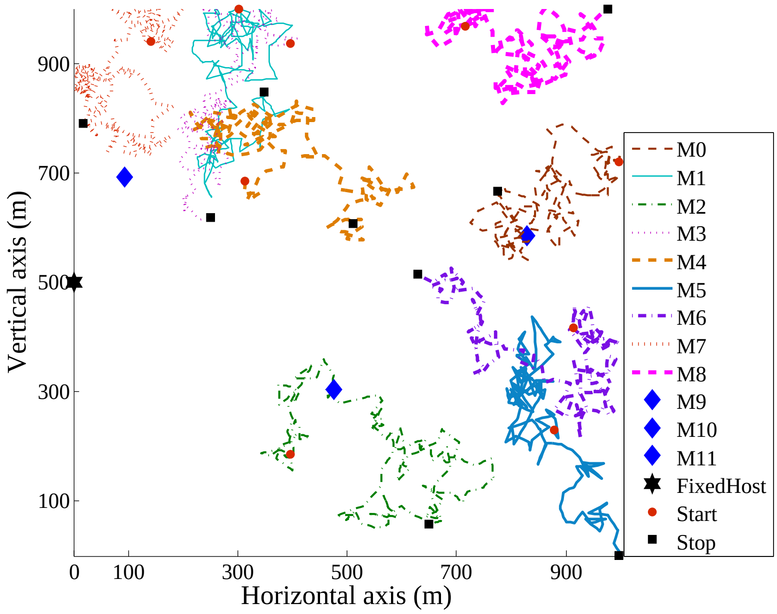


Figure 3.2: Trajectories: Drones follow random paths while transmitting UDP traffic to the static destination "FixedHost" node

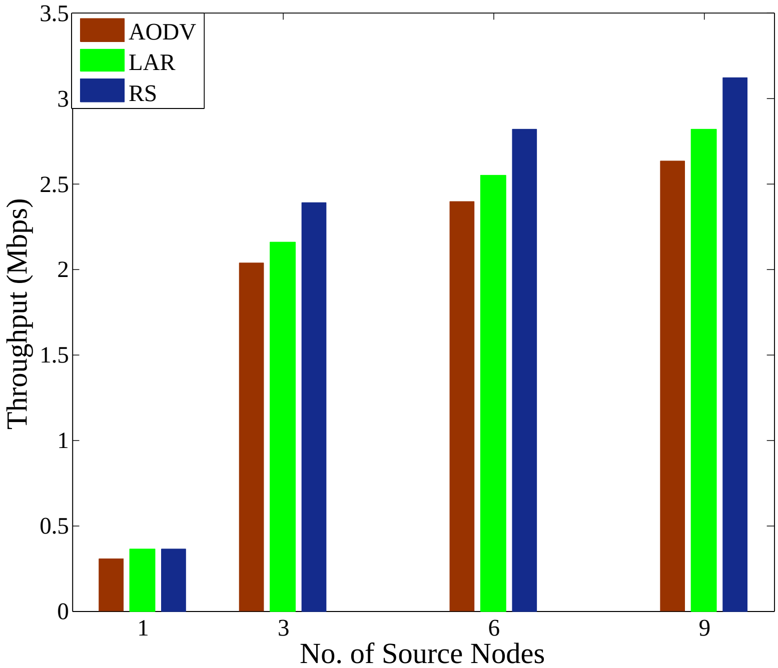


Figure 3.3: Comparison of the achieved network throughput for AODV, LAR and RS schemes for the random mobility scenario using free space channel propagation model. The number of source drones nodes vary from 1 to 9

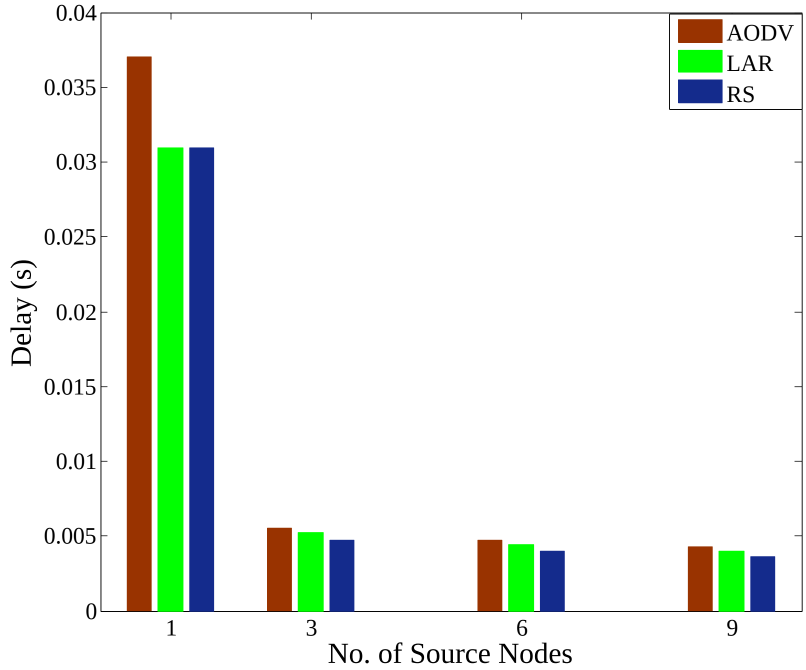


Figure 3.4: Comparison of packet delays for AODV, LAR and RS schemes for the random mobility scenario. The number of source drones nodes vary from 1 to 9

already calculated relinquishing the route error and route discovery overhead.

Figure 3.4 shows the corresponding packet delays at the destination node. Delays are calculated as the time interval between the packet reception. We observe reduced packet delays for RS since as soon as the source desires to transmit, it already has the route (if available) to the destination, and the transmission starts without a route discovery after initially acquiring knowledge of the neighbor nodes.

Figure 3.5 shows the achieved network throughput with increasing source nodes using Rayleigh channel propagation. Rayleigh fading model is reasonable when there is no line of sight between the sender and receiver and the incoming radio waves are received after being reflected or scattered by objects in the environment. We can observe that the overall achieved network throughput with Rayleigh fading is less compared to the free space model, which is expected due higher packet loss due to fading but RS still outperforms LAR and achieves approx. $2\ \% - 5\ \%$ higher network throughput.

Until now, we have observed that the overall achieved network throughput for RS is higher than LAR and AODV. We are now interested in evaluating the number of packets received from drones individually and compare them using the AODV, LAR, and RS protocols. Figure 3.6 and Figure 3.7 shows the cumulative sum of the received packets for M1 and M2 respectively, when three source nodes M0, M1, and M2 transmit simultaneously to the destination node. We chose M1 and M2 to evaluate the performance of a node that is relatively closer (M1) and requires less number of hops to connect to the destination and a node that it is relatively further (M2) and requires a higher number of hops for connectivity during the mission.

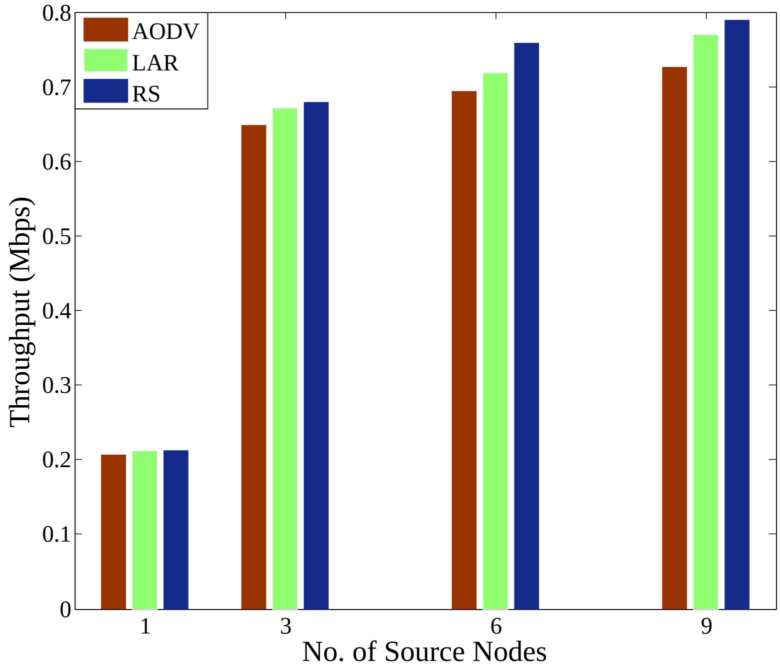


Figure 3.5: Comparison of the achieved network throughput for AODV, LAR and RS schemes for the random mobility scenario using Rayleigh channel propagation model. The number of source drones nodes vary from 1 to 9

We observe that the individual comparison shows diversity at different time instances i.e., although RS performs better in terms of the sum of received packets and achieved throughput but at some instances AODV or LAR performs better, e.g. the cumulative sum of received packets in Figure 3.6 for M1 was better with AODV until 700 s and for M2 in Figure 3.7 LAR performed better until 200 s. This is because RS finds the route that maintains connectivity for a longer time and avoids the route discovery process rather than a route that can also provide higher throughput. Although, the results show that RS achieves higher overall performance in terms of the total number of packets received but still lacks achieving better performance during the complete mission time. We so believe that better link throughputs can be achieved with a link aware routing algorithm that is left for future investigation.

Also, since our mission is to provide coverage to multiple events through multimedia traffic, we need to evaluate if the achieved throughput is sufficient to support such a scenario. From Figure 3.3 the average network throughput is around 0.7 Mbit/s when three MAVs in the network transmit. In general, the lowest quality MPEG video traffic requires 192 kbit/s of data rate. Considering the throughput results achieved, it can be stated that with this setup multimedia traffic can be supported but the quality can be adapted at the application layer based on the available data rates at particular time instances. However, a good quality video link is required to be maintained during the mission time. Further improvement can be added by incorporating a link aware protocol and introducing QoS support at lower layers.

