

An Operational Model for Unmanned Aerial Vehicle-assisted Device-to-Device Relaying

Daniel Joseph Alapat

Delft University of Technology

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by

Daniel Joseph Alapat

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday, July 10 2026 at 10:00 AM.

Student number:	6133576	
Project duration:	November 1, 2025 – July 10, 2026	
Faculty:	Electrical Engineering, Mathematics and Computer Science (EEMCS)	
Thesis Committee:	Dr. Ir. Eric Smeitink	Thesis advisor
	Ir. Rogier Noldus	Daily Supervisor
	Dr. Ing. Edgar van Boven	Daily Co-Supervisor
	Dr. Arash Asadi	External Committee Member

Cover: AI generated, Gemini Nano Banana Pro

Abstract

In the aftermath of severe flooding, earthquakes, or warfare, the failure of ground-based cellular infrastructure often leaves affected populations and first responders without vital communications connectivity. While Unmanned Aerial Vehicles (UAVs) and 5G NR Device-to-Device (D2D) relaying offer a promising solution for rapid network restoration, a significant gap exists between terrestrial relaying standards and a functional, deployable aerial network. This thesis bridges this gap by designing a 3GPP-aligned operational model for UAV-based relaying.

By adapting mature 5G terrestrial relaying standards to the unique constraints of an aerial network, the proposed operational model introduces specific architecture enhancements to directly address the critical needs of these network-denied environments. For localised use cases through UE-to-UE (U2U) architectures, the operational model helps stranded individuals contact emergency services and supports local coordination. Additionally, for core-connected use cases through UE-to-Network (U2N) architectures, the operational model restores public network access, bridging the isolated disaster zone back to the core network.

The proposed operational model prescribes specific protocol procedures for synchronisation, discovery and connection establishment tailored for aerial networks. To overcome the high collision rates caused by standard decentralised Mode 2 protocols in high-density environments, the operational model introduces a critical architectural enhancement: UAV-governed scheduling, which leverages centralised coordination to ensure reliable out-of-coverage connectivity. Furthermore, the operational model incorporates the specific signalling exchanges required to retrieve real-time radio environment data, enabling the UAV to dynamically optimise its 3D position to maximise network throughput.

The effectiveness of the proposed operational model is systematically evaluated through system-level simulations. The simulations reveal that while standard Mode 2 resource allocation suffers from severe half-duplex and physical collisions under high network loads, the proposed UAV-governed scheduling eliminates steady-state collisions entirely. This coordination guarantees near-perfect packet delivery ratios and cuts end-to-end latency by more than half compared to the uncoordinated baseline. Ultimately, the results demonstrate that UAV-based relaying provides a highly effective 3GPP-aligned solution for rapid network restoration in an emergency scenario.

Preface

This thesis marks the completion of my Master's degree in Computer and Embedded Systems. It has been a challenging and rewarding journey, and I would like to express my sincere gratitude to everyone who supported me throughout this process. I extend my thanks to the professors, lecturers, and teaching assistants, as well as my classmates, who shared their enthusiasm and knowledge.

First and foremost, I would like to thank Dr. Ir. Eric Smeitink, Ir. Rogier Noldus, and Dr. Ing. Edgar van Boven for their invaluable guidance, encouragement, and constructive criticism. Their careful reviews continually challenged me to elevate the quality of my work and think more critically. I would especially like to acknowledge Rogier for his rigorous attention to detail, and his technical critiques were instrumental in refining my thesis. I am equally grateful to Edgar for consistently maintaining a broader perspective, encouraging me to look beyond immediate technical hurdles. Together, their supervision not only shaped this project but also deepened my enthusiasm for the field.

I also wish to express my heartfelt gratitude to my parents for their steadfast support. Their financial backing allowed me to focus entirely on my education, and their constant encouragement provided the strength I needed during the most demanding phases of my studies. I am equally grateful to my sister, who consistently checked in on me during periods of stress, reminding me that I was never navigating these challenges alone.

To my friends, thank you for your encouragement, understanding, and support. I would like to especially thank Rose Mary Francis for her unwavering patience and the push she gave me whenever I needed it most, which kept me moving forward. I also owe a great deal of thanks to Jerin Thomas and Ishaan Gupta for always being there to listen to my ideas and explanations, which made the process significantly more enjoyable.

To everyone who contributed to my success, whether academically or personally: thank you. Without you, the completion of this thesis would not have been possible.

*Daniel Joseph Alapat
Delft, July 2026*

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Nomenclature

Abbreviations

Abbreviation	Definition
3GPP	3rd Generation Partnership Project
A2X	Aircraft-to-Anything
ACK	Acknowledgement
ADC	Analogue-to-Digital Converter
ARQ	Automatic Repeat Request
B-ACK	Block Acknowledgement
BRID	Broadcast Remote Identification
BS	Base Station
BSR	Buffer Status Report
CQI	Channel Quality Indicator
D2D	Device-to-Device
DAA	Detect-and-Avoid
DAC	Digital-to-Analogue Converter
DBS	Drone Base Stations
DHCPv4	Dynamic Host Configuration Protocol version 4
DNS	Domain Name System
E2E	End-to-End
FR1	Frequency Range 1
GBR	Guaranteed Bit Rate
gNB	Next Generation NodeB
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUE	Ground User Equipment
GUI	Graphical User Interface
HD	Half-Duplex
ILP	Integer Linear Programming
IP	Internet Protocol
IUC	Inter-UE Coordination
L2	Layer 2
L3	Layer 3
LoS	Line-of-Sight
LTE	Long-Term Evolution
MAC	Medium Access Control
MC	Mission-Critical
MCS	Modulation and Coding Scheme
MSISDN	Mobile Station International Subscriber Directory Number (Mobile Number)
NACK	Negative Acknowledgement
NAS	Non-Access-Stratum
NIB	Network-in-a-Box
NR	New Radio
NTN	Non-Terrestrial Network
OoB	Out-of-Band
P2P	Peer-to-Peer
PC5	Reference point for Sidelink D2D communication

Abbreviation	Definition
PDR	Packet Delivery Ratio
PDU	Protocol Data Unit
PER	Packet Error Rate
PLMN	Public Land Mobile Network
PRB	Physical Resource Block
ProSe	Proximity Services
PSCCH	Physical Sidelink Control Channel
QoS	Quality of Service
RF	Radio Frequency
RLC	Radio Link Control
RRA	Radio Resource Allocation
RRC	Radio Resource Control
RSC	Relay Service Code
RSRP	Reference Signal Received Power
SCI	Sidelink Control Information
SDAP	Service Data Adaptation Protocol
SL-DRB	Sidelink Data Radio Bearers
SLPP	Sidelink Positioning Protocol
SL-SRB	Sidelink Signalling Radio Bearers
SLSS	Sidelink Synchronisation Signal
SMS	Short Message Service
SN	Sequence Number
SNIR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SRAP	Sidelink Relay Adaptation Protocol
S-RSRP	Sidelink Reference Signal Received Power
S-RSSI	Sidelink Received Signal Strength Indicator
STP	Successful Transmission Probability
TDD	Time-Division Duplexing
TR	Technical Reports
TS	Technical Specification
U2N	UE-to-Network
U2U	UE-to-UE
UAV	Unmanned Aerial Vehicle
UE	User Equipment
Uu	Reference point for standard cellular communication
V2X	Vehicle-to-Everything
VoIP	Voice over Internet Protocol

1

Introduction

In modern society, cellular mobile connectivity is essential for safety and coordination. Whether managing a rescue operation or providing updates to loved ones, communication is a critical service. This seamless experience relies on critical infrastructure, specifically cellular base stations, which are frequently compromised during disasters, leaving the affected population and first responders stranded. This loss of service typically results either from the exhaustion of backup power after a grid outage or from direct physical damage to the base station itself. Current rapid-response solutions are slow to deploy or impractical (as detailed in Section 1.1), underscoring the need for autonomous, rapidly deployable alternatives to address gaps in the failed infrastructure [1].

To strengthen the robustness of the communication network during such outages, modern cellular architectures must integrate alternative, highly resilient technologies to enable rapid network restoration. This is where Device-to-Device (D2D) communication emerges as a vital technology, enabling User Equipment (UE) to communicate directly with one another, bypassing traditional base stations and the core network. It was initially introduced by 3GPP in Release 12 (2015) [2] as Proximity Services (ProSe) for LTE, primarily to enhance public safety applications. This direct communication is facilitated by the PC5 reference point, commonly referred to as Sidelink. Today, this Sidelink-based D2D communication enables a wide range of applications, including local content sharing, Vehicle-to-Everything (V2X) and Mission-Critical (MC) services.

D2D technology provides the basis for extending network reach through relaying, a recognised use case for bridging coverage gaps and enhancing signal quality. Relaying was standardised in 5G New Radio (NR) by 3GPP in Release 17 (2022) [3] with UE-to-Network (U2N) relays and further in Release 18 (2024) [4] with UE-to-UE (U2U) relays. A U2N relay is a UE connected to the cellular network that plays the role of a gateway for remote UEs outside the network's coverage area, which connect to the relay via D2D communication. In contrast, a U2U relay facilitates direct local communication by acting as a bridge between multiple UEs connected through D2D communication, independent of network connectivity.

To rapidly establish a localised temporary network in an emergency, the concept of relaying becomes indispensable. While 3GPP standards define the functional mechanics of relaying, the effectiveness of a temporary network depends heavily on the placement of the relay node. Without a relay positioned at the right location to bridge the coverage gap, the temporary network is ineffective for isolated users. This is where Unmanned Aerial Vehicles (UAVs) offer a transformative solution. Their agility, speed of deployment, and ability to operate above physical obstacles allow them to reach areas that are otherwise inaccessible. By integrating a relay function onto a UAV, it can be flown directly over a network-denied area to establish a vital communication link.

While the integration of UAVs and D2D relaying offers immense potential for rapid communication restoration, a significant gap exists between theoretical utility and practical, 3GPP-aligned implementation. The 3GPP standards provide a comprehensive and mature framework for terrestrial relaying,

defining robust procedures for direct discovery, link establishment, security mechanisms, synchronisation, and resource allocation. Although 3GPP specifications define the functional architecture for Sidelink relays, they remain broad foundational protocols designed primarily for ground-based applications. The existing standards provide a broad toolbox of potential configurations rather than a prescriptive solution. Moreover, certain mechanisms, such as resource allocation, are not optimised for the specific requirements of aerial emergency networks. Without a concrete operational model to bridge these gaps, the concept of a UAV relay remains a theoretical proposition rather than a deployable reality.

Beyond the protocol architecture, the effectiveness of an aerial relay is fundamentally determined by its physical position in three-dimensional space. Unlike fixed terrestrial base stations, a UAV relay possesses the unique capability to autonomously adjust its location to improve the communication link. Simply deploying a drone into a disaster zone is insufficient. It must be positioned at a location that maximises signal quality and throughput for the ground users. This necessitates an integrated approach where the network logic actively utilises real-time radio environment data, rather than solely managing the connection lifecycle. By incorporating positioning signalling directly into the operational model, the relay can dynamically optimise its location and ensure peak operational efficiency.

This thesis aims to bridge the gap between theoretical potential and practical deployment by designing a 3GPP-aligned operational model for UAV-based relaying. Moving beyond high-level architecture, this research prescribes specific protocol choices tailored for disaster scenarios, adapting mature ground-relay standards to the unique constraints of aerial platforms. Furthermore, the research incorporates signalling exchanges to retrieve the radio environment data required by an autonomous positioning algorithm, enabling the UAV to dynamically optimise its location for maximum network performance. Finally, by introducing a novel, UAV-governed resource allocation strategy specifically designed for an emergency aerial relay use case, this model transitions the concept from a theoretical abstraction into a functional, 3GPP-aligned network solution.

1.1. Motivation

In the immediate aftermath of a disaster, communication is a fundamental necessity for survival and coordination. Rescue efforts and public safety depend on the exchange of information between first responders and the affected population. However, traditional ground-based cellular base stations are highly vulnerable to physical damage and power failures during a crisis. This vulnerability often results in a critical communication gap at the moment when connectivity is most vital. This is illustrated in Figure 1.1, where ground users (UE_1 and UE_2) are cut off from the emergency services.

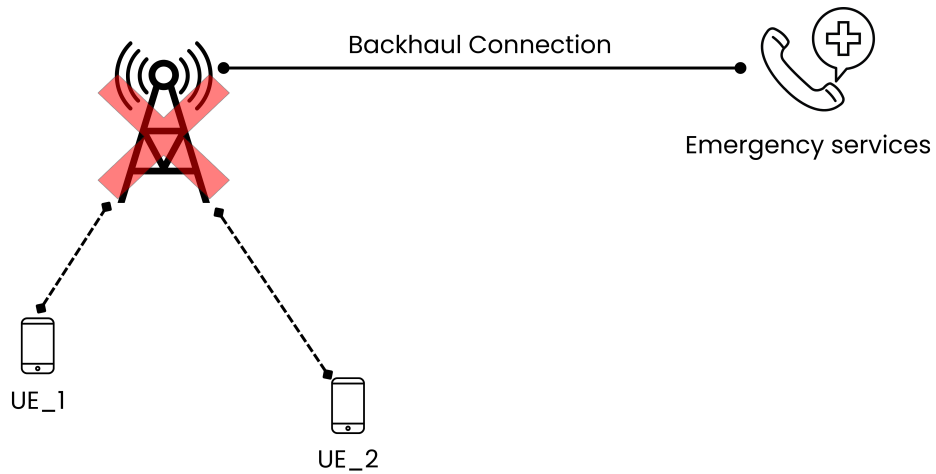


Figure 1.1: The disabled base station leaves UE_1 and UE_2 isolated from the emergency services.