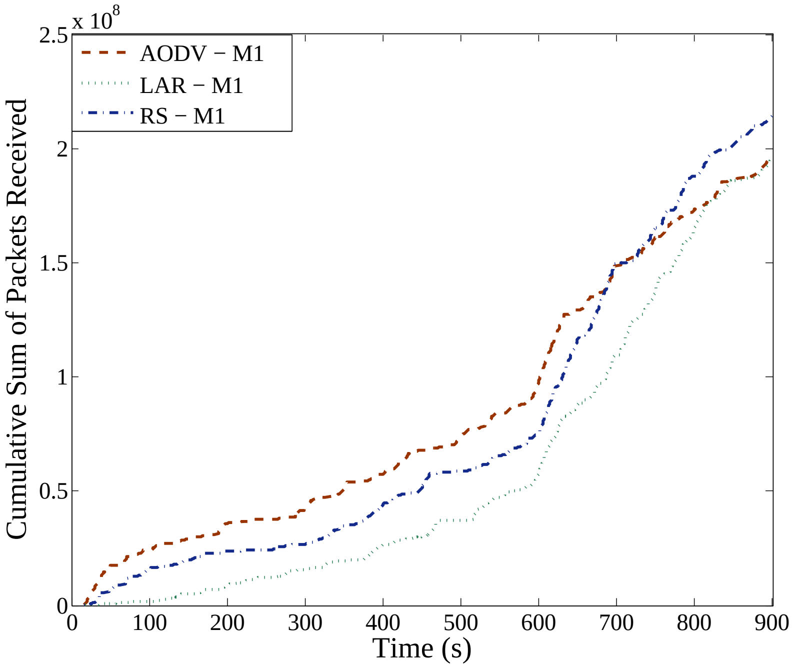


Figure 3.6: Cumulative sum of packets received from MAV1 while MAV0, MAV1 and MAV2 simultaneously transmit to the destination node

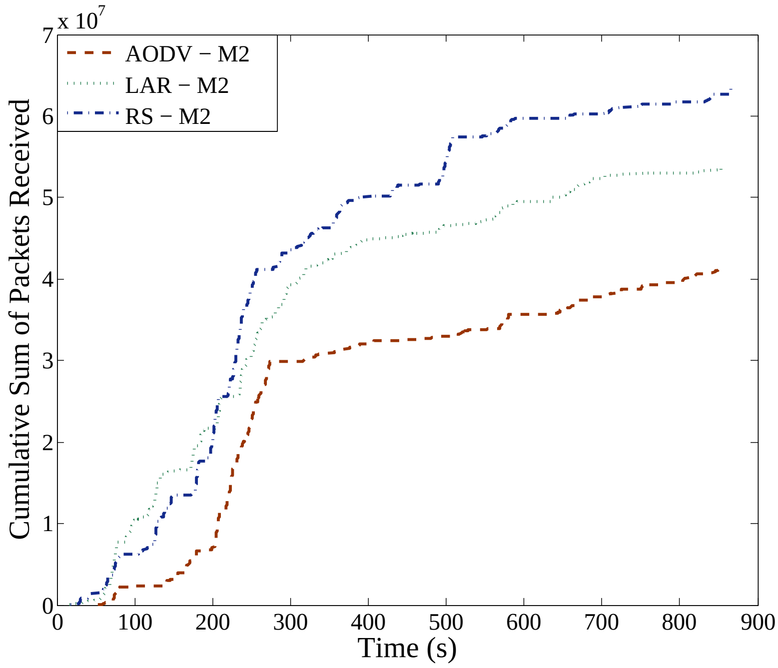


Figure 3.7: Cumulative sum of packets received from MAV2 while MAV0, MAV1 and MAV2 simultaneously transmit to the destination node

3.5.2 Coverage Mission

We now investigate the performance of our proposed protocol for the coverage mission scenario. The trajectories for this scenario that the drones follow are computed while demonstrating a multi-drone system that provides a high-quality overview image of a given area of interest as shown in Figure 3.8. The paths are then optimized based on the computed picture points [MF12] to provide maximum aerial coverage in the given mission time. The maximum mission time is set to 17 minutes considering the energy constraints of the quadrotors. The idea here to simulate using the real data set mission paths is that these paths resemble our defined mission scenario of providing coverage to multiple areas of interest through multimedia transmission. The computed trajectories for the coverage mission scenario are shown in Figure 3.9. The destination node denoted by ★ is kept stationary and all other nodes transmit while they are moving. All other parameters are kept the same as given in Table 3.1 except for the simulation time. The simulation time is set to 1000 s such that all drones complete their mission path in the given time.

Figure 3.8: Overview image of the area of interest for coverage mission with three paths optimized to provide maximum aerial coverage

All drones start and stop at the same point and so, in general, they are initially and at the end closest to the destination node. Therefore, higher throughput is achieved at the start and at the end of the mission or whenever the node gets closer to the destination. It is also important to note that some paths are shorter than the others and allowing some drones to remain within the communication range of the destination during the mission. Routing is not required in such a scenario. A drone might thus only need two hops to transmit its packets to the destination or communicates directly otherwise.

Figure 3.10 shows the cumulatively achieved network throughput using Free space propagation model for the coverage mission scenario. M0 (Figure 3.9) is the source node when 1 node is transmitting, M0, M1, and M2 when 3 nodes transmit, and so on. The

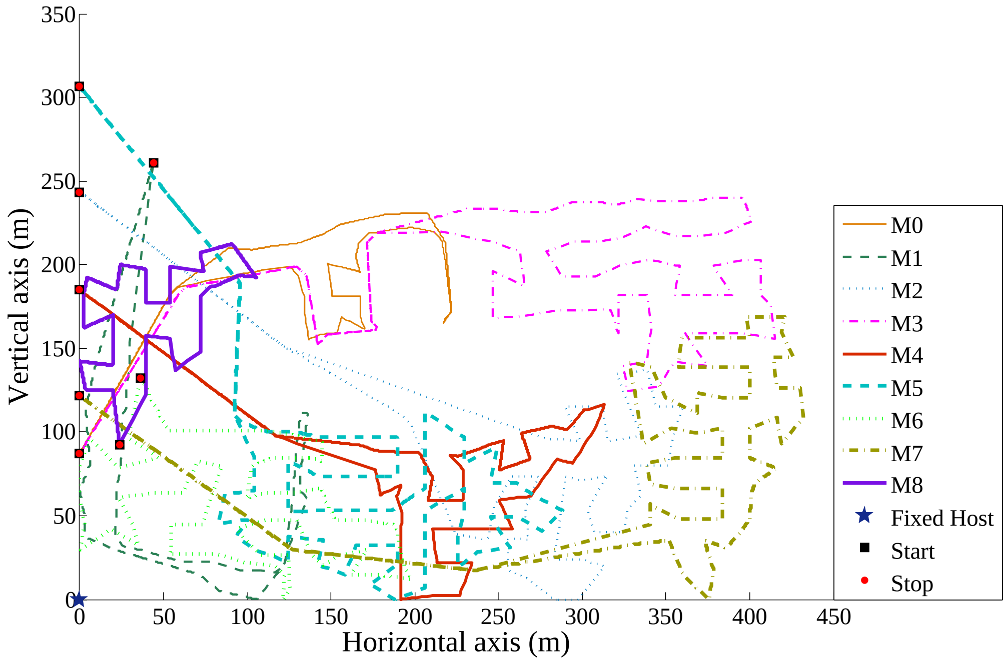


Figure 3.9: Trajectories: Drones follow mission paths while transmitting UDP traffic to the static destination "FixedHost" node

RS algorithm still performs better than LAR although not much of a gain is visible. This is due to the reason that only two hops at maximum are required for connectivity between the source and the destination. All drones connect directly to the destination at the start and end of the mission. Also, drones with shorter paths connect directly to the destination and routing is not required. However, since the route is already calculated and known a slight improvement in the achieved throughput is noticed for drones where routing is required. Similarly, the packet delays reflected in Figure 3.11 show minimal improvement with the RS approach.

The RS algorithm avoids route error and route discovery overhead to improve the network performance in terms of throughput and packet delays but is useful for larger networks where connectivity and route discovery with multiple hops is required. The performance can further be improved by adding link awareness mechanism that could select routes supporting higher bandwidth.

3.6 Summary

In this chapter, we introduce common routing protocols and their limitations in the context to drone networks. We proposed an RS routing algorithm that utilizes the location and trajectory information of the nodes to calculate the routing path from a source to the destination. We simulated the RS algorithm using random paths and mission paths

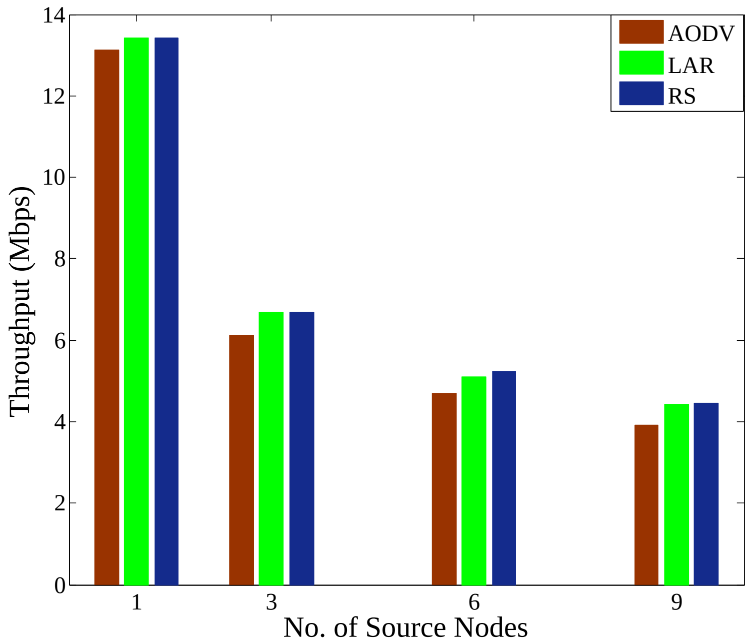


Figure 3.10: Comparison of the achieved network throughput for AODV, LAR and RS schemes using free space channel propagation model for the mission scenario. The number of source drones nodes vary from 1 to 9

and compared our approach with AODV and LAR protocols. The simulation results demonstrate that the RS algorithm outperforms AODV and LAR protocol in terms of network throughput and delay, and is suitable for large drone networks where multi-hop communication is required. The proposed solution, however, lacks in finding routes that also provide high bandwidth links. A link aware routing protocol may prove fruitful but is left for future investigation.

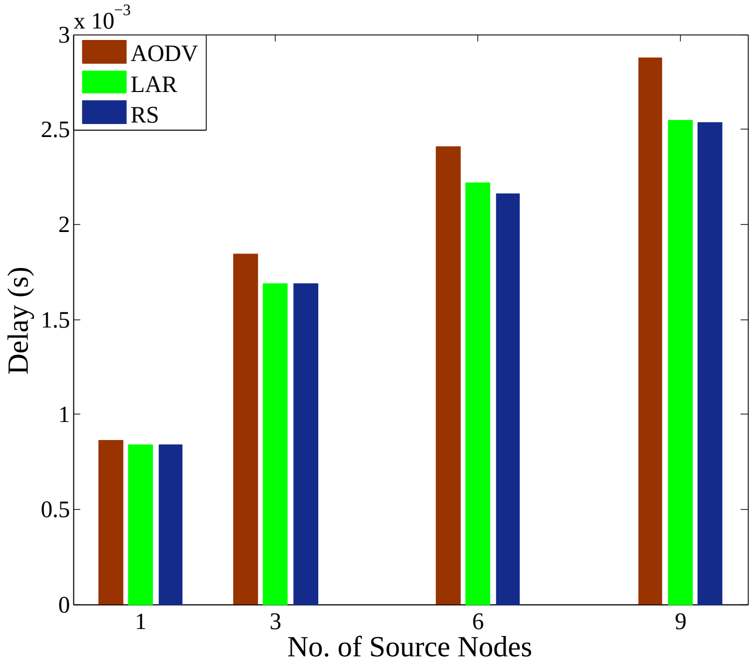


Figure 3.11: Comparison of packet delays for AODV, LAR, and RS schemes for the mission scenario. The number of source drones nodes vary from 1 to 9

4 Rate-adaptive multicast video streaming from teams of drones

4.1 Introduction

Multicasting is an efficient way to transmit identical data to multiple users compared to unicasting [dMCGA03, JR05]. Multicasting, however, is challenging in terms of achieving reliability, fairness among multicast nodes and communication performance [CCS+07, Naf07, VZ13, ZLCP04]. Mobility is the foremost challenge both for aerial communication and multicast video streaming since the network topology changes frequently and the link conditions of the wireless nodes fluctuate [HYM16, FB08]. Multicast video streaming over IEEE 802.11 is unreliable due to the lack of feedback from receivers. High video data rates and variable wireless link conditions due the mobility of the drones require feedback from the receivers for link estimation to gain reliability and rate adaptation accordingly.