While rapid-response solutions exist, they have significant drawbacks that limit their effectiveness in a disaster scenario. One common alternative is satellite connectivity. While satellite links are independent of local ground infrastructure, they have historically required specialised hardware or modified mobile phones, making them inaccessible to the general population that possesses only standard commercial mobile phones. Although satellite-enabled hardware has emerged in modern smartphones, these services remain limited to specific models. Furthermore, emerging Non-Terrestrial Network (NTN) technologies that enable standard mobile phones to communicate directly with satellites via 3GPP protocols face significant challenges, including high latency, limited bandwidth, and substantial operational costs.

Another common alternative is a Network-in-a-Box (NIB), in which a complete 5G network, including a portable gNB (5G base station) and core network, is deployed to provide full functionality. However, these solutions face immense logistical hurdles, requiring heavy transportation and specialised personnel for setting up, which often results in slow deployment. Furthermore, hosting a full core network is often overkill for an emergency scenario, where basic communication is the primary requirement. The energy-intensive processing required for backhaul, authentication, and mobility management consumes excessive power and generates significant signalling overhead.

D2D relaying via 3GPP Sidelink offers a lightweight, transformative solution. Unlike standard cellular communication (Uu reference point), which requires constant coordination with a central base station and a complex core network, Sidelink is designed for direct, decentralised data exchange, which significantly reduces signalling overhead and power consumption. By integrating this relay function onto a UAV, the system gains the agility and speed of deployment necessary to establish a connection in a network-denied area. Because the model is 3GPP-aligned, it will work with all standard commercial UEs, ensuring immediate accessibility for the general population without requiring hardware modifications.

Furthermore, 3GPP D2D offers distinct advantages over other wireless technologies, such as Bluetooth and Wi-Fi Direct. Utilising licensed cellular frequencies provides significantly less interference, higher bandwidth, and better propagation properties than the crowded unlicensed spectrum used by Bluetooth or Wi-Fi Direct, allowing for superior range and building penetration. Additionally, the use of 3GPP message integrity checks and authentication procedures ensures mutual authentication and prevents unauthorised node spoofing, which is not natively guaranteed by other short-range wireless technologies.

1.2. Research Gap

While 3GPP TS's define the architectural requirements and procedures for Sidelink and UE relaying, these standardised protocols are primarily designed for terrestrial, D2D scenarios and lack explicit provisions for aerial relaying. Consequently, the existing literature lacks a 3GPP-aligned operational model that simultaneously addresses the unique signalling and resource management challenges posed by a dynamic UAV platform.

A significant portion of the existing literature on UAV-assisted networks focuses predominantly on performance maximisation through trajectory design and resource allocation, often abstracting the underlying communication protocols into generic mathematical models. Extensive research has been dedicated to optimising UAV placement [5, 6, 7, 8, 9], 3D trajectories [10, 11, 12, 13, 14] and transmission power [12, 13, 15, 16, 17, 18, 19, 20] to maximise network throughput. While these contributions are vital for understanding theoretical performance bounds, they often treat the communication link as a protocol-agnostic data pipe. Such models frequently assume that the real-time data required for such optimisation is readily available, without considering the practical signalling procedures required to acquire it.

Conversely, studies that explicitly position UAV relaying within the context of D2D often limit their scope to high-level architectural requirements without addressing the functional mechanics of the 3GPP protocol stack [21]. These papers [22, 23, 24, 1] cite 3GPP releases to validate the feasibility of UAV-

based relays, acknowledging that standards for Sidelink and relaying exist, but treat the 3GPP specifications as a static backdrop rather than an operational blueprint. In conclusion, much of the current literature on this application fails to address the practical implementations of 3GPP-aligned procedures for the unique constraints of UAV-assisted relays.

1.3. Research Goal

While existing 3GPP standards provide the fundamental protocols for relaying, these standards do not account for aerial relays. The primary goal of this thesis is to design an operational model for UAV-based relaying using 3GPP-aligned D2D communication. To achieve this, the research adapts and extends standard 3GPP relay procedures to address the unique constraints of UAVs deployed in emergency scenarios. A major focus is placed on establishing connectivity in the absence of fixed terrestrial infrastructure and the development of an optimised, UAV-governed resource allocation strategy for the PC5 reference point. Within the proposed operational model, signalling is explicitly integrated to facilitate an autonomous positioning algorithm, providing the necessary radio environment data for the UAV to determine its optimal location dynamically. Finally, the research aims to validate this model through a system-level simulation, evaluating the performance of the operational model and its specific protocol enhancements in network-denied areas.

1.4. Research Questions

In order to achieve the research goal described in Section 1.3, the research questions are formulated as follows:

1. **RQ1:** To what extent are the current 3GPP specifications for terrestrial relays suitable for the specific requirement of aerial relaying?
2. **RQ2:** What needs to be added to the 3GPP standards to fulfil the requirements of an operational model for UAV-assisted relaying based on device-to-device communication?
3. **RQ3:** What resource allocation strategy can be designed to maximise throughput and mitigate collisions within this aerial relay architecture?
4. **RQ4:** What specific signalling exchanges are required within the operational model to provide the radio environment data necessary for a positioning algorithm to dynamically optimise the UAV's three-dimensional location?
5. **RQ5:** How does the proposed 3GPP-aligned model, inclusive of the resource allocation strategy and signalling support for UAV positioning, perform when evaluated through system-level simulation?

1.5. Methodology

The research methodology is centred on bridging the gap between 3GPP standards and a functional aerial relay system through rigorous, systematic evaluation and architectural design. The foundation of this work involves a rigorous analysis of 3GPP TSs, with a focus on NR Sidelink, UE-to-UE, and UE-to-Network relaying. To ensure a holistic understanding of the system, the operational model is decomposed into the underlying constituent stages. By evaluating each stage individually from the specific perspective of an aerial scenario, it becomes possible to identify protocol gaps and architectural constraints that would otherwise be difficult to discern.

Building upon this analysis, the research moves toward the proposal of an operational model. A central component of this design is the development of a novel resource allocation strategy and the necessary signalling required to retrieve real-time radio environment data. Unlike standard terrestrial implementations, this approach focuses on enabling the UAV to act as an autonomous coordinator for the Sidelink interface in an out-of-coverage environment. The final phase of the methodology involves validating the proposed model through system-level simulations and a detailed analysis of the resulting performance data. Using a custom discrete-event simulator developed in Python, the performance of the integrated model is evaluated across various scenarios. This quantitative evaluation ensures that

the prescriptive protocol choices and resource allocation strategies effectively meet the requirements of a rapidly deployable, 3GPP-aligned network solution.

1.6. Thesis Structure

The remainder of this thesis is organised as follows:

Chapter 2 establishes the theoretical foundation by reviewing current literature on aerial relaying and analysing the relevant 3GPP Technical Specifications (TS). This chapter further defines the system architecture and describes the specific operational context for UAV-based relaying.

Chapter 3 presents the core contributions of this thesis, detailing the proposed operational model for the U2U and U2N relay architectures. It describes the specific protocol adaptations for synchronisation, discovery, and connection establishment, as well as the design of the UAV-governed resource allocation strategy and the signalling exchanges for autonomous positioning.

Chapter 4 is dedicated to the evaluation of the proposed model. It introduces the custom discrete-event simulation environment developed in Python, defines the evaluation metrics, and establishes baseline comparisons. This is followed by an analysis of the simulation results, assessing the performance of the operational model, resource allocation strategy, and positioning signalling under various test conditions.

Chapter 5 concludes the thesis by summarising the research findings and outlining recommendations for future work.

2

State of the Art

This chapter establishes the theoretical and technical foundation of the thesis by analysing existing research and industry standards. The first section presents a systematic review of academic literature focusing on peer-reviewed papers from reputable sources published from 2015 to the present. In addition to academic research, this chapter provides a rigorous analysis of the latest 3GPP TS retrieved from the official 3GPP portal [25], utilising the current documentation up to Release 19 [26]. By evaluating the state-of-the-art in both theory and standardisation, the chapter identifies the technical gaps addressed in this work. Finally, the chapter defines the proposed system architecture for UAV-assisted D2D relaying in network-denied environments and outlines the assumptions that govern the operational model.

2.1. Related Work

The deployment of UAV-assisted relay networks has emerged as a transformative solution to restore connectivity after a disaster. Several studies have explored different architectural approaches to this challenge. Saif et al. [21] propose a post-disaster coverage extension model that employs a single static UAV acting as an aerial base station. The system utilises D2D communication to connect with ground user devices located at the edge of the UAV's coverage, which serve as optimal relays to forward signals to out-of-coverage users. However, while the authors discuss D2D communication, they do not frame the implementation within specific 3GPP standards. Building on the concept of aerial management, Alsharoa et al. [22] propose 'UAV-Direct,' a framework where a single UAV functions as an aerial base station responsible for resource allocation for existing D2D UE pairs, while also acting as a relay for ground users located outside direct D2D range. Although the authors motivate the work using LTE-Direct (ProSe) concepts, the proposed high-level management protocol relies on custom signalling frames rather than adhering to the specific 3GPP D2D standard specifications. This work was subsequently extended to a multi-UAV architecture [23], where the authors shift the optimisation objective from maximising minimum throughput to maximising the system's energy efficiency, incorporating constraints related to UAV battery consumption and charging requirements.

Other models address specific disaster response constraints, such as multi-hop routing and damage assessment. Ghosh et al. [24] propose a multi-hop D2D relaying framework designed to bridge communication between separated disaster zones using a dual-UAV relay chain. Notably, this approach defines a custom time-frame format for signalling rather than utilising standard 3GPP structures and integrates energy transfer to support intermediate ground relays. Similarly, Rani et al. [1] introduce a sensor-aided model where the UAV performs real-time damage assessment to identify communication "blackspots". Based on sensory feedback, the algorithm autonomously adjusts routing to adapt to the changing environment.

The Backhaul connection between the drone and the core network poses a challenge in UE-to-Network scenarios. Addressing this challenge, Ansari et al. [27] propose SoarNet, a model that utilises

Free Space Optics (FSO) to establish the backhaul link for aerial Drone Base Stations (DBS). This approach solves the dual challenges of data rate and endurance, as laser beams provide high-speed data transmission while simultaneously transferring energy to prolong the drone's flight duration. This is accomplished by utilising an airborne solar panel array to convert the optical beam into electrical power. Complementing this, Banagar et al. [28] develop a stochastic-geometry framework for 3D two-hop cellular networks with wirelessly backhauled UAVs. They address the weak backhaul links due to the down-tilted antennas by proposing the addition of a directional up-tilted antenna at the BS and derive exact coverage probability expressions using realistic 3GPP antenna models. The overview of the Literature analysis is provided in Table A.1 in Appendix A.

2.1.1. Position, Trajectory and Transmit Power Optimisation Literature

The physical positioning of a UAV is a critical determinant of network performance. Unlike fixed terrestrial infrastructure, UAVs possess the unique capability to dynamically adjust their three-dimensional coordinates to mitigate channel impairments and maximise coverage. The performance benefits of such mobility are demonstrated by Firozjae et al. [9], who compare static relaying with mobile trajectories and conclude that dynamic placements yield superior results by reducing the average transmission distance to ground users. Extensive research has focused on formulating this as a mathematical optimisation problem to maximise specific network metrics. These papers have been analysed to identify the specific parameters required as input to the UAV positioning algorithm, which are incorporated as signalling exchanges within the proposed operational model.

While many models utilise classical optimisation frameworks, such as the model proposed by Bor-Yaliniz et al. [6], which uses quadratically constrained mixed-integer programming or Sabzehali et al. [8], which employs Integer Linear Programming (ILP) to optimise the number of deployed drones, others have introduced unique constraints. For instance, Pourbaba et al. [10] optimise for full-duplex relaying in vehicular environments, while Ji et al. [11] jointly optimise flight paths with local cache placements to protect the network against eavesdropping. In contrast, Barik et al. [14] take a predictive approach, determining trajectories based on machine-learning-driven forecasts of user demand rather than real-time channel feedback. Collectively, these studies establish the mathematical foundation for UAV placement.

Beyond the relay's physical placement, transmit power management is essential to reduce co-channel interference. To address this, Wang et al. [18] propose a successive convex algorithm to carry out transmission power planning alongside trajectory design, ensuring that the sum throughput is maximised while respecting the power budgets of the UAV and D2D pairs. Similarly, Monemi et al. [15] formulate a hierarchical mixed-integer-non-linear-programming problem to minimise the total transmit power of all the users while maintaining strict reliability and capacity requirements for the cellular network.