While existing license-based wireless communication technologies can in principle be used for drone applications, they bear infrastructure requirements that may not be available in disaster areas. IEEE 802.11, on the contrary, is easy to setup, does not require an infrastructure, falls in the unlicensed spectrum [FMZ07], and is supported by many drone platforms [HYM16]. However, IEEE 802.11 has not been designed for multipoint-to-multipoint networks where the antenna orientation, distance, terrain, and topology changes frequently between the drones and multicast receiver nodes, causing unstable links between them [AHS+14].

The multicast frames in IEEE 802.11 are group addressed and are not acknowledged by the receivers. Thus the ability to gain feedback from the receivers about packet reception remains an issue [VZ13]. Since the source remains ignorant of the packet loss due to the missing feedback mechanism, it cannot retransmit the lost packets or adapt the link transmission rate. Multiple approaches to provide feedback exist such as promiscuous reception of unicast packet [GM02, Tou98], polling-based schemes [PFGC13, PKBV09], and leader-based approaches [CCS+07, PSC+06, KK01]. These approaches, however, require modifications in the MAC layer to be operable. The MAC layer of each node, therefore, shall be tailored to the requirements of the scheme being used. Given the constraints of multicasting over 802.11 with mobility, the node providing feedback may at times lose connectivity with the source due to fluid topology, fading or link attenuation. This may render all other multicast recipients suffer from a possible smooth video reception. A feedback mechanism for retransmission and rate adaptation is required to achieve reliability and to satisfy receivers' QoE without MAC layer modifications.

The results in this chapter are achieved in cooperation with Vladimir Vukadinovic, Evşen Yanmaz, Christian Bettstetter, and Andrea Cavallaro and are published in [MVC16, MYBC16]. Parts of this chapter are taken from [MVC16, MYBC16].

In this chapter, we address the problem to reliably multicast video streams over an 802.11 ad-hoc network to satisfy the receivers' quality of experience (QoE) while both the source and the receiver nodes are mobile. To deal with the complexity of multicast video streaming from multiple drone sources, we propose an Application-Layer Video Multicast Gateway (ALVM-GW) as a central coordination entity. The proposed scheme allows application-layer feedbacks, eliminating the need to alter the MAC layer and making the node providing feedback dynamic and responsive. The receiver nodes of a multicast group are dynamically elected to gain feedback based on their changing link conditions while they are mobile. The rate at which the traffic is being generated, the *video encoding rate*, the *link transmission rate*, and the *frame rate* are regulated such that the delay between the reception of packets is bounded to meet the Quality of Service (QoS) requirements.

While application-layer error correction schemes [AKWP10, VZ13] and application-layer multicast tree-driven routing protocols [AY, WZ07, ARM06] are investigated, an application-layer multicast approach that regulates the *link transmission rate*, the *video encoding rate*, and the *frame rate* for highly mobile drone networks is a contribution to this thesis. The proposed solution can be used with IEEE 802.11 ad-hoc networks without modifying the MAC layer. We demonstrate our framework through emulation and testbed experiments to evaluate the performance in terms of goodput, delay and received video quality.

4.2 Multicasting using IEEE 802.11

Approaches that can be used to multicast over IEEE 802.11 include the legacy 802.11 multicast, 802.11aa amendments, and solutions to gain feedback on packet reception from members of a multicast group. A comparison of the existing approaches, 802.11aa Group Addressed Transmission Service (GATS) methods, and our proposed approach is presented in Table 4.1.

4.2.1 IEEE 802.11aa amendments

The 802.11aa GATS specifies the directed multicast service (DMS), the groupcast with retries (GCR) unsolicited retries, and GCR Block ACK besides the legacy multicast service [SCGS13]. The legacy multicast mechanism is No-Ack/No-Retry service that uses the basic fixed transmission rate.

The *DMS* converts multicast traffic to unicast frames intended for individual recipients of the multicast group. Reliability is ensured through retransmissions until frames are received correctly by all the recipients in the group. This is the most reliable scheme but it has a higher overhead and is not scalable.

Table 4.1: Comparison of schemes for multicasting over 802.11

Ref.	Scheme	Changes to MAC?	Reliability	Scalability	Rate adaptation	Multicast groups	Hops	Evaluation
[PFGC13]	Polling based	Yes	None	Low	Joint reception correlation	1	1	Testbed
[PKBV09]	Polling based	Yes	None	Low	User experience in time	1	1	Simulation
[CCS+07]	Leader based	Yes	High	Low	Auto rate fallback	1	1	Simulation
[PSC+06]	Leader based	Yes	None	High	Beacon Signal	1	1	Simulation
[MCB12, SCGS13]	Directed multicast	Yes	High	Low	None	1	1	Testbed
[MCB12, SCGS13]	Unsolicited retries	Yes	Implementation dependent	High	None	1	1	Testbed
[MCB12, SCGS13]	Block ACK	Yes	Implementation dependent	Implementation dependent	None	1	1	Testbed
Our [MVC16, MYBC16]	Dynamic leader	No	Medium	High	RTP packet feedback	1 & 4	1 & 2	Testbed & Emulation

The *GCR unsolicited retries* aim to increase reliability by retransmitting the same frame several times. Since there is no feedback mechanism, the method offers smaller overhead, higher scalability but lower reliability [MCB12].

The *GCR Block ACK* scheme sends a burst of multicast frames and requests a block ACK of the transmitted frames from one or more recipients. The choice and number of recipients from which to gain a feedback is left to the implementation. Frames not received correctly by one or more recipients can be retransmitted until the retry limit is reached. This scheme offers a trade-off between reliability, overhead and scalability [MCB12].

4.2.2 Multicast feedback schemes

Approaches to gain feedback on packet reception from members of a multicast group over IEEE 802.11 wireless access networks can be categorized as the promiscuous reception of a unicast transmission, polling schemes, and leader-based protocols [VZ13].

In *promiscuous reception*, the source sends data to a member of the multicast group as unicast traffic while other members listen in promiscuous mode [GM02, Tou98]. This approach requires every member to be informed of the MAC and IP address of the node receiving the unicast traffic. If the target node leaves the multicast group without informing the source, other members of the group will experience total packet loss.

The *polling scheme* asks every receiver of the multicast group if it has received the packet and retransmits otherwise [PKBV09, PFGC13]. Packet acknowledgments (ACKs) are requested through a control frame called request for ACK (RACK) upon which all members shall respond while the data packet is re-multicast if one of the response is missing. This consumes additional network resources and is inefficient for video multicast streaming.

The *leader-based* approach chooses a member of the multicast group as the leader of the group tasked to send ACKs for the received packets. Negative ACKs (NACKs) can be sent by other members of the group if a packet is not received [PSC+06, CCS+07, KK01]. The drawback of this scheme is that all members of the multicast group need to handshake with the source to be recognized as the member of the multicast group. The

Leader-Based Protocol (LBP) [KK01] addresses the reliability problem by sending ACKs against the received packets but does not address the other challenges. The SNR-based auto rate for multicast (SARM) [PSC+06] uses a supplementary link-level signaling to collect signal-to-noise-ratio (SNR) values of the multicast nodes and selects the leader experiencing the worst channel conditions. The rate is adapted based on SNR-PSNR relation such that the peak-signal-to-noise-ratio (PSNR) of the receiver shall be greater than thirty to adapt the PHY rate to 1, 5.5 or 11 Mbit/s. However, the rate is adapted per beacon signal rather than per multicast data frame. SARM improves QoS and adds reliability but does not address other challenges of performance and fairness. Leader-based Multicast with Auto Rate Fallback protocol (LM-ARF) [CCS+07] overcomes the rate adaptation drawback of per beacon signal by using per frame rate adaptation as in 802.11 ARF rate adaptation scheme. The multicast data rate is increased if the AP receives ten consecutive ACKs from the leader while the data rate is decreased upon two consecutive retransmissions. However, a modification in the MAC layer for CTS-to-self frame is required to reserve the channel for multicast traffic. LM-ARF addresses the challenges of reliability through ACKs, performance, and fairness through rate adaptation but does not address the challenge of delay bounds for video multicasting.

4.3 Application-layer rate-adaptive multicast video streaming

To multicast multiple video streams of different areas from camera-mounted drones, we use a *multipoint-to-point-to-multipoint* architecture with a two-hop wireless network topology (Figure 4.1). Multiple drones unicast video streams to an ALVM-GW, which (i) transcodes the incoming video streams, (ii) forms multicast groups, and (iii) multicasts the videos to the mobile wireless recipients as an overview (low quality) videos. A viewer can then select an overview video to receive its high-quality stream.

Let M drones stream videos through a shared network channel. Let C_{R_i} be the channel capacity at a given transmission rate R_i where $R_i \in \{6, 9, 12, 18, 24, 36, 48, 54\}$ Mbit/s for IEEE 802.11a. Let $I = \{I_i\}$ and $\mathbb{O} = \{O_i\}$, $i \in \{1, \cdots, N\}$ be the input and output HD video streams at the ALVM-GW, respectively. The transmission rate R_i remains the same for all O_i. Let the HD video stream of O_i be encoded at a rate r_i.

Let $\mathbb{O}_f = \{O_{f_1}, O_{f_2}, \cdots, O_{f_N}\}$ be the overview video streams and r_f be the fixed encoding rate of $\mathbb{O}_f$ (in our case $r_f = 350$ kbit/s). The required transmission rate T_R for multicasting video streams from M drones is

$$T_R = \sum_{i=1}^{M} r_i + (M \times r_f). \tag{4.1}$$

The packet loss and video distortion will be minimum if

$$T_R \leq C_{R_i}. \tag{4.2}$$

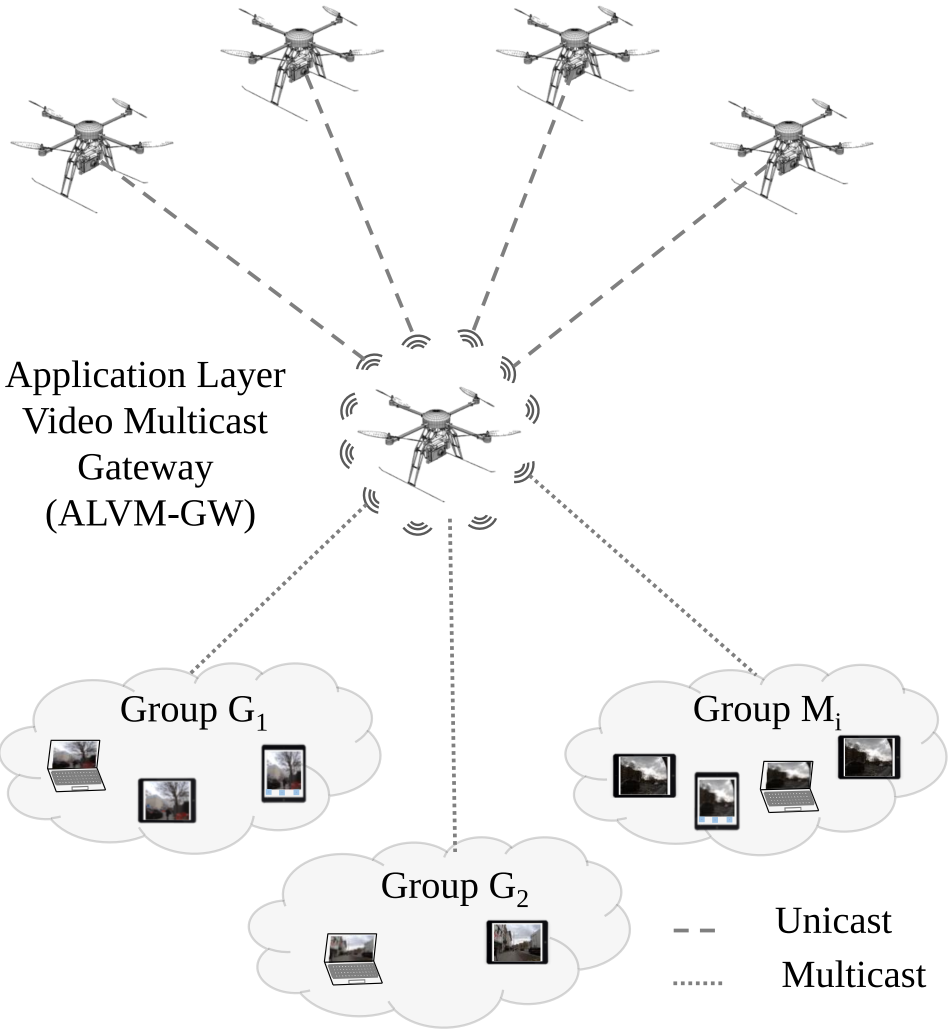


Figure 4.1: Multiple drones unicast video streams to an ALVM-GW that forms multicast groups and multicasts the videos to the mobile wireless recipients.

The objective is to regulate all the r_i such that Eq. 4.2 is satisfied. Once a viewer selects one of the overview videos to receive its high-quality stream, the selection is communicated to the ALVM-GW so that it can create the multicast group(s). The encoding rate the ALVM-GW should use to transcode the video stream is the one that allows all viewers of a multicast group to experience seamless and smooth video reception while the receivers are mobile and their reception conditions change.

To solve the problem, we propose an Application-Layer Rate Adaptation (ALRA) multicast scheme that selects members of the multicast group based on their signal quality as designated nodes. The signal quality measure used in emulation is signal-to-interference-noise-ratio (SINR) while for experimental evaluation received signal strength

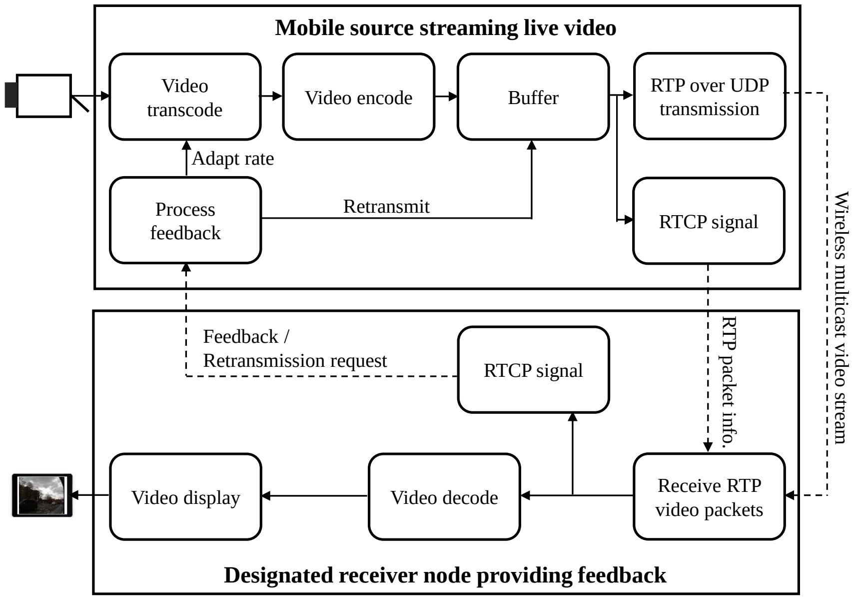


Figure 4.2: Source multicasts live video stream over the wireless medium as RTP packets. RTCP signaling provides RTP packet information to the receiver nodes. Designated nodes provide feedback about packet reception or packet loss. The source retransmits lost packets and performs rate adaptation.

(RSS) is used. The selected designated nodes acknowledge the reception of the packets on behalf of the group. The member with the highest signal quality is assigned the role of *primary* designated node P. Other members in the hierarchy of signal quality become part of the set of *secondary* designated nodes S, which serve as the backup of P. Non-designated nodes are part of the set of *best effort* nodes, B, which do not provide feedback and receive videos on a best-effort basis. The feedback received from the designated nodes by the ALVM-GW is used for retransmission upon packet loss and for rate adaptation in order to reduce video distortion (Figure 4.2).

The ALVM-GW performs functions including *video transcoding*, *multicast group management*, *process feedback* and *group probing* (Figure 4.3). Video streams from M drones are transcoded to $\mathbb{O}_f$ and $\mathbb{O}$ streams. Multicast groups G_j, $j \in \{1, \cdots, M\}$, are formed when members send a join request to the ALVM-GW by selecting a particular video stream to be viewed in high quality. A state table is maintained by the ALVM-GW for the nodes leaving and joining the multicast group.

The *multicast group management* function processes the *join* group, *leave* group and *deregistration* requests. The join request follows the *role assignment* process (Algorithm 2), while the leave request and non-response follow the *deregistration* process. The *process feedback* function processes the feedback received from the P and S for rate adaptation. The *probe group* is a signaling packet sent to a multicast group G_j to get the signal quality, Node ID and IP information of all the members of the group. Due to mobility and dynamic link conditions of the members of the multicast group, roles are re-evaluated through probing and are re-assigned subsequently.

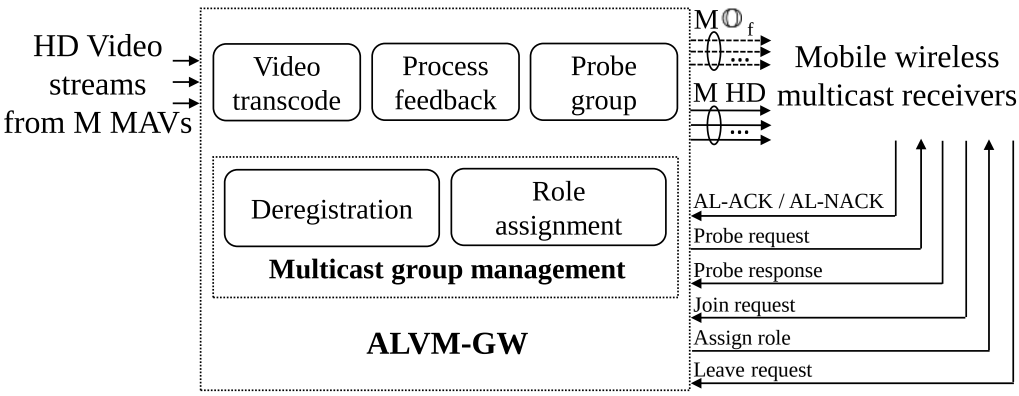


Figure 4.3: The application-layer video multicast gateway (ALVM-GW) takes in input M high-quality video streams from the drones and transcodes them to M low-quality and M high-quality videos. The ALVM-GW manages multiple groups, and adapts transmission and video encoding rates based on the feedback received from the multicast group members.

4.3.1 Role assignment and de-registration

The role assignment process defines which members of the multicast group are designated nodes or best effort nodes. The notation used is listed in Table 4.2. The role assignment procedure is defined in Algorithm 2. Fewer than half of the nodes in a multicast group G_j can be designated nodes. The node with the highest signal quality with the ALVM-GW of G_j becomes the P. After the P, the set of S of G_j have the strongest link with ALVM-GW and are assigned IDs representing their hierarchy based on their signal quality with the ALVM-GW. The ALVM-GW calculates the signal quality Q_V of a node V requesting to join a multicast group G_j and assigns the role as designated or best effort member of the group. The first node that joins a multicast group G_j is assigned P. A node is assigned to S of G_j if

$$\frac{\text{card}(S)+1}{\text{card}(G_j)+1} < 0.5. \tag{4.3}$$

A new node joining G_j can change roles between P and S_i if $Q_V > Q_P$ or $Q_V > Q_{S_i}$, respectively. Otherwise, it is added as a member to G_i as B_i. The number of designated nodes can be adjusted based on the network density to make the approach scalable.

A *de-registration* process is initiated when a multicast member node requests to leave the multicast group or if there is no response from the node. If the leave request is from a node that is not a designated node, it is removed from the group. However, for de-registration of a designated node, the *probe group* function is activated, followed by the *role assignment* process.

Algorithm 2: Role Assignment at ALVM-GW to V joing G_j

Notation: See Table 4.2.

Input: V, Q_V, Q_P, Q_{S_i}, Q_{B_i}, card(S), card(G_j).

Output: Role is assigned to V joining G_j.

```
if card(G_j) > 0 then
    if card(S) > 0 then
        if (card(S)+1)/(card(G_j)+1) > 0.5 then
            if Q_V > Q_P then
                G_j ← V, B ← S_n, S ← P, P = V
            else if Q_V > Q_{S_i} then
                G_j ← V, B ← S_n, S ← V
            else
                G_j ← V, B ← V
            end
        else if  Q_V > Q_{S_i} then
            G_j ← V, B ← S_n, S ← V
        else
            G_j ← V, B_i = V
        end
    else if card(G_j) ≥ 2 then
        if Q_V > Q_{B_1} then
            G_j ← V, S_1 = V
        else
            G_j ← V, S_1 = B_1, B_1 = V
        end
    else
        G_i ← V, B_1 = V
    end
else
    G_j ← V, P = V
end
```

Table 4.2: Notation

Notation	Description
M	Number of drones streaming videos
G_j	Multicast groups where $j \in \{1, \cdots, M\}$
card(G_j)	Cardinality of a multicast group G_j
V	A new mobile receiver node
Q_V	Signal quality of V
P	Primary designated node of G_j
Q_P	Signal quality of P
$S = \{S_1, \cdots, S_n\}$	Secondary designated nodes S_i of G_j
card(S)	Cardinality of the S
Q_{S_i}	Signal quality of S_i
$B = \{B_1, \cdots, B_n\}$	Best effort nodes B_i of G_j
card(B)	Cardinality of B
Q_{B_i}	Signal quality of B_i

4.3.2 Feedback from designated nodes

Feedback from the multicast nodes is required to address the *reliability* challenge. An application-layer acknowledgment, `AL-ACK`, is issued upon packet reception, whereas an application layer negative acknowledgment, `AL-NACK`, is issued upon packet loss. While the P is responsible for sending `AL-ACK`s to the ALVM-GW (see Figure 4.4(a)) upon packet reception, either a P or S_i can send an `AL-NACK` to request retransmission in the case of a packet loss (Figure 4.4(b)). The transmission of an `AL-NACK` involves contention at the MAC layer to gain channel access since it is a data packet from the MAC view-point. However, the ALVM-GW reacts to the first received `AL-NACK` whereby the pending `AL-NACK`s are dropped.