While these studies highlight the importance of power control for spectral efficiency, the dynamic optimisation of transmit power is not the focus of this work. Instead, this thesis concentrates on a UAV-governed resource allocation strategy to reduce interference. This is achieved by coordinating the time-frequency resources and implementing collision-avoidance scheduling to minimise resource overlap among users. A summary of these papers and their specific optimisation methods is provided in Table 2.1.

2.1.2. Radio Resource Allocation Literature

The efficiency of D2D communication depends heavily on the underlying radio resource allocation (RRA) strategy [29]. The NR Sidelink Mode 2 framework serves as the primary RRA mode for out-of-coverage scenarios, in which UEs independently sense and select subchannels from a common resource pool. While this decentralised approach is designed for flexibility, the evaluation by Ali et al. [29] demonstrates significant performance degradation in high-density environments due to increased collision rates. Furthermore, Annu et al. [30] identify "collision and half-duplex problems" as primary hurdles in the standardised RRA, while Wang et al. [31] emphasise that relying on distributed sensing

Table 2.1: Overview of Mathematical Position, Trajectory and Transmit Power Optimisation Literature.

Authors and Reference	Optimisation Method
Yang et al. [5]	Particle Swarm Optimization (PSO)
Bor-Yaliniz et al. [6]	Quadratically-constrained mixed integer non-linear optimization
Pourbaba et al. [10]	Non-convex/Convex approximation
Selim et al. [7]	Joint Energy and 2D Position Optimization
Ji et al. [11]	Block alternating descend and successive convex approximation
Zhang et al. [12]	Closed-form joint trajectory design and power control
Sabzehali et al. [8]	Integer Linear Programming (ILP)
Firozjae et al. [9]	Stochastic Geometry and Successful Transmission Probability (STP) analysis
Zeng et al. [13]	Iterative Successive Convex Optimization
Barik et al. [14]	Neural Networks
Monemi et al. [15]	mixed-integer-nonlinear-programming (MINLP)
Nguyen et al. [16]	Fractional Programming
Tatar Mamaghani et al. [17]	Elevation-angle dependent parameter analysis
Wang et al. [18]	Difference of Two Convex functions programming
Wang et al. [19]	Difference of Two Convex functions programming
Deng et al. [20]	DA-STD3 deep reinforcement learning

schemes without a centralised coordinator often leads to sub-optimal throughput and high latency.

To mitigate these limitations, recent research has explored leveraging UAVs as intelligent coordinators to restore centralised management in the absence of a gNB. Conserva et al. [32] provide a thorough analysis of radio resource assignment for UAV-enhanced Sidelink, building on which Conserva et al. [33] develop a mathematical framework for UAV-aided communication that moves beyond simple snapshot assumptions to capture the temporal coupling of resource selection, allowing for more realistic throughput evaluations. Additionally, You et al. [34] expand the scope of coordination by proposing a strategy that incorporates energy harvesting and task offloading, while Dong et al. [35] propose the use of radio maps to manage frequency assignment based on the topology.

The complexity of these RRA strategies increases when moving towards multi-UAV relay networks. Zhong et al. [36] address this complexity by jointly optimising relay deployment, channel allocation and relay assignment to maximise total network capacity. Recognising the lack of a central controller in self-organised D2D networks, the authors propose a decentralised alternating optimisation approach and a model-free online learning algorithm. The trend towards holistic management is further exemplified by Pan et al. [37], who formulate a multi-objective optimisation problem to simultaneously address UAV deployment, 3D positioning, transmit power, flight velocity and channel assignment. The study highlights the trade-offs between maximising network capacity and minimising the number of UAVs and their energy consumption.

2.2. 3GPP Standardisation

The Third Generation Partnership Project (3GPP) is a global collaboration that defines the protocols, interfaces and procedures that underpin modern cellular communication systems. The organisation coordinates and produces a suite of Technical Specifications (TS) and Technical Reports (TR), which specify end-to-end architectures, radio interfaces, core network functions and service-layer requirements that ensure interoperability across devices and operators worldwide.

As part of this effort, 3GPP has defined Device-to-Device (D2D) communication (originally introduced in LTE as Proximity Services (ProSe) and later extended to 5G as NR Sidelink), which enables two UEs to communicate directly over the PC5 reference point without traversing the traditional network infrastructure. Building on this D2D foundation, 3GPP has standardised relay operations for both UE-to-UE (3GPP TS 23.304 Clause 6.7 [38]) and UE-to-Network (3GPP TS 23.304 Clause 6.5 [38]) architectures. These applications are extensively specified within the standards, covering fundamental functions such as direct discovery (3GPP TS 23.304 Clause 5.2 [38]), link establishment (3GPP TS

38.331 Clause 5.8 [39]) and security mechanisms (3GPP TS 33.303 [40]).

Beyond general relay capabilities, 3GPP has introduced several UAV-specific A2X (Aircraft-to-Anything) applications that utilise the PC5 reference point. Two notable examples are Broadcast Remote Identification (BRID) and Detect-and-Avoid (DAA) (3GPP TS 23.256 [41]). BRID enables a UAV to periodically broadcast its identification information, allowing nearby devices or authorities to determine its status. DAA supports information exchange that enables UAVs to detect potential conflicts and take avoidance actions. In both cases, 3GPP provides the communication support via PC5 but does not define the detailed application payloads themselves, which are governed by external aviation regulatory bodies. Given the growing role of UAVs in public safety and disaster response, there is increasing interest in how UAVs might leverage existing 3GPP relay mechanisms. Defining such an operational model, similar to how BRID and DAA were mapped onto PC5, could support future deployments in which UAVs help maintain connectivity in infrastructure-limited environments.

2.2.1. Technical Specification Analysis

To understand how existing 3GPP capabilities can be applied to UAV-based relay operations, a set of relevant 3GPP TSs was identified and analysed. These specifications provide the formal definitions of Sidelink communications and relay procedures. The overview of the 3GPP TS analysis is provided in Table B.1 in Appendix B. The following summaries highlight the core documents that form the basis of the proposed operational model.

1. **3GPP TS 23.303 [42]:** Establishes the architectural baseline for ProSe within the LTE framework. It defines the fundamental mechanisms for Direct Discovery and communication over the PC5 reference point, detailing the discovery modes that allow devices to identify one another. It also introduces the protocol stacks required for UE-to-Network relaying to extend connectivity to out-of-coverage devices.
2. **3GPP TS 23.304 [38]:** Specifies the system architecture for ProSe services within the 5G system. This document is central to this thesis as it defines the 5G architectures for both UE-to-Network and UE-to-UE relays. It details the distinctions between Layer-2 and Layer-3 relaying models, as well as the mechanisms for relay selection, authorisation and Quality of Service (QoS).

2.3. System Architecture

The proposed system is designed for operation in network-denied environments, such as disaster-stricken areas or conflict zones. In these scenarios, terrestrial base stations (gNBs) are either destroyed or rendered inoperable, leaving a population of Ground User Equipment (GUEs) without cellular connectivity. Upon the failure of traditional terrestrial infrastructure, a D2D-enabled UAV is deployed to the location of the failed site to function as an aerial relay node. By utilising the Sidelink interface, the UAV effectively restores local connectivity and bridges the gap between stranded users. Consistent with the architecture defined in the 3GPP Technical Specifications (3GPP TS 23.303[42] and 3GPP TS 23.304[38]), this thesis focuses on two primary relaying solutions:

1. **UE-to-UE Relay:** The UAV facilitates direct communication between multiple GUEs that are within the UAV's coverage area (Figure 2.2).
2. **UE-to-Network Relay:** The UAV acts as a bridge between out-of-coverage GUEs and a distant operational gNB, thereby providing backhaul connectivity (Figure 2.3).

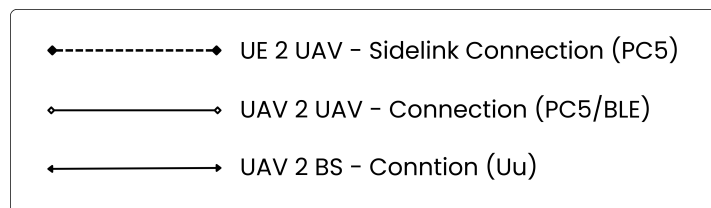


Figure 2.1: Annotation for interfaces.

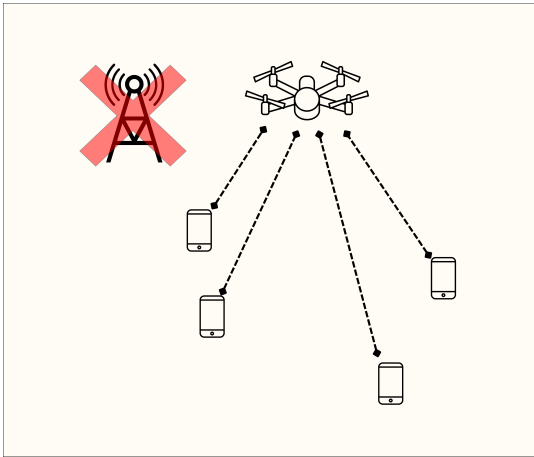


Figure 2.2: Single UAV UE-to-UE relay.

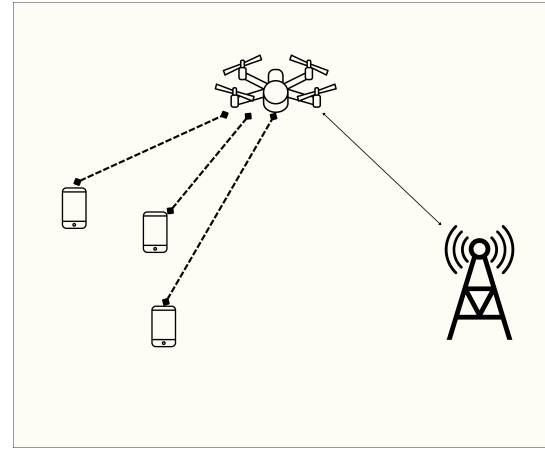


Figure 2.3: Single UAV UE-to-Network Relay.

While this thesis focuses on a single-UAV architecture, the architecture can be further extended to multi-UAV configurations. In such systems, multiple UAVs coordinate to form a relay chain or distributed mesh, significantly expanding the coverage area for both U2U (Figure 2.4) and U2N (Figure 2.5) services.

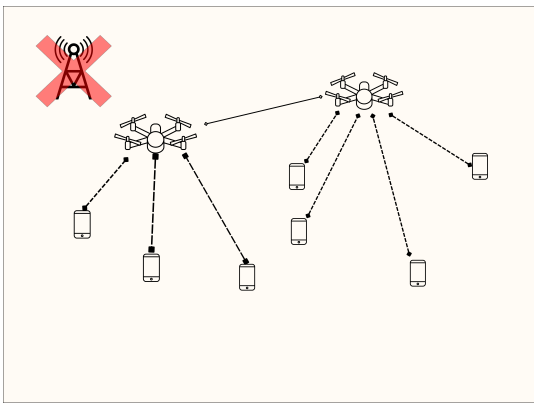


Figure 2.4: Multi-UAV UE-to-UE relay.

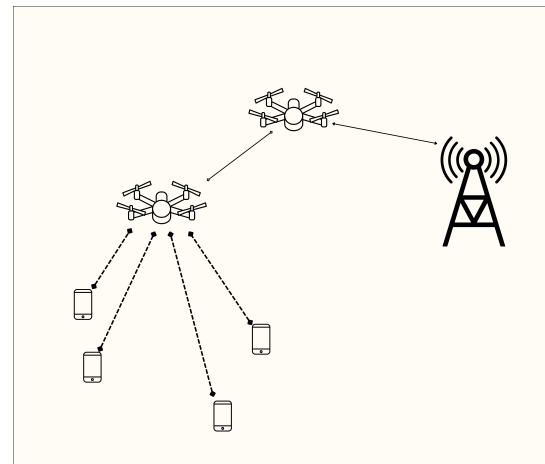


Figure 2.5: Multi-UAV UE-to-Network relay.

2.4. System Assumptions

The following assumptions define the scope and operational boundaries of the proposed architecture:

1. **UAV-Centric Connectivity:** Ground users are assumed to establish connections exclusively through the UAV relay. Direct peer-to-peer communication between ground users without the UAV's mediation is outside the scope of this model.
2. **5G NR Exclusive:** The proposed scenarios are designed exclusively around 5G New Radio specifications. Backward compatibility or integration with legacy generations, such as 4G LTE ProSe, is not evaluated.
3. **Closed Network Topology:** The operational environment is modelled as a strictly isolated system consisting only of the designated GUEs and the serving UAV. The presence of, or interference from, external third-party devices or overlapping adjacent networks is not considered.
4. **Protocol-Compliant Equipment:** All participating devices are assumed to be fully capable and provisioned with the requisite software. It is assumed that network operators have successfully deployed the necessary protocol stack updates to all devices.