The *performance* and *fairness* challenges are addressed through continuous feedback about packet reception and rate adaptation. Since the nodes are mobile, the P may not maintain the strongest link with the ALVM-GW during the whole mission. The S_i take over in the case the P fails or loses its signal strength with the ALVM-GW. The S_i listens to the `AL-ACK`s sent by the P in promiscuous mode. If a S_i does not hear an `AL-ACK` from P, the highest S_i in the hierarchy of signal quality sends an `AL-ACK`, and so on. The ALVM-GW retransmits the packet upon an `AL-NACK` or if an `AL-ACK` is not received. However, before retransmission the ALVM-GW waits for a back off time to get an `AL-ACK` or an `AL-NACK` from any of the S_i.

The S_i node sends an `AL-ACK` upon packet reception to the ALVM-GW if an `AL-ACK` or an `AL-NACK` is not received from the P. This indicates to the ALVM-GW that the P no longer maintains the strongest link with the ALVM-GW or is no longer a member of the multicast group. If a feedback is received from S_i while there is no response from P, the ALVM-GW sends a *probe group* signal to evaluate the link condition of the members of the multicast group and re-assigns the roles. This scenario is presented in Figure 4.4(c).

A loss of feedback indicates either a network congestion problem or that the desig-

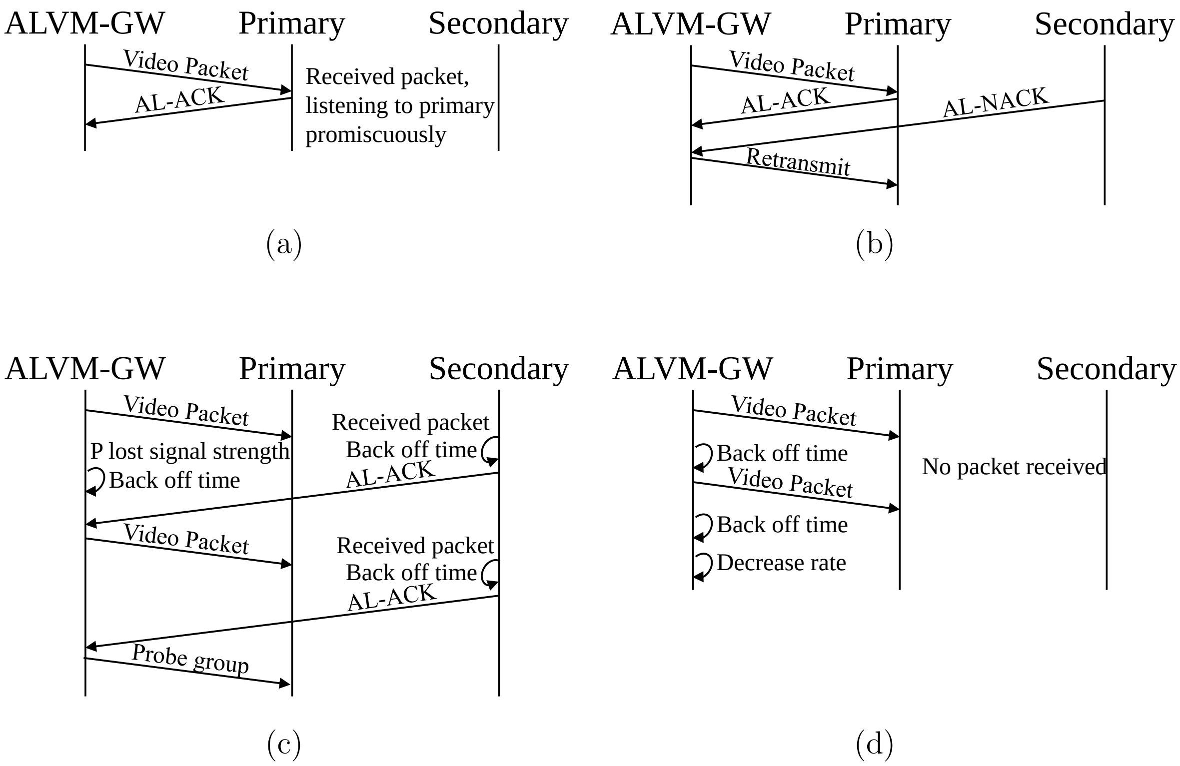


Figure 4.4: ALVM-GW video multicasting and reception response from the P and S_i. (a) P sends `AL-ACK`s for the received packets. (b) S_i generates an `AL-NACK` for retransmission. (c) ALVM-GW evaluates multicast members link condition and re-assign roles. (d) The ALVM-GW decreases the transmission and video encoding rate upon signal loss.

nated nodes are out of the communication range from the ALVM-GW. The ALVM-GW decreases the transmission rate and the video encoding rate upon signal loss, i.e. when no `AL-ACK` or `AL-NACK` is received from any of the P or S_i, as presented in Figure 4.4(d). Nevertheless, a *probe group* signal followed by a *role assignment* process is initiated as soon as the rate is decreased twice consecutively.

4.3.3 Rate adaptation

The video encoding and transmission rates are regulated based on the feedback received from the P and S_i. While feedbacks about packet reception are received, the encoder is instructed to regulate the rates for the next Group of Picture (GoP). Because videos are streamed using the Real-time Transport Protocol (RTP), we use RTP Control Protocol (RTCP) signaling to gain feedback about the reception of the RTP packets.

In Emulation

Inspired by the 802.11 MAC layer rate adaptation schemes, ARF or AARF for IEEE 802.11 [LMT04], we adapt the *video encoding rate* upon two consecutive `AL-ACK`s or two consecutive `AL-NACK`s. The *video encoding rate* is initially set to 2500 kbit/s (encoding rate for 720p HD video), it can increase to 8192 kbit/s (the average encoding rate of the input videos) and it can decrease down to a minimum of 350 kbit/s (an application-dependent parameter). The *video encoding rate* is increased by 5 % for the next GoP upon two consecutive `AL-ACK`s and decreased by 5 % upon two consecutive `AL-NACK`s. The first `AL-ACK` or `AL-NACK` received corresponding to a RTP packet from any P or S_i nodes is counted. The encoding rate is decreased gradually until no feedback about the packet reception is received, i.e. a signal loss.

The *link transmission rate* is increased upon ten consecutive `AL-ACK`s from the designated nodes and is decreased upon the signal loss i.e. when no feedback is received from any of the designated nodes. The rates used are $6, 9, 12, 18, 24, 36, 48,$ and 54 Mbit/s.

In Testbed

In addition to the *link transmission rate* and the *video encoding rate*, the *frame rate* is also adapted in the testbed setup. The *link transmission rate* adaptation scheme remains the same as in emulation while the *video encoding* and the *frame* rates are adapted as follows. The numbers are percentages are chosen after comparing different values.

The *video encoding rate* is initially set to 512 kbit/s, it can increase to 8192 kbit/s and can decrease down to 128 kbit/s. It is increased by 5 % upon an `AL-ACK` and is decreased by 5 % upon three consecutive `AL-NACK`s. The packet is retransmitted in the later case.

The *frame rate* is initially set to 25 frames/s and is decreased by one frame/s down to a minimum of 10 frame/s upon three consecutive `AL-NACK`s, is the video encoding rate is already at its minimum. It is increased again upon one
tt AL-ACK.

4.4 Results and discussion

4.4.1 Emulation evaluation

We used the Extendable Mobile Ad-hoc Network Emulator (EMANE) for physical and MAC layers in conjunction with the Common Open Research Emulator (CORE) for the higher layers [AGA11]. Emulated devices represent drones that stream their videos to the emulated ALVM-GW. The streaming functionality that includes transcoding of the video sequences is carried out using GStreamer [Gst]. The downstream video transmissions to the first responders are received as *overview* videos. Once the first responder selects a particular video for a high-quality stream, it joins the multicast group as described in the former sections. The server (ALVM-GW) and client (multicast viewer) applications are implemented in C language. The ALVM-GW acts as a server to multicast multiple

Table 4.3: Emulation parameters

Parameters	**Values**
Radio interface	802.11a
Channel frequency	5 GHz
Channel propagation model	Two-Ray
Transmission power	12 dBm
Noise figure	4 dBm
Transmission rate	$\{6, 9, 12, 18, 24, 36, 48, 54\}$ Mbit/s
Maximum transmission unit (MTU)	1472 Bytes
Average input video encoding rate	8120 kbit/s
Overview video encoding rate	350 kbit/s
Frame rate	29.97 frames/s
Area bound	600 $m \times 600$ m
Routing protocol	OSPF-MDR
Emulation time per run	600 s
Number of runs	10

video streams encoded at a rate of 350 kbit/s for overview videos. The client application receives the video streams and displays them side by side.

Once a video stream for high quality is selected, the request is sent to the ALVM-GW for transmitting the selected video stream. With this, the *overview* video streams are paused while the window for high quality stream opens up to stream at an allowable video encoding rate. The parameters used for the emulated setup are listed in Table 4.3.

We compare our proposed approach with legacy 802.11a multicast. To simulate dynamically changing wireless link conditions of the drones and multicast recipients, we use line and random mobility models. With line mobility, drones and multicast members move away from the ALVM-GW with a constant speed of 1.33 m/s in a direction until they are 600 m apart. With random mobility, drones and multicast recipients move randomly within the given bounded area using a random walk mobility model. Two-ray fading model is used due to the fact that for most wireless propagation cases, two paths (direct path and ground reflected path) exist from transmitter to receiver. The results are evaluated in terms of goodput, packet loss, delay, and video encoding rate. The results presented in Figures 4.5, 4.6, 4.7, 4.8, and 4.9 are the mean values from ten emulation runs. The emulation evaluation is conducted for the following scenarios.

- A drone sending a video stream to a receiver. The receiver moves away from the drone using the line mobility.