2.5. Use Cases

The practical utility of a UAV-based relay system becomes evident when traditional terrestrial infrastructure is entirely absent. By supporting both U2U and U2N scenarios, the system addresses distinct operational needs ranging from localised survival coordination to backhaul connectivity. The primary use cases for such architectures include the following:

1. **Emergency Service Contact:** Allowing stranded individuals to reach first responders localised within the disaster zone via direct U2U routing, or utilising a U2N link to route emergency calls to dispatch centres.
2. **Local Coordination and Updates:** Enabling nearby users to confirm each other's safety and coordinate evacuation efforts via U2U relay.
3. **Communication and Internet Access:** Providing affected populations with a bridge to the functioning cellular network via a U2N relay, allowing them to contact family outside the disaster zone, and access the internet.
4. **Information Gathering:** Providing a data link for automated location updates and status monitoring of affected persons.

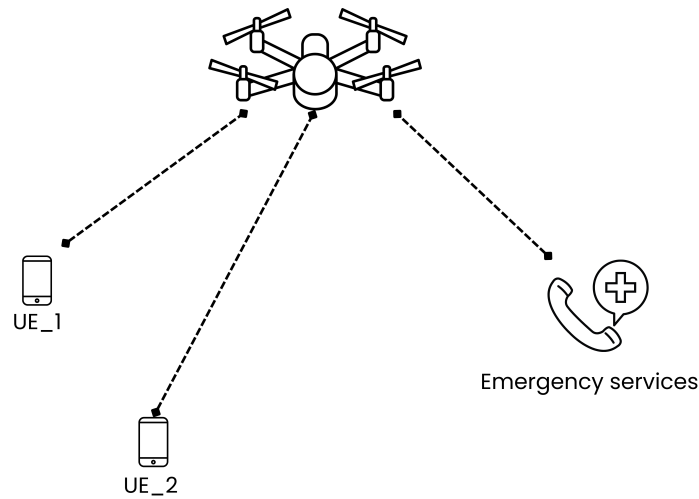


Figure 2.6: Illustration of the localised connectivity provided by the UAV relay, facilitating communication between stranded users (UE_1 , UE_2) and emergency services.

2.5.1. U2U Relay: Flood Response illustrative case

To illustrate the deployment of this system, consider a severe flooding event in the Alblasserwaard polder in South Holland. In this scenario, the primary base stations are rendered non-functional due to physical water damage or power failure. Although some surrounding base stations remain active, they are geographically too distant to provide coverage to users within the flooded zone. In response to the crisis, the emergency services deploy a D2D-enabled UAV as a U2U relay to the area. Simultaneously, an emergency response team is deployed to the area by boat, equipped with mobile devices capable of connecting to the UAV (represented as 'Emergency services' in Figure 2.6).

Residents trapped on the upper floors of their homes, unable to escape the rising water, attempt to call 112, the emergency number (denoted UE_1 in Figure 2.6). Because both the trapped residents and the rescue boat are connected to the same UAV-governed PC5 network, emergency calls are routed to personnel on the boat, enabling immediate coordination and extraction. Within the same neighbourhood, an elderly couple living down the street from their children can utilise the relay to establish a voice call (communicating as UE_1 and UE_2 in Figure 2.6). Even though the public network is down, the UAV facilitates direct communication between their devices, allowing them to reassure each other about their safety and coordinate their immediate needs. The system also supports proactive rescue efforts. For instance, if a person is unconscious, their mobile device, having automatically connected to

the UAV upon receiving the UAV relay's discovery announcement, continues to send periodic location updates (see Section 3.1.7 for details of the mechanism). If emergency dispatchers observe that a device is active, but the user is not responding to incoming calls, they can initiate a targeted search-and-rescue operation at those coordinates. As demonstrated in this application example, the proposed U2U architecture effectively addresses the three localised use cases.

2.5.2. U2N Relay: Earthquake Response illustrative case

To illustrate the deployment of a U2N UAV relay, consider a severe earthquake in the Apennine Mountains of central Italy that physically destroys the cellular base stations in a town like Amatrice. While a base station situated in an unaffected neighbouring valley remains fully operational, the mountainous terrain and sheer distance prevent ground users in the disaster zone from establishing a direct Uu connection. Because repairing the destroyed ground infrastructure in such terrain will take a considerable amount of time, the affected population is left entirely without external connectivity.

In response, a UAV is deployed over the town to act as an aerial U2N relay. Due to its elevated altitude, the UAV can see over the geographic obstructions, establishing a Line-of-Sight (LoS) backhaul connection to the distant gNB while simultaneously providing localised Sidelink coverage to the stranded users below. Unlike the U2U scenario, this relay bridges the ground users directly back into the cellular core network. This provides the affected population with internet access, voice calls and SMS services that would otherwise be unavailable.

The stranded residents can initiate voice calls or route messages to family members outside the disaster zone to confirm their safety. Simultaneously, local responders can utilise the U2N connection to coordinate rescue efforts with national command centres.

2.6. Frequency Spectrum

According to 3GPP TS 38.101-1 clause 5.2E [43], NR Sidelink communications are allocated specific operating bands within Frequency Range 1 (FR1), namely n14 (788–798 MHz), n38 (2570–2620 MHz), n79 (4400–5000 MHz) and n47 (5855–5925 MHz). The distribution of these designated Sidelink bands across the broader radio spectrum is visualised in Figure 2.7. While the n38, n47 and n79 bands provide higher frequencies suitable for localised, high-bandwidth services, band n14 holds particular significance for emergency response networks.

The 3GPP standards explicitly designate the n14 band for public safety services, supporting both in-coverage and out-of-coverage Sidelink operations. Because the primary objective of the proposed UAV relay operational model is to restore life-saving connectivity and coordinate first responders during critical disaster scenarios, this application aligns with the public safety classification. Consequently, the n14 band serves as the ideal candidate for this architecture. Utilising this lower-frequency 700 MHz spectrum is highly advantageous for an aerial relay, as its superior propagation characteristics and building penetration capabilities maximise the effective coverage footprint for stranded users in heavily obstructed environments.

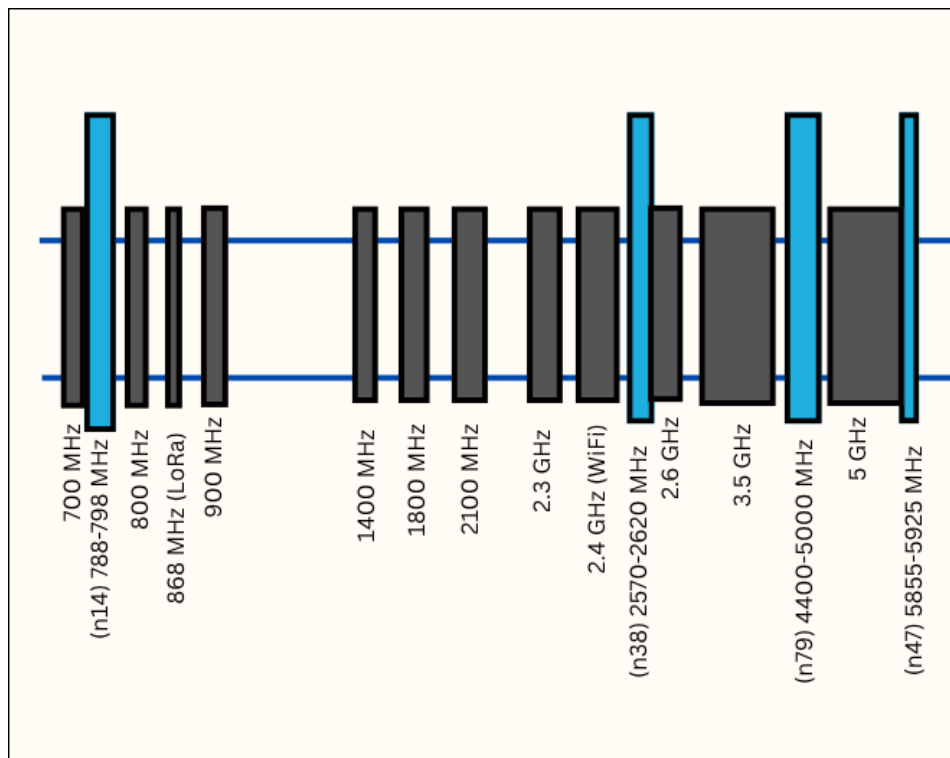


Figure 2.7: Distribution of 3GPP FR1 operating bands designated for Sidelink communication

3

Operational Model

The primary objective of this chapter is to present the proposed 3GPP-aligned operational model for UAV-based relaying. This chapter describes specific protocol choices and architectural enhancements to adapt existing 3GPP terrestrial relay standards for network-denied emergency scenarios. To ensure a systematic evaluation, the operational model is divided into two primary sections: the UE-to-UE (U2U) Architecture and the UE-to-Network (U2N) Architecture.

3.1. UE-to-UE Relay Operational Model

In the U2U relay architecture, the UAV functions as a centralised bridge for Ground User Equipment (GUEs) within its coverage area, operating independently of any terrestrial network connectivity. This section breaks down the operational model into discrete stages. For most stages, the relevant 3GPP standards are first analysed, followed by their application to the aerial relay use case and the proposal of specific protocol modifications.

3.1.1. Stage 1: Pre-provisioning

The pre-provisioning stage encompasses the essential parameters and authorisations that must be established for both the UAV and the GUEs before a disaster occurs. This stage is critical because, in a network-denied environment, nodes cannot retrieve configuration data or request authorisation from the central core network. Parameters must be provisioned while the GUEs are still connected to a functional network to ensure a seamless transition to the D2D relay system upon terrestrial infrastructure failure. These requirements are categorised into UAV-specific operational preparations and cellular-specific protocol configurations.

UAV Authorisation and Compliance

Before deployment of the relay system, the UAV must be provisioned with the necessary flight authorisations and clearances from the relevant local aviation authorities to operate within the designated emergency airspace. This is especially important if the relay system is being deployed in response to a network-denied scenario caused by warfare, as an unauthorised drone can be perceived as a threat.

D2D Sidelink Capability Enabling

Although modern commercial mobile devices are physically capable of direct communication, cellular operators often disable D2D features due to a lack of widespread consumer applications. For the proposed operational model to be effective, operators must ensure that NR Sidelink Services and the PC5 reference point are enabled in the software of the GUEs. This enables the GUE to automatically initiate D2D relay discovery scanning as soon as its cellular network connection is lost.

Out-of-Coverage Resource Pool configuration

Because the system operates in an out-of-coverage scenario, GUEs cannot rely on a base station for real-time resource scheduling. Consequently, GUEs must be pre-provisioned with specific resource pools (defined sets of time-frequency resources) to be used in out-of-coverage conditions. These pre-configured pools ensure that all GUEs have knowledge of which resource to monitor for discovery announcements and which resource pools are valid for transmission and reception.

System Deployment

The initial deployment of the system is a manual process conducted by authorised personnel. During initialisation, the UAV is provided with the GPS coordinates of the failed gNB as its starting location. Once the UAV reaches these coordinates and establishes initial network connectivity, it begins dynamically optimising its position based on the connected GUEs to improve network performance.

3.1.2. Stage 2: Synchronisation

Synchronisation is the process by which all nodes in a wireless network establish and maintain a common timing reference. This reference is fundamental to cellular communication, as it ensures that multiple devices can accurately align their transmission and reception windows to prevent data overlap and interference. In a traditional terrestrial network, synchronisation is intrinsically managed by the gNB, which acts as a master clock to provide a consistent reference for all connected devices. However, in a decentralised D2D environment where a gNB is absent, the system must rely on an alternative common reference to ensure that the UAV and all GUEs remain temporally aligned.

Current 3GPP Sidelink Synchronisation Specifications

In out-of-coverage scenarios, 3GPP specifications mandate a decentralised framework where the Global Navigation Satellite System (GNSS) serves as the primary common timing reference. Because most modern commercial UEs are equipped with GNSS receivers, they are configured to periodically scan for satellite signals in the background. To ensure all nodes in a Sidelink cluster maintain alignment, the standard establishes a strict synchronisation hierarchy based on the quality of the timing source. According to 3GPP TS 38.331 Clause 5.8.6.2 [39], the synchronisation priority hierarchy is defined as follows:

- **Primary Priority (GNSS):** Nodes with a direct lock to a GNSS satellite act as the root timing source for the entire cluster.
- **Secondary Priority (GNSS-synced):** Nodes that do not have a direct satellite lock but are synchronised to a node with a valid GNSS reference. An indirect GNSS lock serves as the next level of timing reference.
- **Tertiary Priority (Independent):** In the event that no GNSS-based root is detectable, nodes revert to an independent mode, utilising their internal oscillators to maintain timing.

Application of Specification to Aerial Relaying

An inherent advantage of utilising a UAV as a relay node is its operating altitude, which typically ensures a clear LoS to the GNSS constellation. Unlike GUEs, which may suffer from signal masking by buildings or terrain, the UAV's elevated position allows it to maintain a stable primary-priority GNSS lock. In this scenario, the UAV serves as the timing reference for any GUE that lacks a direct GNSS signal. Under the standard 3GPP synchronisation hierarchy, these GUEs identify the UAV as a GNSS-synced reference and align their slot timing to the UAV's GNSS-derived clock, thereby maintaining temporal alignment across the cluster.

Conversely, in the event that the UAV loses satellite visibility and subsequently its GNSS-based synchronisation, the standard procedures facilitate a dynamic reselection of the timing root. The UAV will recognise that its clock has been demoted in priority and initiate a synchronisation search. If a GUE within the cluster maintains a valid GNSS signal, the UAV will synchronise to that GUE. This ensures that the relay system remains anchored to the most accurate clock available, even when the UAV loses

direct satellite visibility.

A critical vulnerability arises in the highly unlikely event that neither the UAV nor any of the connected GUEs can acquire a GNSS signal, such as during periods of extreme cloud cover or a global GNSS failure. In such a scenario, the 3GPP hierarchy defaults to the lowest-priority level, independent mode. While one node will act as a synchronisation root, advertising its internal clock via Sidelink Synchronisation Signals (SLSS), the lack of a centralised master allows multiple independent roots to emerge within the same area. Because these nodes rely on internal oscillators that drift naturally without an external reference, the localised timing pockets will eventually diverge, leading to a split network in which the GUEs are no longer temporally aligned. This results in increased packet collisions and the potential collapse of the decentralised communication link.

Proposed Operational Model

The operational model proposed in this research mainly uses the decentralised synchronisation hierarchy as mandated by the 3GPP standards, rather than designating the UAV as the master clock under all conditions. This approach adheres to the fundamental principles of the standard, ensuring that the system remains robust by removing the UAV as a single point of failure for synchronisations. This leverages the high precision, global timing reference of GNSS, which is universally integrated into modern smartphones, ensuring maximum interoperability and timing accuracy.

To mitigate the risk of a split network in the rare event of total GNSS failure across all nodes, the model proposes a modification to the priority hierarchy. This involves the introduction of a UAV-governed synchronisation mode that takes precedence specifically over the standard independent mode. If no GNSS or GNSS-synced signal is detected, the ground users are instructed to synchronise specifically to the UAV's internal clock over other independent peers. This can be facilitated by repurposing a single reserved bit within the broadcast message (such as the `MasterInformationBlockSidelink` payload) to signal the presence of the aerial relay. By identifying this flag, GUEs can distinguish the UAV from other independent peers, ensuring that the entire cluster remains anchored to a single timing reference and preventing the temporal divergence that leads to network fragmentation.

3.1.3. Stage 3: Relay Discovery

Relay discovery is the process by which a node identifies other potential communication partners within its proximity and determines their specific service capabilities. This is the first stage in initiating a relay session, as it provides the mechanism for out-of-coverage GUEs to locate the UAV and verify that it can facilitate the required connectivity. In a standard terrestrial architecture, this role is performed by the gNB, which continuously broadcasts its Public Land Mobile Network (PLMN) ID and system parameters to announce the availability of a network to all mobile devices in its range. Similarly, in a decentralised relay environment, the UAV must employ discovery procedures to advertise its presence and relay services, allowing ground users to initiate a connection.

Current 3GPP Sidelink Discovery Specifications

The 3GPP architecture for 5G Sidelink defines a structured framework for direct discovery over the PC5 reference point, as detailed in 3GPP TS 23.304 [38] and 3GPP TS 24.334 [44]. This framework allows UEs to identify potential relay candidates and their associated services without the assistance of a gNB. The standard supports two distinct operational modes for discovery.

- **Model A (Announcement):** This follows an "I am here" mechanism where a potential relay UE periodically broadcasts announcement messages. These messages contain information about the relaying services provided, allowing the monitoring UEs to passively scan the Sidelink interface and identify available candidates.
- **Model B (Solicitation and Response):** This follows a "Are you there?" mechanism. The remote UE acts as a discoverer by transmitting a solicitation message searching for a specific service. A relay UE (the discoveree) monitors these solicitations and transmits a response message only if it can provide the requested connectivity.

A central parameter in both models is the Relay Service Code (RSC), a 24-bit identifier that uniquely specifies the connectivity service offered by the relay and identifies the authorised user groups the relay is intended to serve. It is through this specific parameter that a GUE is able to differentiate between a U2U relay and a U2N relay with core network connectivity. Although the 3GPP specifications define the transport and length of the RSC, the specific format of the code is determined by the service provider or public safety authority. During the relay selection process, when a UE detects a discovery message with a matching RSC, it first verifies if the signal quality is sufficient to maintain a reliable link. This is achieved by evaluating the Sidelink Reference Signal Received Power (S-RSRP). A relay UE is only considered a valid candidate if the measured signal strength exceeds a preconfigured threshold.

$$S\text{-RSRP}_{\text{measured}} > \text{sl-ThreshRSRP}_{\text{config}} \quad (3.1)$$

Where $\text{sl-ThreshRSRP}_{\text{config}}$ represents the minimum required S-RSRP level provided during the pre-provisioning stage. If multiple relay candidates meet this criterion, the GUE selects the candidate with the highest measured S-RSRP to initiate the connection establishment phase. In out-of-coverage scenarios, discovery procedures are performed using Sidelink Mode 2 autonomous resource allocation (explained in Section 3.1.6). Furthermore, the 3GPP standards provide an option to configure dedicated Sidelink Discovery resource pools that are logically and physically segregated from the resource pools assigned for PC5 signalling and user-plane data.

Proposed operational model

The 3GPP direct discovery framework is fully applicable to the aerial relaying architecture without requiring modifications to the underlying protocol. However, to optimise for the unique constraints of a network-denied emergency environment, the proposed operational model mandates specific configuration choices, specifically the use of Model A discovery and the physical segregation of the resource pool.

For this specific UAV-assisted architecture, Model A (Announcing) discovery is preferable over Model B (Solicitation and Response) for its inherent efficiency in battery conservation of GUEs and overall network stability. In this model, the UAV acts as the announcing UE, periodically broadcasting its availability to all nearby GUEs. This approach allows GUEs to remain in a passive monitoring state, significantly reducing the energy expenditure associated with transmitting active solicitation queries, a critical factor in disaster scenarios where GUEs have limited access to power sources. Furthermore, by centralising the signalling burden on the UAV, which typically possesses a higher energy capacity and a privileged LoS position, the network prevents the discovery resource pool from becoming congested with redundant GUE solicitation messages. This centralised approach minimises the risk of packet collisions and maximises the probability of successful discovery for all devices within the aerial relay's footprint. To further ensure link reliability, the proposed operational model mandates that the network be configured with dedicated discovery resource pools that are physically segregated from the resource pools for other messages. This allocation ensures that the UAV's periodic discovery announcements remain highly visible and are not drowned out by the high-volume traffic. This segregation is also required for the resource allocation strategy proposed in Section 3.1.6.

3.1.4. Stage 4: Connection Establishment

Once the GUE has successfully discovered the UAV and verified its service capabilities via the RSC, the system transitions from the discovery phase to the connection establishment phase. This stage involves the creation of a PC5 Unicast link, a dedicated one-to-one signalling connection that serves all subsequent data exchanges between the GUE and the UAV. As illustrated in Figure 3.1, this process is initiated by the GUE, which transmits a `Direct Communication Request`. To prevent unauthorised access, the protocol mandates a strict authentication and security procedure, which is facilitated through the `Direct Security Mode Command` and `Direct Security Mode Complete` exchange. During which, the UAV and GUE perform mutual authentication and negotiate ciphering and integrity protection algorithms. Following the successful establishment of the security context, the UAV responds with a `Direct Communication Accept` message, which establishes a Layer 2 connection between the two nodes. Once the Layer 2 link is active, the UAV performs an IP address configuration, providing the GUE with a unique IP address. Depending on the pre-provisioned configuration, this is achieved using

either IPv4 (with DHCPv4) or IPv6 (via Router Advertisement) address type. Once the IP allocation is complete, the connection is fully established, enabling the UAV to begin its role as a relay.

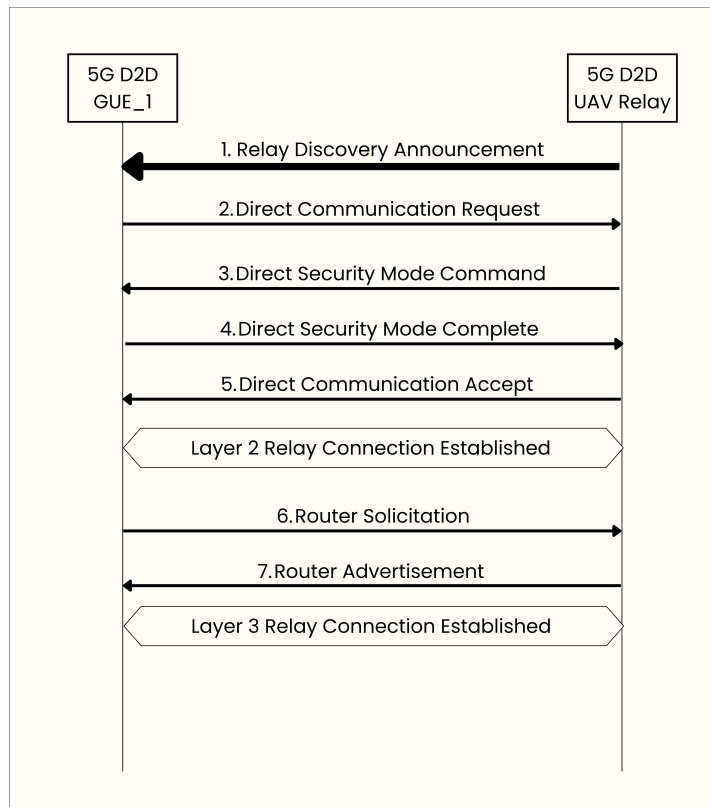


Figure 3.1: U2U connection establishment process.

3.1.5. Stage 5: Relaying Architecture

This section details the operational relaying mechanism employed by the UAV to facilitate communication between all connected GUEs. In this stage, the UAV serves as the central bridge for the cluster, receiving transmissions from a source GUE and forwarding them to the intended destination GUE. According to 3GPP TS 23.304 [38], there are two distinct relaying architectures to implement this forwarding logic.

- **Layer 2 (L2) Relaying:** In this architecture, the UAV functions as a transparent bridge at the data link layer. It forwards traffic based on the Layer-2 IDs found in the Sidelink Media Access Control (MAC) headers and utilises the Sidelink Relay Adaptation Protocol (SRAP) for routing, without inspecting the encapsulated IP packets.
- **Layer 3 (L3) Relaying:** In an L3 architecture, the UAV functions as an IP router or gateway. Instead of transparently bridging MAC frames, the UAV operates at the network layer, terminating the IP packets received from the source GUE and routing them to their final destination based on their IP headers.

Proposed Operational Model

The proposed operational model mandates the use of an L3 relaying architecture for all UE-to-UE communication. The reason for this decision to mandate an L3 architecture over an L2 architecture for the U2U scenario is driven by the necessity for application-layer intelligence, specifically regarding out-of-coverage identity resolution. A limitation of 3GPP out-of-coverage D2D communication is the requirement for UEs to find peers over the PC5 interface using their ProSe Application Layer IDs. These ProSe IDs are mapped to MSISDNs (phone numbers) and stored within the core network's ProSe Application Server. Establishing a connection requires a UE to have provisioned the ProSe Application

Layer IDs of all necessary local contacts while still connected to the core network. This is highly unrealistic for a disaster scenario.

While 3GPP standards define an L2 relaying mechanism capable of operating in out-of-coverage environments, it relies heavily on the Sidelink Relay Adaptation Protocol (SRAP), which is the sublayer responsible for routing data using Layer-2 Local IDs without terminating higher-layer traffic. Because an L2 relay relies on SRAP to function merely as a transparent bridge, the UAV cannot inspect the encapsulated IP packets to read the intended destination. Consequently, if a UE attempts to discover a peer without knowing its specific Layer-2 ID, the UAV is forced to blindly forward the discovery solicitation message to every connected node. This generates excessive broadcast signalling, congesting the physical spectrum. Crucially, this architectural limitation introduces severe scalability issues, as the number of connected UEs increases, the volume of redundant discovery traffic multiplies.

By mandating an L3 architecture, the system leverages the 3GPP standard that allows an L3 U2U Relay to act as a localised IP router and Domain Name System (DNS) server for connected endpoints. Simply put, when a GUE detects the UAV, it connects directly to it. The UAV then assigns the GUE a unique local IP address and records the mapping between the user's MSISDN and this new IP address in its internal registry. When the GUE subsequently wants to communicate with another user, it sends a standard DNS request containing the target MSISDN. The UAV looks up this number in its registry and returns the correct assigned IP address, allowing a direct routed connection. Thus, the UAV functions as an autonomous IP gateway, leveraging the standard IP networking stacks natively integrated into all commercial smartphones. This natively solves the identity resolution problem without requiring prior core-network authorisation or spectrum-heavy broadcast discovery.

Beyond protocol simplicity, the L3 architecture provides the UAV with the necessary IP awareness to manage the localised network cluster effectively. Because the UAV terminates traffic at the network layer (Layer 3), it can implement intelligent traffic shaping and Quality of Service (QoS) prioritisation. This allows the relay to distinguish between critical emergency signalling and non-essential background data, ensuring that life-safety communications are prioritised within the limited Sidelink resource pools.

The novel UAV-governed resource allocation strategy proposed subsequently in Section 3.1.6 operates independently of the network routing layer. Therefore, it is architecturally agnostic and fully capable of supporting both L2 and L3 relaying.