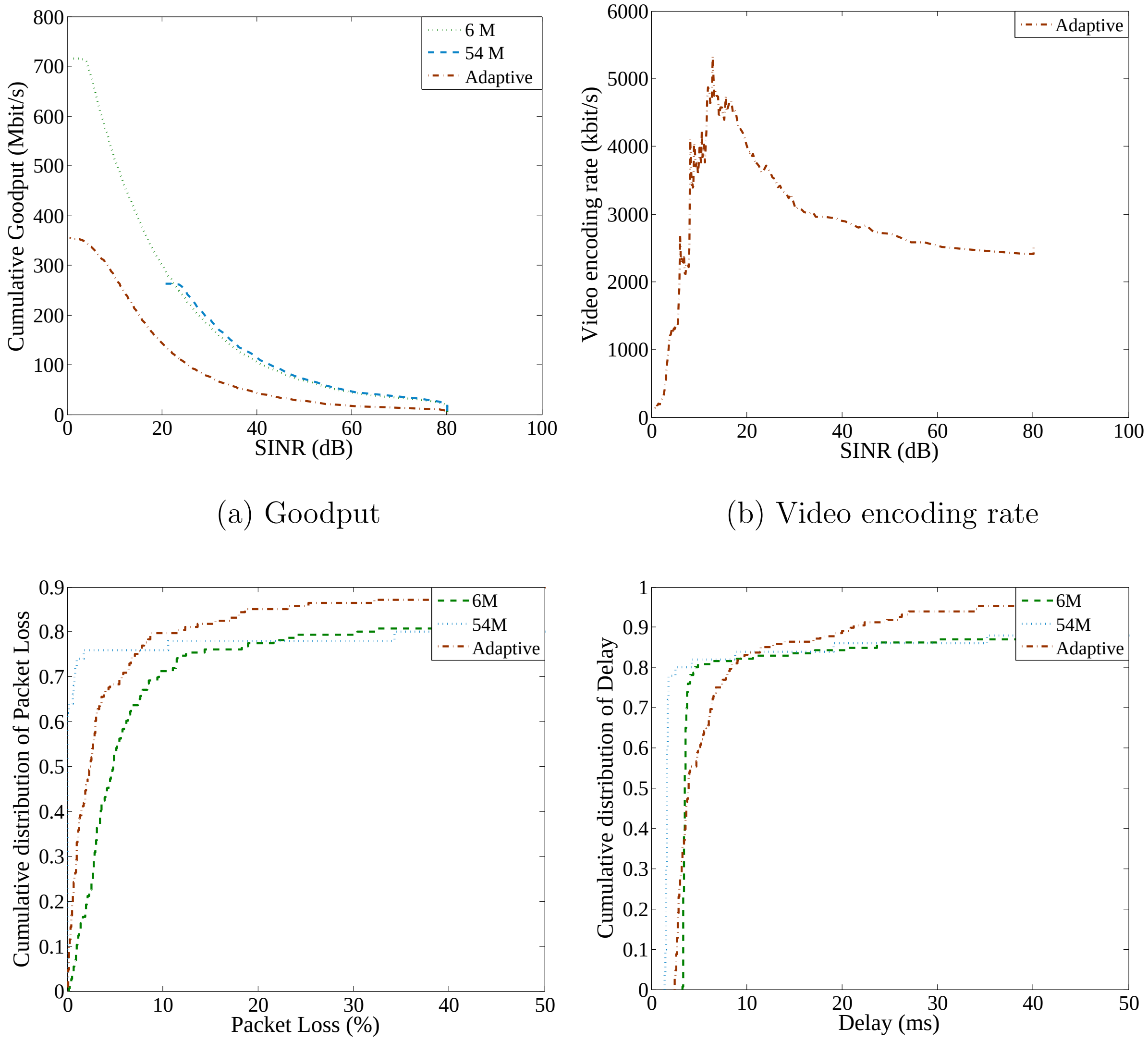
- A drone multicasts a video stream to four receivers. The drone and the receivers are static. The distance between the drone and P is 50 m, S_1 and drone is 100 m, and B_1 and B_2 are 200 m away from the drone.

- ALVM-GW multicasts four video streams to four receivers that move away using random mobility.
- A two-hop scenario where four drones send their video streams to the ALVM-GW. The ALVM-GW multicasts the video streams to four receivers. The drones and the receivers are mobile using random walk mobility while the ALVM-GW is static and in between the drones and the receivers.

Figure 4.5(a) presents the cumulative goodput at the multicast receiver for the transmission rate of 54 Mbit/s, 6 Mbit/s and the rate adaptive scheme. The cumulative goodput is calculated by adding the payload of the received video packets. It can be observed that the number of bytes received with 6 Mbit/s transmission rate is higher than the adaptive stream. This is because the video is streamed at a constant bit rate (CBR) of 8 Mbit/s while for the rate-adaptive approach the video is encoded at 2500 kbit/s (Figure 4.5(b)) at the start and the transmission rate is set to the lowest, i.e. 6 Mbit/s. As the ALVM-GW receives consecutive AL-ACKs the video encoding rate increases and so the goodput also increases. However, since the receiver node is moving away the signal strength decreases, the goodput when the transmission rate is set to 54 Mbit/s remain lower since the receiver loses connectivity at SINR of 20 dB. The decrease in SINR also leads to the higher packet loss (Figure 4.5(c)). As the ALVM-GW receives AL-NACKs, the video encoding rate is reduced until the receiver node moves out of communication range and the signal is completely lost. The corresponding delays remain under the 250 ms bound (Figure 4.5(d)). Although with this one-one video stream scenario the CBR traffic with fixed transmission rate at 6 Mbit/s performs better in terms of goodput but the video playback of the rate adaptive scheme remains smooth due to lower packet losses.

Figure 4.6(a) - (d) present the goodput, video encoding rate, packet loss and delay, respectively, observed at the primary designated node when four multicast receiver nodes remain static placed at 50 m ($N1$ and P_1), 100 m ($N2$ and S_1), and two nodes at 200 m($N3, N4$ and B_1, B_2). The nodes $N1, N2, N3$, and $N4$ are for fixed transmission rate and P_1, S_1, B_1, and B_2 are for rate adaptive scheme. The performance for $N3$ and B_1 is shown in Figure 4.7.

The emulation is run for 600 s to observe the rate adaptation behavior of the proposed approach. As expected, considering the single receiver node results (Figure 4.5), the video encoding rate is regulated based on the received feedback from the designated nodes (Figure 4.6(b)). Note that in this scenario P and S_1 provide feedback to the ALVM-GW and the rate (transmission and video encoding) is regulated accordingly. Since the nodes are static, the received `AL-ACK`s allows a gradual increase in the video encoding rate. The goodput (Figure 4.6 and Figure 4.7) for the CBR video encoding and fixed transmission rate at $N1$ and $N2$ remains higher than P_1 and B_1 because of higher encoding rate of 8 Mbit/s. Nevertheless, as observed in Figure 4.6(c) and Figure 4.7(b), the probability that the packet loss at P_1 and B_1 remains under 10 % is more than 90 %. This, however, is not the case with $N1$ and $N2$. We noticed that the received video gets highly distorted or no playback is seen when the packet loss goes beyond 10%



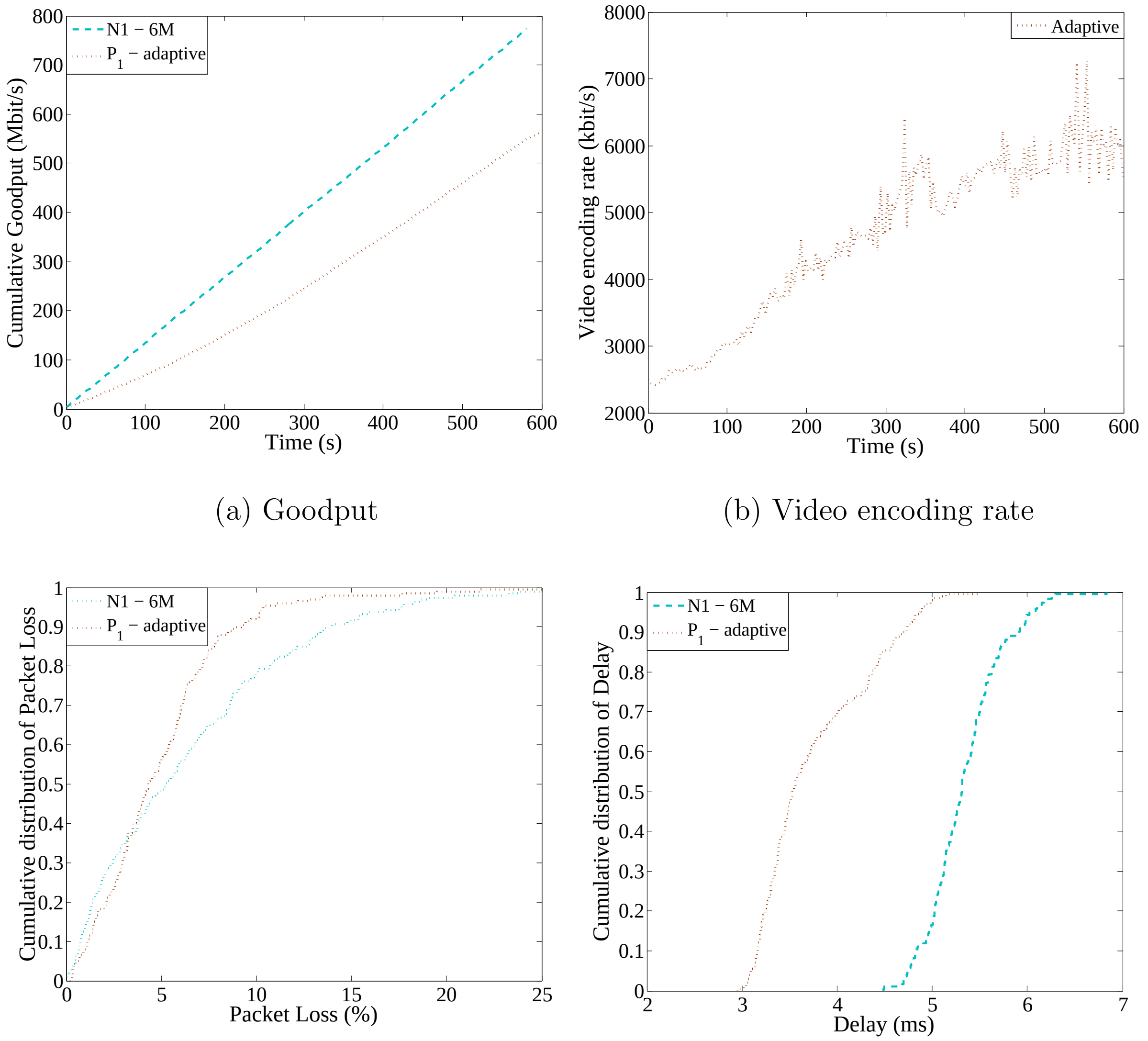
(a) Goodput

(b) Video encoding rate

(c) Packet loss

(d) Delay

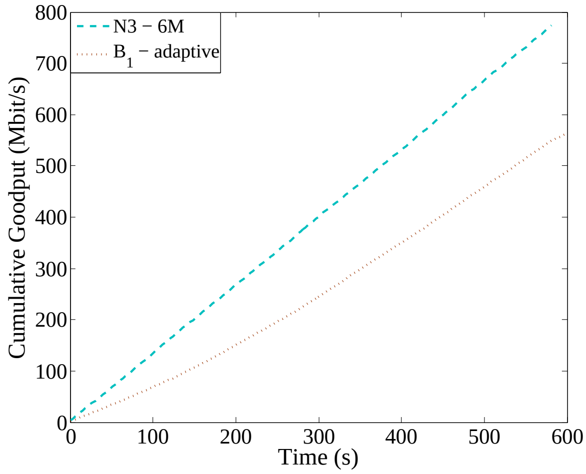
Figure 4.5: Performance of one video stream multicast to one receiver node that moves away from the source from 10 m to 600 m.