Identity Resolution and Directory Services

A core feature of this proposed model is the UAV's role as a localised directory and DNS server. In a network-denied disaster scenario, the MSISDN is the only practical identifier that a user (GUE_1) possesses for a target peer (GUE_2). Since the core network is unavailable to resolve these identities, the UAV populates a local mapping table using the `User Info` information element (defined in 3GPP TS 24.334 Section 12.5.1.3) exchanged during the connection establishment phase described in Section 3.1.4. To facilitate this, it is required that the GUE securely stores its own MSISDN locally while connected to the core network prior to the outage, subsequently transmitting it within the User Info field to identify itself.

Before initiating a communication session with another user (GUE_2), GUE_1 performs a DNS query to the UAV using the target's (GUE_2) phone number as the query string. By resolving these queries locally, the UAV eliminates the need for network-wide discovery broadcasts. This resolution process facilitates three critical outcomes:

1. **Successful Resolution:** If the target phone number (GUE_2) is present in the UAV's mapping table, the UAV returns the corresponding local IP address to GUE_1 . The source device (GUE_1) then initiates an IP-based session, which the UAV routes through its stack to the destination, as illustrated in Figure 3.2.
2. **Network Presence Verification:** If the DNS query does not result in a match, the source device (GUE_1) receives an error response. This provides immediate feedback to GUE_1 that the intended

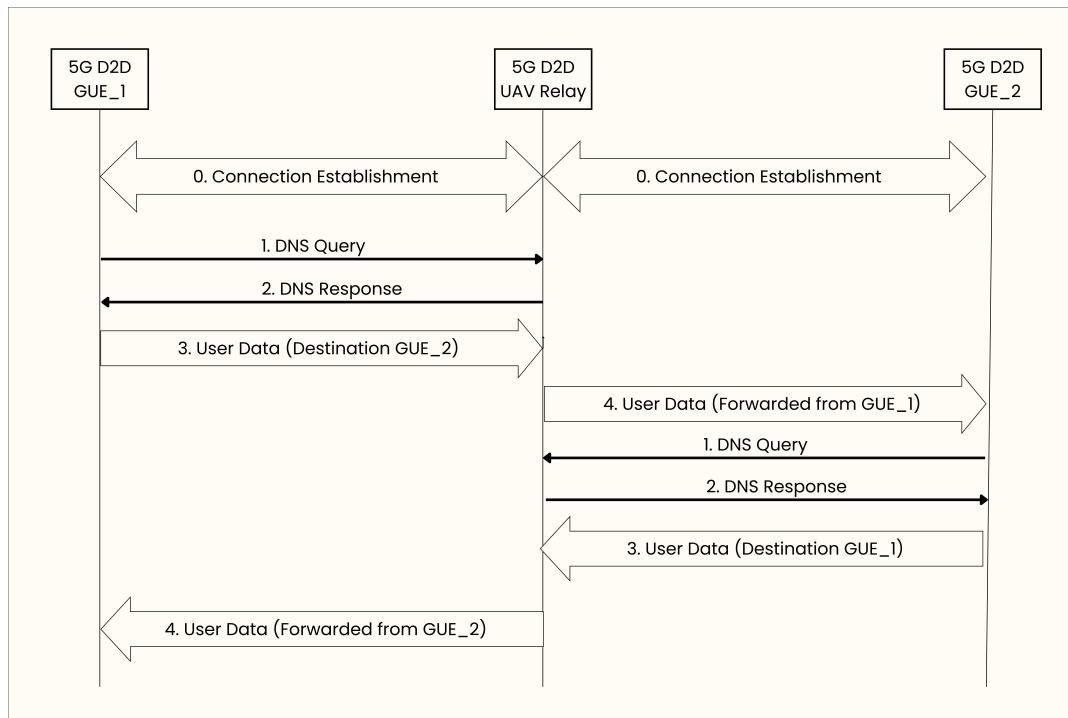


Figure 3.2: Relaying and identity resolution process in U2U networks.

recipient is currently not connected to the UAV relay, preventing GUE_1 from wasting battery and radio resources.

3. **Emergency Service Access:** Specific emergency identifiers (e.g., 112) are pre-provisioned as reserved entries in the UAV's directory. When any GUE queries an emergency number, the UAV provides the IP address of the local emergency service node. This ensures that civilians can reach first responders using familiar dialling codes, and the UAV acts as a bridge to these critical resources.

3.1.6. Stage 6: Resource Allocation

This section addresses the resource allocation mechanisms essential for managing the Sidelink spectrum and ensuring reliable communication between all nodes. This section begins by explaining the current 3GPP specifications for resource allocation, which define two primary operation modes: Mode 1 and Mode 2. In Mode 1, the network (via a base station) centrally manages and schedules resources for the devices, while Mode 2 allows devices to autonomously select their own resources from a shared pool. Given the absence of fixed terrestrial infrastructure in the proposed disaster scenario, the subsequent sections focus on Mode 2 in detail. Furthermore, this section explores the inherent limitations of the standard 3GPP resource allocation strategy when applied to an aerial relay environment and proposes a novel algorithm specifically designed to optimise performance for this UAV-assisted architecture.

Current 3GPP Mode 2 Resource Allocation Specifications

For the specific requirements of an out-of-coverage emergency environment, 3GPP Mode 2 is the requisite choice as it allows UEs to function without a central controller. This autonomous resource selection is governed by a sensing-based principle, where the burden of coordination is distributed across all nodes in the network. The procedure is strictly partitioned between the Physical layer (layer 1), which performs the environment sensing and filtering, and the MAC layer (layer 2), which executes the final selection logic.

The process begins at the physical layer during the sensing window, the duration of which is defined

dynamically based on the sub-carrier spacing and the UE's processing capabilities. During this window, the UE continuously monitors the Physical Sidelink Control Channel (PSCCH) to decode the Sidelink Control Information (SCI) transmitted by neighbouring devices. By decoding these messages, the UE gains precise knowledge of the time-frequency resources already reserved by other nodes for their current transmission and up to two subsequent retransmissions. Simultaneously, the UE measures the Reference Signal Received Power (RSRP) associated with these detected transmissions.

When the MAC layer triggers a request for resources, the physical layer identifies a selection window and prepares a set of all possible candidate resources S_A . An exclusion process is then performed, where any candidate resource is removed from S_A if it overlaps with a resource already reserved by a neighbour, provided the measured RSRP of that neighbour's signal exceeds a pre-configured threshold. To ensure that the UE is never entirely blocked from transmitting, the standard requires that the remaining set S_A must contain a minimum percentage (typically 20%) of the total available resources in the selection window. If the exclusion is too aggressive and this target is not met, the UE iteratively relaxes the RSRP threshold in 3 dB steps until the required volume of candidate resources is available.

Once the physical layer has pruned the available spectrum, the filtered subset of valid candidates is passed to the MAC layer. Rather than selecting the best slot, which would lead to multiple UEs potentially choosing the same resource and colliding, the MAC layer performs a random selection from the candidate set. This approach is fundamental to distributed systems as it minimises the probability of collisions between peers who have sensed the same environment. Upon selecting a resource, the UE includes its own reservation data in its transmitted SCI, effectively claiming the slot for up to two future transmissions. As a final safeguard, the standard allows for a re-evaluation check immediately before the transmission slot to ensure that the selected resource has not been pre-empted by a higher-priority user.

To further mitigate the hidden node problem, where a transmitter cannot detect an interferer that is visible to its intended receiver, 3GPP Release 17 introduced Inter-UE Coordination (IUC). This mechanism allows an assisting UE to provide feedback to a peer regarding resource suitability, either by providing sets of preferred or non-preferred resources or by sending a specific conflict indication upon detecting a likely collision. Despite these sophisticated mechanisms, a critical limitation remains in the standard Mode 2 framework when applied to this specific application. While 3GPP implements a strict logical separation between Sidelink Signalling Radio Bearers (SL-SRB) for the control plane and Sidelink Data Radio Bearers (SL-DRB) for the user plane, both contend for resources within the same common Sidelink resource pool. Because there is no dedicated physical channel reserved for signalling, a mission-critical connection pulse must undergo the same contention-based sensing and probabilistic selection as standard data. The lack of physical separation between the control plane and user plane, combined with the inherent scaling issues of the Mode 2 sensing strategy in high-density scenarios, as highlighted by Ali et al. [29], presents a significant inefficiency for this system scenario. These limitations serve as motivation for the dedicated resource allocation strategy proposed below.

Proposed Resource Allocation Strategy

While standard NR Sidelink Mode 2 provides a robust framework for decentralised networks, its sensing-based resource selection inevitably leads to half-duplex deafness and dropped packets at the aerial relay. Since the UAV cannot simultaneously transmit and receive on separate sub-channels within the same frequency band, uncoordinated random access creates severe bottlenecks. To eliminate contention-based collisions, this thesis proposes a strictly UAV-governed resource allocation strategy that operates within a deterministic Time-Division Duplexing (TDD) framework to separate GUE and UAV transmissions.

Initial link establishment uses standard Mode 2 procedures within a pre-configured common resource pool. However, upon assessing an incoming `Direct Communication Request`, the UAV issues an acceptance message. This explicitly transitions the connecting GUE from the autonomous Mode 2 sensing into a UAV-governed Command Mode, making the aerial relay the sole arbiter of the shared physical medium.

To systematically resolve the half-duplex constraint, the algorithm uses a rigid TDD architecture where each transmission slot spans exactly 1 ms as illustrated in Figure 3.3. The time domain is divided into a continuous series of 20 ms TDD frames, nested within a larger 100 ms Super Frame. Each 20 ms frame is structurally isolated into three distinct phases:

- **Downlink Phase (Slots 1–9):** Strictly reserved for the UAV to transmit or forward control signalling (e.g., Data ACKs and Resource Grants) and forward User Plane data down to target GUEs.
- **Uplink Phase (Slots 10–19):** Strictly reserved for the GUEs to transmit their control signalling (e.g., Status Report and Resource Request) and originating User Plane data up to the UAV.
- **Guard Periods:** Two 0.5 ms guard buffers (0.0-0.5 ms and 9.5-10.0 ms) are intentionally left to provide necessary switching time between the transmission phases.

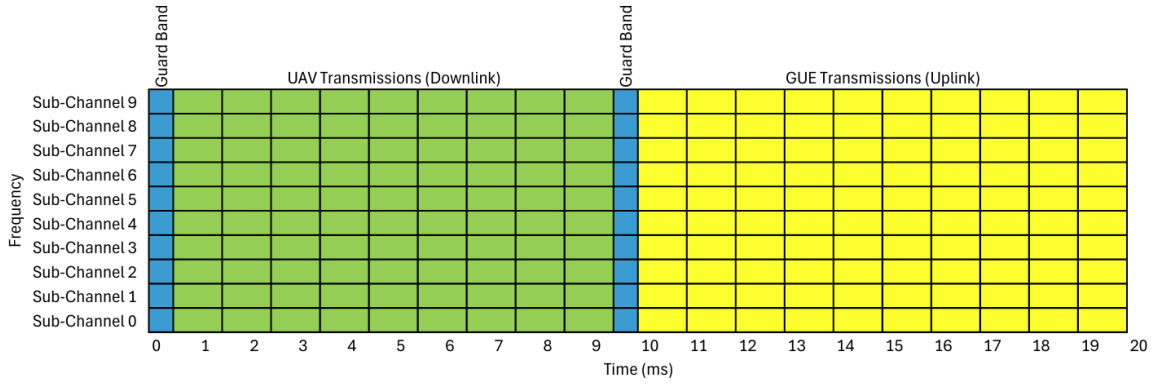


Figure 3.3: Proposed TDD frame.

To support dense user clusters, the algorithm layers a dynamic split-plane architecture over the TDD frame in the frequency domain. The available frequency sub-channels are logically partitioned into a Control Plane (SL-SRB) and a User Plane (SL-DRB). The central scheduler dynamically maps these logical planes to optimal physical resource blocks based on prevailing link conditions. Upon connection, the UAV assigns each GUE a dedicated, collision-free Control Plane slot. Repeating every 100 ms, this low-bandwidth heartbeat allows the UE to maintain its PC5 link, provide periodic location telemetry for autonomous positioning, and transmit Buffer Status Reports (BSR) with minimal overhead. Conversely, the high-bandwidth User Plane remains entirely unallocated during steady state. When application data is ready, the GUE transmits a Resource Request (Table 3.2) within its dedicated heartbeat slot, prompting the UAV to issue an on-demand Resource grant (Table 3.3).

Unlike the standard IUC framework, which only suggests preferred resources, this dedicated signalling operates as an absolute command. This modifies the standard MAC layer logic. Rather than maintaining a candidate set S_A based on local sensing, the GUE is configured to enter a UAV-governed Command Mode. In this state, the GUE bypasses its own sensing and exclusion processes, instead utilising the exact resources allocated by the UAV. This transition eliminates the uncertainty of random selection and prevents collisions at the UAV's receiver.

The Centralised UAV Scheduler

To execute this architecture, the UAV employs a custom resource scheduler to manage all time-frequency blocks within the TDD frame. The scheduler handles the Control Plane and User Plane using entirely distinct allocation methodologies.