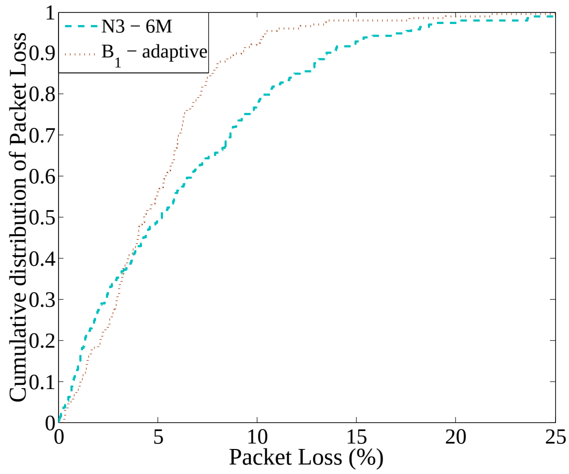
(a) Goodput (b) Video encoding rate

(c) Packet loss (d) Delay

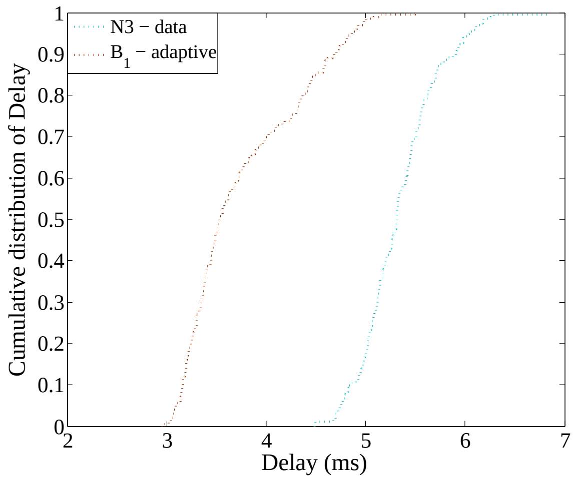
Figure 4.6: Measurements at the primary node when one video stream is multicast to four receivers. All nodes are static, primary node being at a distance of 50 m from the source.



(b) Goodput

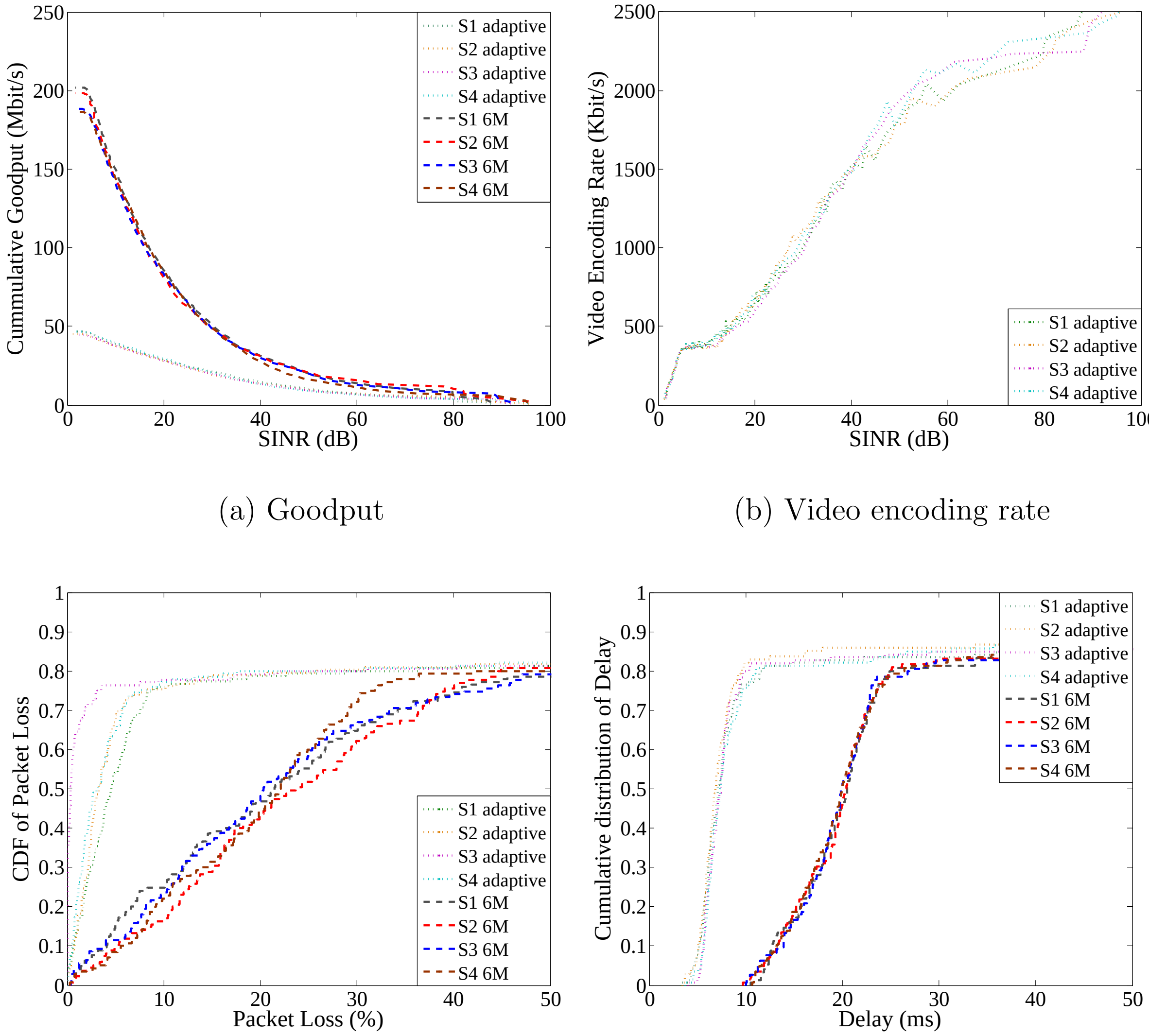


(b) Packet loss



(c) Delay

Figure 4.7: Measurements at the best-effort node when one video stream is multicast to four receivers. All nodes are static, best-effort node being at a distance of 200 m from the source.



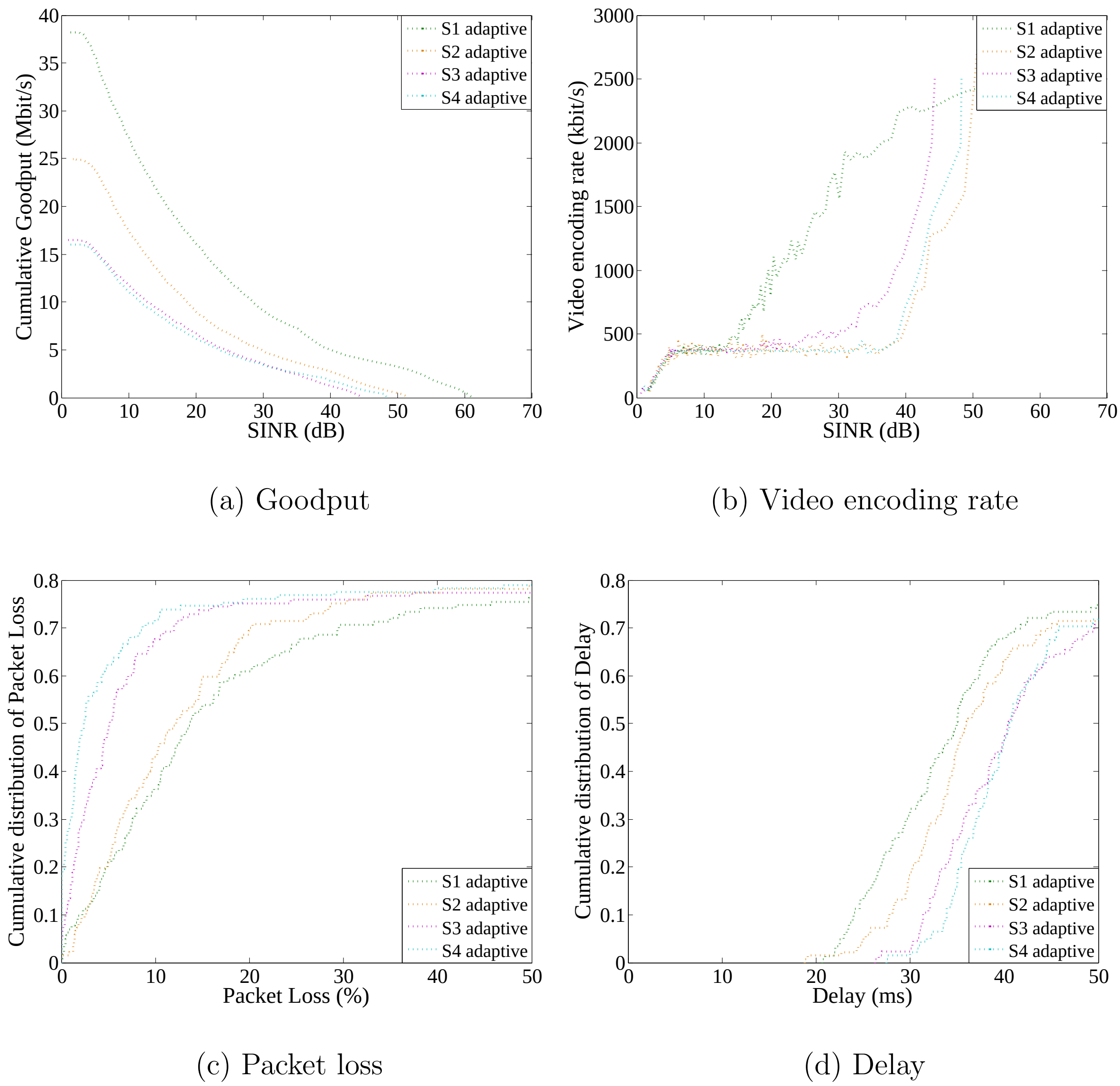
(a) Goodput

(b) Video encoding rate

(c) Packet loss

(d) Delay

Figure 4.8: Performance of four video stream multicast to four receiver node that moves away from the ALVM-GW using random walk mobility.



(a) Goodput

(b) Video encoding rate

(c) Packet loss

(d) Delay

Figure 4.9: Performance of two-hop video stream multicast when the drones ($M = 4$) and the receiver nodes are mobile using random walk while the ALVM-GW is static, and in between the drones and multicast nodes.

Figure 4.10: Sample frames captured at 2 s intervals representing received video quality with CBR 6 Mbit/s (first row) and our rate adaptive scheme (second row) for a multistream video multicast.

even though the delay (Figure 4.6(d) and Figure 4.7(c)) for packet reception remains low.

Figure 4.8(a) - (d) present the goodput, video encoding rate, packet loss, and delay, respectively, for four video streams with four multicast receivers. The receiver nodes move away from the ALVM-GW using a random walk mobility model. Each receiver selects a different video to be streamed in high-quality. Higher packet loss for CBR video encoding and fixed transmission of 6 Mbit/s do not render the playback of the video streams. We observe high goodput for 6 Mbit/s due to the high encoding-rate. However, since the GoP can be composed of several packets, a low packet loss is acceptable for smooth video reception, otherwise, the video is either highly distorted or not received completely. The video reception experience with the proposed rate adaptive scheme remains smooth.