Control Plane: When a GUE connects, the scheduler assigns it a persistent Control Plane heartbeat. This assignment guarantees a deterministic, collision-free slot in the Uplink phase that repeats every

100 ms. Since a 100 ms Super Frame consists of five 20 ms TDD frames, and each frame has 10 Uplink slots, a single Control Plane sub-channel supports exactly 50 users. Because the TDD frame strictly separates Uplink from Downlink in the time domain, the GUE can safely transmit on the UAV's control frequency during the Uplink phase without interfering with the UAV's Downlink broadcasts.

User Plane: User Plane resources are assigned purely on demand to maximise spectral efficiency. When the scheduler receives a `Resource Request` during a GUE's heartbeat slot, it parses the Buffer Status Report (BSR) and QoS class to determine the appropriate resource allocation strategy:

- **Aperiodic Grants (Data Bursts):** For non-continuous traffic such as text messages or images, the scheduler dynamically reserves free slots within the Uplink phases of upcoming frames. Aperiodic grants include a built-in expiration timer; once the burst duration concludes, the scheduler automatically reclaims the time-frequency coordinates, immediately returning them to the available pool.
- **Periodic Grants (Voice Calls):** For latency-sensitive, continuous traffic such as voice calls, the scheduler locks in a relative offset. This guarantees the GUE a recurring physical resource for the duration of the call. To free this recurring lock, the system relies on an explicit release mechanism: upon terminating the call, the GUE transmits a `Resource Request` with a BSR of zero, prompting the scheduler to immediately de-allocate the resource.

3.1.7. Stage 7: Positioning Signalling

While 3GPP release 18 introduces the Sidelink Positioning Protocol (SLPP) for location sharing, its substantial protocol overhead and reliance on the Mode 2 resource allocation render it unsuitable for high-density emergency scenarios. To avoid these limitations, this thesis proposes a low-layer unified telemetry heartbeat mechanism. Once the dedicated signalling framework is established, the GUE utilises its periodic SL-SRB control slot to transmit critical telemetry data to the UAV. This channel and positioning signalling is a vital data source for the autonomous operation of the aerial relay. The requirement for this continuous feedback loop is driven by two primary objectives: automated optimisation of the UAV position and automated acquisition of ground user data.

The first objective involves the dynamic optimisation of the UAV's spatial positioning. To maintain the highest possible QoS for the cluster, the UAV requires real-time data regarding the geographical distribution and channel conditions of all connected GUEs. By aggregating the data from these signals, the UAV's positioning algorithm can calculate the optimal 3D centroid to minimise path loss and maximise aggregate throughput. Furthermore, this feedback allows the UAV to perform fine-grained link adaptation, adjusting the Modulation and Coding Scheme (MCS).

The second objective is the acquisition of victim data for search and rescue operations. In a disaster environment, the ability to pinpoint a user's location through their cellular device is a significant asset for first responders, particularly in scenarios where the GUE is unable to manually initiate an SOS request. As discussed in the application example in Section 2.5.1, this capability is best illustrated by the example of an unconscious individual. Even without user intervention, the smartphone's automated connection to the UAV relay allows the system to harvest the device's 3D GPS coordinates. This passive discovery transforms the aerial relay into a remote sensing platform, providing rescue teams with the exact coordinates of survivors who might otherwise remain undetected in the disaster zone.

To ensure this information is delivered with minimal spectral overhead, the signalling is structured as a single, compact telemetry packet, detailed in Table 3.1. The location info encompasses the 3D coordinates along with an accuracy metric and timestamp, while the channel information provides a multi-dimensional view of the radio environment, consisting of:

1. **S-RSRP (Sidelink Reference Signal Received Power):** Used for calculating the radio distance between the UAV and the GUE.
2. **S-RSSI (Sidelink Received Signal Strength Indicator):** Used to estimate the Signal to Noise and Interference Ratio (SNIR) of the channel.
3. **CQI (Channel Quality Indicator):** Informs the UAV of the appropriate MCS level required for reliable data transfer.

4. **PER (Packet Error Rate):** Provides a metric for link reliability, allowing the UAV to identify nodes experiencing high packet loss.

Upon reception of these packets, the UAV updates its internal Node Registry, a database that tracks the state of every GUE in the cluster. The positioning algorithm utilises the 3D coordinates to calculate a weighted centroid, prioritising users with lower S-RSRP values to ensure that the relay remains within range of the most disadvantaged nodes. Simultaneously, the UAV's resource manager maps the reported CQI and PER to an optimal MCS for the next transmission. This closed-loop control system ensures that the network is constantly self-optimising to mitigate the effects of GUE mobility and environmental fluctuations. By piggybacking this data on the existing low-bandwidth signalling heartbeat established in Section 3.1.6, the system maintains a high degree of situational awareness and network intelligence without congesting the user plane resources required for communication. This periodic update ensures that the UAV possesses a near-real-time map of the cluster's movement and link reliability.

Table 3.1: Proposed Telemetry Signalling message for GUE-to-UAV Status Reporting.

Information Element	Size (bits)	Description
Message Type	4	0x00 for this message
Sequence Number	16	To uniquely identify the PC5 message for tracking, increments sequentially
Timestamp	64	GPS Time
Latitude	32	3D coordinate (WGS84 standard)
Longitude	32	3D coordinate (WGS84 standard)
Altitude	16	Height above sea level
Accuracy	8	GPS Confidence metric
S-RSRP	8	Received power metric in dBm
S-RSSI	8	Total received energy metric
CQI	4	4-bit channel quality index (0-15)
PER	8	Cumulative packet error rate percentage
Spare	8	Reserved for future use
Total	208 bits	26 Bytes

3.1.8. Stage 8: Link Maintenance and Release

The transition to a centralised coordination model significantly simplifies the operational overhead associated with link maintenance and connection release. Unlike standard 3GPP Sidelink procedures, where link establishment is typically triggered only when active data is ready for transmission, the proposed architecture provides a mechanism for devices to remain connected to the network regardless of their data transmission status. By assigning each GUE a dedicated, recurring slot on the SL-SRB, the UAV maintains a persistent state for every associated node. This allows the UAV to distinguish between a node that is simply idle and one that has moved out of range or suffered a power failure. This predictability ensures that spectral resources are never wasted on stale connections and that the network can scale efficiently as survivors move through the disaster zone. The control plane facilitates a bidirectional exchange of signalling between the GUE and the UAV. To ensure efficient decoding, every control message in both uplink (GUE to UAV) and downlink (UAV to GUE) is transmitted with a four-bit Message Type field.

The GUE utilises its dedicated SL-SRB slot to transmit one of three primary uplink message types based on its current operational requirements:

1. **Status Report:** (Message Type = 0x00) This is the default message sent during the heartbeat interval when no user-plane data is pending. It contains the 3D coordinates and channel metrics as defined in Table 3.1.
2. **Resource Request:** (Message Type = 0x01) This message is sent when the GUE has application data ready for transmission and requires an allocation on the user plane (SL-DRB). As detailed in Table 3.2, this message provides the UAV with the specific characteristics required to issue an appropriate user-plane grant.

3. **Link Release:** (Message Type = 0x02) This message is used to disconnect from the UAV and gracefully terminate the PC5 connection, as described in Table 3.5.

Conversely, the UAV employs its reserved downlink control slots to manage the cluster state and respond to GUE requests through the following message types:

1. **Resource Grant:** (Message Type = 0x04) Issued in response to a Resource Request. This message defines the specific time-frequency resources and MCS level for the GUE's user plane transmission (Table 3.3).
2. **Release ACK:** (Message Type = 0x08) Acknowledges a Link release message from a GUE. As defined in Table 3.6, it confirms the successful removal of the node from the Registry.
3. **Data ACK:** (Message Type = 0x0F) Provides ARQ feedback to acknowledge the successful reception of user data sent by the GUE on the granted SL-DRB resource (Table 3.4).

Resource Request

When a GUE needs to transmit user-plane data, such as an emergency voice call or an image, it must transition from the idle state to an active state. To initiate this, the GUE transmits a Resource Request (described in Table 3.2) in its next scheduled control slot. The primary purpose of this message is to provide the UAV's scheduler with the metadata required to allocate a sufficiently large and prioritised SL-DRB resource. The request includes a Buffer Status Report (BSR), which indicates the volume of data awaiting transmission, and a QoS index, which identifies the priority of the data. For example, a low-latency QoS index ensures that the UAV prioritises a voice traffic over a background file transfer. The CQI and PER metrics are also part of this request, as the UAV must know the current channel quality to select the optimal MCS for the high-bandwidth grant.

In response to the Resource Request, the UAV transmits a Resource Grant (Table 3.3). This message provides the GUE with the specific time-frequency coordinates for its user-plane transmission. It includes a Resource Index, an MCS Index (chosen from the GUE's reported CQI), a Grant Type flag, a periodicity interval, and a Grant Timer, which defines the number of consecutive subframes for which the allocation remains valid. Depending on the QoS requirement, the UAV issues one of two distinct grant types:

1. **Aperiodic Grant:** Issued for bursty, one-time data transfers such as images or SMS. The allocation is valid for a single burst as defined by the Grant Timer.
2. **Periodic Grant:** Issued for continuous traffic like voice calls. This grant provides a recurring resource that remains active until explicitly terminated.

Table 3.2: Proposed Signalling message for GUE-to-UAV Resource Request.

Information Element	Size (bits)	Description
Message Type	4	0x01 for this message
Sequence Number	16	To uniquely identify the PC5 message for tracking, increments sequentially
Buffer Status Report (BSR)	8	Index of pending data volume (3GPP standard)
QoS Class	6	Identifies traffic type (e.g. Voice, text, image)
CQI	4	Channel Quality Index for MCS selection
PER	8	Packet Error Rate for reliability tracking
Spare	34	Reserved for future use
Total	80 bits	10 Bytes

To maintain spectral efficiency, user-plane resources are reclaimed as soon as they are no longer required. For aperiodic data, the resource is released implicitly via the Grant Timer. Due to the high processing and signalling latency involved in reassignment, there is little spectral benefit in explicitly releasing a short data burst. Once the timer expires, the UAV immediately returns the time-frequency coordinates to the common pool for other users. For periodic traffic, such as voice calls, an explicit release, such as the call ending, is required to reclaim the recurring bandwidth. This is achieved by the GUE transmitting a Resource Request (Table 3.2) with the BSR set to zero. This signal informs

Table 3.3: Proposed Signalling message for UAV-to-GUE Resource Grant.

Information Element	Size (bits)	Description
Message Type	4	0x04 for this message
Sequence Number	16	To uniquely identify the PC5 message for tracking, increments sequentially
Grant Type	1	Flag distinguishes between Aperiodic and Periodic Grants
Resource Index	12	Time and Frequency coordinates for the SL-DRB allocation
MCS Index	5	5-bit MCS index (0-31) determined by the UAV
Grant Timer	8	Duration in subsequent subframes for which the grant is valid
Periodicity	8	The number of slots between the start of each burst (0 for Aperiodic grants)
Spare	26	Reserved for future use
Total	80 bits	10 Bytes

the UAV that the periodic session has ended, so it can release the user-plane resource and update the Node registry, returning the GUE to its idle state.

To ensure reliable data delivery of user-plane transmissions, without overwhelming the Sidelink with signalling overhead, a Block Acknowledgement (B-ACK) mechanism is employed. This mechanism follows the logic of 5G Radio Link Control (RLC) Status PDUs [45] and Wi-Fi (IEEE 802.11n) reliability protocols. Rather than acknowledging each individual Protocol Data Unit (PDU) or transport block, which would consume excessive control-channel bandwidth, the UAV aggregates the reception into a Data Ack message (Table 3.4). The UAV transmits the Data Ack message upon the expiration of the Grant Timer.

This report utilises the Selective Repeat logic, where a 16-bit Number (ACK SN) indicates the sequence number of the first missing or expected PDU, followed by a Reception bitmap. Each bit in the 32-bit bitmap represents the success (1) or failure (0) of subsequent data units. This allows the GUE to selectively retransmit only the specific data that was lost while significantly reducing the number of required feedback transmissions on the control channel.

Table 3.4: Proposed Signalling message for UAV-to-GUE Data Acknowledgement.

Information Element	Size (bits)	Description
Message Type	4	0x0F for this message
Sequence Number	16	To uniquely identify the PC5 message for tracking, increments sequentially
ACK SN	16	Sequence Number of the first missing packet
Reception Bitmap	32	Each bit represents the status of subsequent packets (1 = ACK, 0 = NACK)
Spare	12	Reserved for future use
Total	80 bits	10 Bytes

Connection Release

The termination of the GUE-to-UAV connection is handled through both explicit and implicit mechanisms to ensure the Node Registry remains accurate. Upon release, the UAV will purge the GUE from its registry of connected users and reassign the dedicated control slot to a new user.

1. **Explicit Release:** This is used for graceful shutdowns. The GUE transmits a Link Release message, as defined in Table 3.5. This follows the structural logic of the 3GPP `DIRECT_COMMUNICATION_RELEASE` found in 3GPP TS 24.334 (Table 11.4.7.1.1) [44]. By including a Release Reason, the GUE can inform the UAV why the link is ending (e.g. "User Shutdown" or "Low Battery").
2. **Implicit Release:** If a GUE suffers a total power failure or moves out of radio range, it will be unable to send an explicit release. In this case, the UAV monitors the GUE's dedicated SL-SRB

slot. If no heartbeat message is detected for a preconfigured number of consecutive slots, and there is no active user plane being received, the UAV assumes the link has failed. This ensures that the stale connection does not continue to occupy spectral resources.