We also conducted emulation for two-hop video streaming. Four drones stream videos to the ALVM-GW that in turn stream the videos to the multicast receivers. The drones and receiver nodes are mobile using a random walk mobility model while the ALVM-GW remains static in between the drones and the receivers. The ALVM-GW adapts the video encoding rate and transmission rate based on the feedback from the designated nodes. Similarly, the drones adapt the rates based on the feedback from the ALVM-GW. The two-hop results in terms of goodput, video encoding rate, packet loss, and delay are presented in Figure 4.9(a) - (d) when four high-quality multicast videos are streamed. The video reception remains smooth as long as the packet loss remains under 20 %. The video gets distorted as the packet loss goes beyond 20%. Note that at 6 Mbit/s transmission rate and CBR video encoding rate, the two-hop multiple video streams are either not played back or highly distorted.

An example of the received frames with CBR 6 Mbit/s and rate adaptive scheme for a multistream video multicast are presented in Figure 4.10.

4.4.2 Testbed evaluation

We built an 802.11a ad-hoc network using Atheros AR9462 wireless cards, which support 802.11abgn and independent basic service set (IBSS). To capture videos, Logitech C920 cameras that support full HD 1080p video quality at 30 frames/s with H.264 video compression are used. NVIDIA Jetson TK1 boards [Jet] are used for processing and video streaming; they have a quad-core 2.3 GHz ARM Cortex-A15 CPU and energy consumption of 1–5 W.

We evaluate our framework with a mobile source and three static receivers (N_1, N_2, and N_3). All nodes are on approximately one meter above the ground. We analyze the effect of the motion of the source on the received video stream quality at distances from 5 to 80 m. The three receivers are placed 5 m apart. We manually select the closest receiver node to the source as P, the second closest as S_1, and the farthest as B_1.

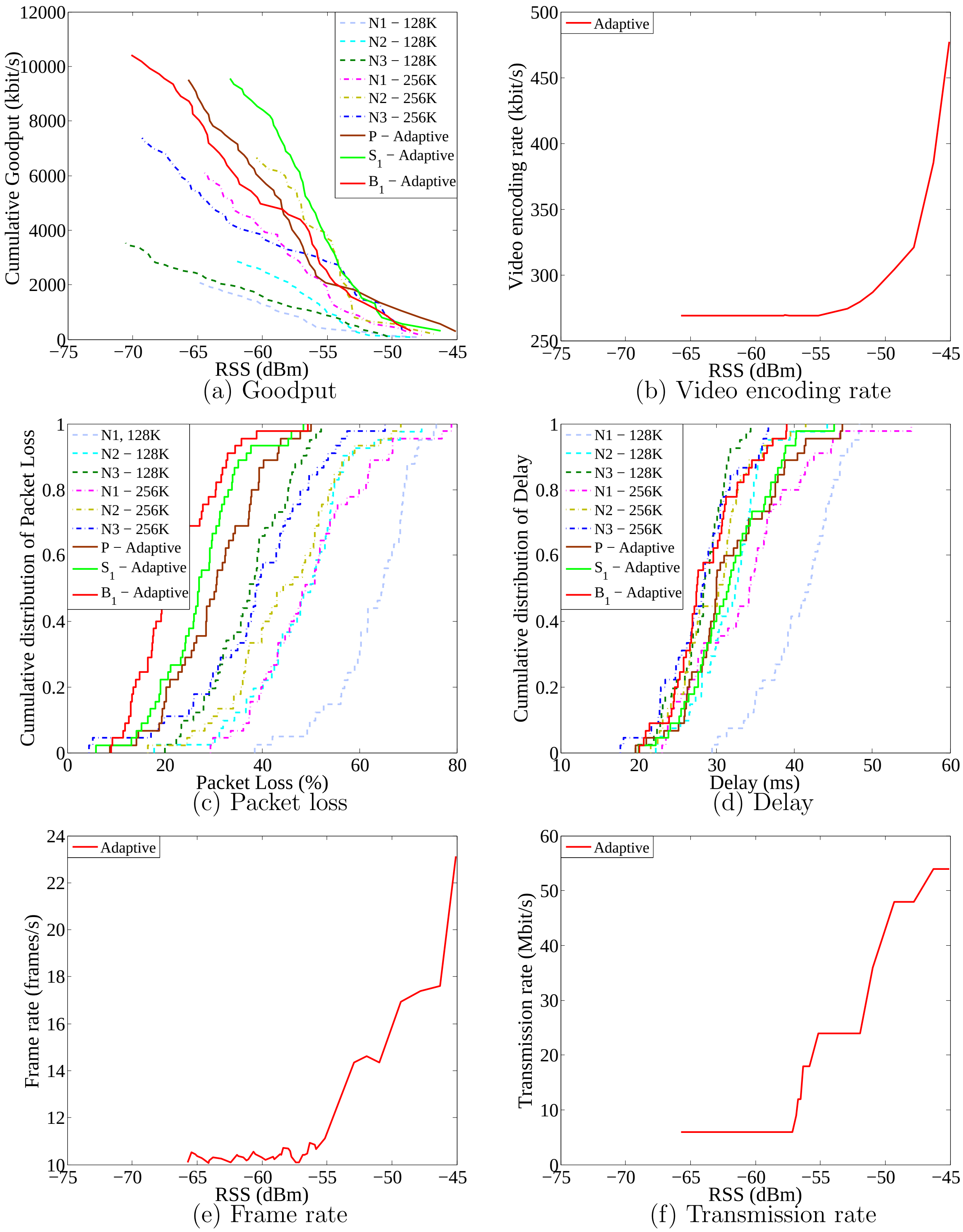
Our rate adaptive approach is compared with a fixed transmission rate of 6 Mbit/s and constant encoding rates of 128 kbit/s and 256 kbit/s. We evaluate performance in terms of received video quality, packet loss, and delay.

Figure 4.11 shows the mean values from five experimental runs. The cumulative goodput is calculated by adding the received bytes as the RSS decreases in order to observe the trend of the received packets with and without the feedback mechanism. The RSS is measured in decibel-milliwatts (dBm). The cumulative goodputs (Figure 4.11(a)) of the receiver nodes P compared to N_1, S_1 compared to N_2, and B_1 compared to N_3 remain higher due to higher and adaptive encoding rate. As it moves away from the receivers, the source adapts the video encoding rate (Figure 4.11(b)), frame rate (Figure 4.11(e)), and transmission rate (Figure 4.11(f)). The packet loss (Figure 4.11(c)) of the receiver nodes remains lower with our approach compared to the fixed 6 Mbit/s transmission due to the feedback and retransmission mechanism. Due to a reduced packet loss, a smoother video is observed compared to the video of the legacy multicast. Balanced delays under bounds are observed in all cases (Figure 4.11(d)).

To compare the received video quality of legacy multicast and our approach, sample frames captured at 5 s intervals are shown in Figure 4.12. A high distortion is noticeable with the fixed rate transmission, while an acceptable video stream is received with the proposed rate adaptive approach.

4.5 Summary

In this chapter, the problem of multicast video streaming is presented. We discussed existing approaches including the legacy multicast approach, IEEE 802.11aa amendments, and approaches to gain feedback from multicast receivers. The shortcomings of the existing approaches are identified. An application-layer rate-adaptive approach to multicast multiple video streams from drones is proposed that does not require modifications in the MAC layer. The proposed approach allows application-layer feedback from multiple receivers and adapts the transmission, video encoding, and frame rates accordingly. The proposed approach is evaluated through emulation and further validated through a testbed setup.



(a) Goodput (b) Video encoding rate

(c) Packet loss (d) Delay

(e) Frame rate (f) Transmission rate

Figure 4.11: Performance of multicast video streaming with the source moving away from the receivers.

Figure 4.12: Sample frames representing received video quality with CBR 6 Mbit/s encoded at 128 kbit/s (top row) and our rate adaptive scheme (bottom row) for a multicast video stream.

5 Conclusions

In this thesis, we study existing works on drone networks with the focus on multi-drone networks. The existing drone projects focus either on safety aspects of the system or on extending the communication range of ground nodes by employing drones and relay nodes. It is observed that the overall network capacity can be increased by using aerial mesh network of drones. However, no tangible study on establishing a self-organizing multi-drone environment exists.

We focused on the networking and communication related issues to routing and video multicast streaming in drone networks. We brief upon the existing studies on drone networks and identify various applications that benefit from drone networks. We highlight the communication requirements for video streaming applications and analyzed if the existing wireless technologies fulfill the demands posed by these drone applications. Applications such as SAR, monitoring and surveillance, and post-disaster assessment are identified that can benefit from multicast video streaming. Multicasting allows efficient utilization of the available network resources for applications that require reception of identical data to multiple recipients. However, multicasting over IEEE 802.11 wireless technology exhibits various challenges. As part of this thesis, these challenges and existing solution addressing these challenges are discussed. We identify the shortcoming of the existing approaches and propose an application-layer solution for multipoint-to-point-to-multipoint video streaming. Moreover, we review existing communication and routing protocols and discuss their suitability for drone networks. A route switching algorithm is proposed that utilizes the location and trajectory information to calculate routes from a source to the destination.

5.1 Summary of the proposed framework

In Chapter 3, we propose a route switching algorithm that exploits path information for calculating the route from source to destination to overcome route discovery and route error overhead. An IEEE 802.11a ad-hoc network is simulated where multiple drones continuously transmit traffic to a ground station at a transmission rate of 54 Mbit/s. To evaluate the performance of the proposed routing algorithm, Omnet++ is selected as the modeling and simulation tool since it provides a framework for wireless and three-dimensional networks, mobility models, and provides strong GUI features. We compare the proposed RS algorithm with LAR and AODV using different mobility scenarios and topology arrangements. Simulation results show that the proposed route switching scheme outperforms LAR and AODV protocols by achieving higher network performance in terms of overall network throughput. The proposed solution, however, require storage and computing cost to maintain the path information of all the nodes in the network and calculate routes from each source to the destination node.

In Chapter 4, we demonstrate the feasibility of an application-layer rate-adaptive multi-video stream multicast that does not require any modifications to the MAC layer and is suitable for mobile robotic platforms equipped with cameras. The transmission, video encoding, and the frame rates are adapted based on the received feedback from multiple designated nodes. Reliability is achieved by retransmissions of lost packets, resulting in fewer packet losses. The role of designated node is switched between multiple receivers to cater for mobility. The feedback of the received packets from the designated nodes is used for rate adaptation. The proposed solution is evaluated through emulation over CORE and EMANE platforms and is further validated in a testbed setup comprising NVIDIA Jetson boards. The proposed framework enables a smooth video reception and outperforms legacy multicast in terms of packet loss and video quality.

5.2 Future work

Routing in aerial networks is one of the challenges in a multi-drone system. To improve network performance through a routing protocol QoS support to gain fairness among the nodes in the network is required. Moreover, link awareness at the network layer for better connectivity can be beneficial. The protocol shall be able to estimate routes that can provide higher throughput in addition to finding routes in advance from a source to the destination node. An evaluation of the overhead cost for link aware routing and route discovery for a multi-drone network is also required to estimate the computation and storage requirements.

The multicast video streaming approach can further be improved by optimally scheduling the transmission time of multiple video streams from the ALMM-GW to the multicast recipients. Another future task to increase reliability can be through the usage of error correction codes to the payload such as the forward error correction code that can help minimize retransmissions enabling higher-quality video streams.

To address the problem of multipoint-to-multipoint video streaming, a distributed approach can also be worked out such that the drones and the receivers enable multi-hop communication and are able to maintain multiple multicast groups without the use of the ALVM-GW as a central entity.

Published work

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