To complete a graceful shutdown, the UAV responds to a Link Release message with a Release ACK, described in Table 3.6. This message follows the structural logic of the 3GPP `DIRECT_COMMUNICATION_RELEASE_ACCEPT` found in 3GPP TS 24.334 (Table 11.4.8.1.1) [44].

Table 3.5: Proposed Signalling message for GUE-to-UAV Connection Release.

Information Element	Size (bits)	Description
Message Type	4	0x02 for this message
Sequence Number	16	To uniquely identify the PC5 message for tracking, increments sequentially
Release Reason	8	Reason Code (low battery, user exit, bad connection, other)
Spare	52	Reserved for future use
Total	80 bits	8 Bytes

Table 3.6: Proposed Signalling message for UAV-to-GUE Connection Release Acknowledgement.

Information Element	Size (bits)	Description
Message Type	4	0x08 for this message
Sequence Number	16	To uniquely identify the PC5 message for tracking, increments sequentially
Spare	60	Reserved for future use
Total	80 bits	10 Bytes

3.2. UE-to-Network Relay Operational Model

In the U2N relay architecture, the UAV functions as a bridge between a distant, operational base station (gNB) and out-of-coverage ground users, effectively restoring backhaul connectivity to the core network. In a disaster scenario where local infrastructure has failed, GUE is often physically isolated by terrain, debris, or sheer distance from the nearest surviving base station. The UAV overcomes this limitation by leveraging its elevated operational altitude to establish a privileged LoS connection with the distant cellular network. By acting as an aerial U2N relay, the drone seamlessly extends the network's edge, utilising its backhaul connection to provide core network connectivity to the connected ground cluster. This transition from a localised network to a core-connected architecture enables stranded users to access full internet routing, external SMS, and calling services that would otherwise remain physically inaccessible.

3.2.1. Hardware Architecture

A fundamental distinction between a U2U UAV relay and a U2N UAV relay lies in the physical hardware requirements of the UAV transceiver. A U2U relay operating in an isolated cluster requires only a single Radio Frequency (RF) chain to manage its localised PC5 Sidelink traffic. An RF chain or RF front-end comprises the antenna, bandpass filters, low-noise amplifiers, local oscillators and the associated analogue-to-digital converters (ADC/DAC). In contrast, a U2N relay must continuously bridge communications between the ground users on the PC5 interface and the distant base station on the Uu interface. While the 3GPP specifications explicitly permit simultaneous Sidelink and Uplink/Downlink transmissions if the device hardware is capable (3GPP TS 38.213 Clause 16.2.4.3 [46]), attempting to multiplex the Uu and PC5 links through a single RF chain introduces severe operational bottlenecks. Although this constraint might be sustainable for a small number of connected GUEs, as the number of users and the volume of core-network traffic increase, this single RF chain design would exacerbate

half-duplex (HD) collisions, effectively crippling the network's reliability.

To resolve this limitation, the proposed operational model mandates that the U2N UAV be equipped with two independent RF front-ends. This dual-transceiver architecture enables the UAV to maintain a 100% operational duty cycle across both the Uu and PC5 links simultaneously, as illustrated in Figure 3.4. By decoupling the interfaces at the hardware level, the UAV can receive incoming data from the gNB over the Uu link while concurrently transmitting packets to a GUE over the PC5 Sidelink. This simultaneous operation greatly reduces cross-domain half-duplex blindness, thereby improving the spectral efficiency and overall throughput of the aerial gateway.

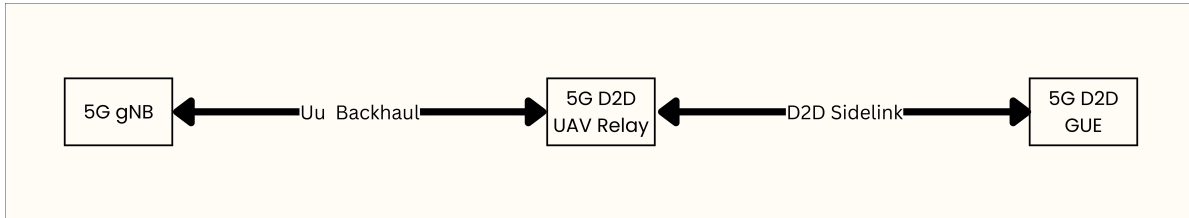


Figure 3.4: Communication chain for the U2N relay architecture.

Crucially, the physical ability to transmit and receive simultaneously hinges on strict frequency separation to prevent self-interference. The high-power signals emitted by the UAV's Uu transmitter would instantly overwhelm its own PC5 receiver if both interfaces operated within the same or adjacent frequency bands. Therefore, the architecture requires an Out-of-Band (OoB) relaying configuration, where the Uu backhaul and the PC5 Sidelink operate on distinctly separated frequency bands. As depicted in Figure 2.7, this spectral separation provides the necessary isolation for the dual RF chains and their respective filters, allowing the UAV to function as a seamless, full-duplex bridge between the core network and the isolated ground cluster.

3.2.2. Backhaul Connection Establishment

Upon deployment to a disaster area, the U2N relay UAV utilises its altitude to establish a clear LoS backhaul connection (via the Uu reference point) to a distant, functional gNB. While this gNB is geographically situated outside the connection reach of the stranded GUEs due to ground-level obstacles, the UAV's elevated position allows it to bypass these obstructions and maintain a stable radio link. The procedure by which the UAV attaches to the cellular network to establish this backhaul connection is identical to that of a standard mobile device. As illustrated in Figure 3.5, this involves completing the standard Radio Resource Control (RRC) Setup, negotiating a security context and requesting a Protocol Data Unit (PDU) session to secure an active IP backhaul link to the 5G Core.

Once the Uu backhaul connection is successfully established, the UAV transitions into its active relay state and initiates its Sidelink operations by broadcasting a Relay Discovery Announcement (Section 3.1.3). Crucially, this broadcast includes a specific Relay Service Code (RSC) that explicitly identifies the UAV as a U2N relay, differentiating it from an isolated U2U relay. Upon detecting this broadcast, stranded GUEs can initiate their connection requests to the UAV relay. The subsequent procedures for Sidelink connection establishment (Section 3.1.4), Resource allocation strategy (Section 3.1.6), and link maintenance (Section 3.1.8) remain identical to the mechanisms detailed in the U2U operational model. From the perspective of the ground user, the connection process to the UAV is exactly the same for the U2U and U2N architectures. The only operational difference is that the UAV now possesses a route to the external internet.

While a single UAV significantly enhances coverage, there are scenarios where the nearest functional gNB remains beyond the LoS range of a single aerial node. In such cases, the backhaul reach can be further expanded by employing a multi-UAV architecture, as depicted in Figure 2.5. By forming an aerial relay chain, intermediate UAVs can forward the backhaul traffic over successive hops, successfully bridging extreme geographical distances to restore core network connectivity.

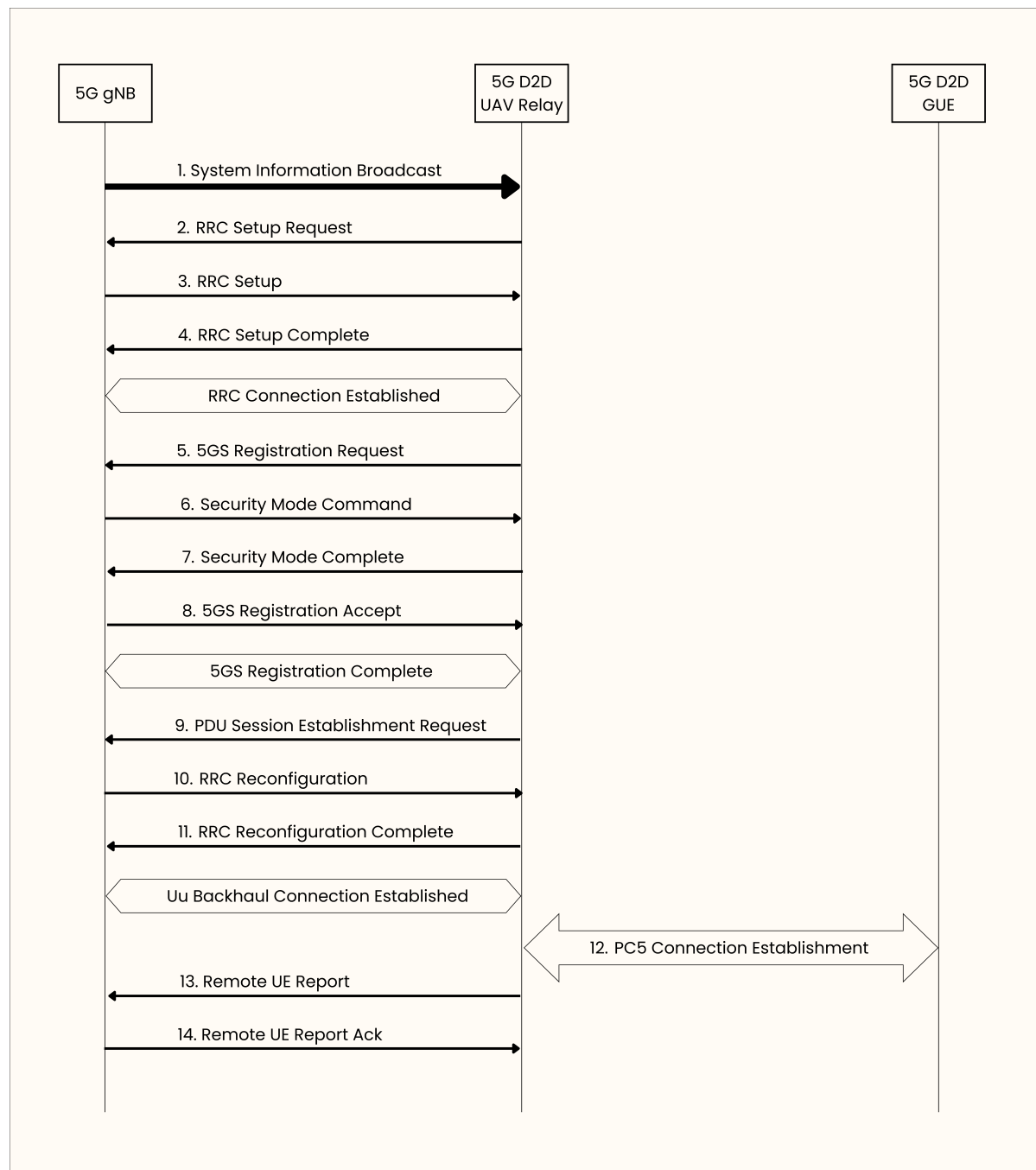


Figure 3.5: U2N connection establishment process.

3.2.3. Relaying Architecture

For the U2N scenario, the operational model proposes a Layer 3 (L3) gateway architecture. In this configuration, the UAV establishes a single RRC connection and PDU session with the 5G Core Network. GUEs connect to the UAV over the PC5 interface and are assigned local IP addresses, effectively utilising the UAV as a cellular-backed network gateway, conceptually similar to a Wi-Fi hotspot.

The primary trade-off of this decision is the loss of granular, per-user visibility within the 5G Core, which compromises core-managed individual subscriber billing. However, this is strictly necessary to

ensure system scalability and reliability through signalling consolidation. In a standard Layer 2 architecture, each individual GUEs would need to flood the network with individual RRC setups and Non-Access-Stratum (NAS) registration signalling. In contrast, the L3 approach consolidates this traffic; the UAV acts as the sole core network client, managing the ground users locally and reducing the signalling overhead.

A further advantage of this unified L3 approach is resilience: if the backhaul connection to the gNB fails, the UAV can seamlessly revert to the isolated U2U operational model. Intra-cluster communication continues uninterrupted via the local DNS registry without requiring GUEs to drop connections and re-establish new out-of-coverage relaying protocols. Due to this architecture, subscriber billing or data logging must be managed locally on the UAV rather than in the core network. Furthermore, security follows a hop-by-hop model; data is encrypted over the PC5 link between the GUE and UAV, decrypted at the UAV for routing, and then re-encrypted using the UAV's Uu connection keys before transmission to the gNB.

Bridging the GUEs to the core network fundamentally alters the user plane traffic characteristics compared to the U2U architecture. In a U2U scenario, communication is localised, consisting of short, relatively symmetrical bursts of emergency voice or text data. Conversely, the introduction of internet connectivity in the U2N scenario shifts the network towards heavily asymmetric, downlink-dominated traffic characterised by larger data bursts. This heavier downlink requirement forces the UAV to spend a large portion of its operational time transmitting to the ground cluster, which increases the probability of HD collisions. To efficiently manage this diverse traffic flow, the gNB can provision multiple distinct data bearers for the UAV. For instance, the network can have a high-priority Guaranteed Bit Rate (GBR) bearer strictly used for voice calls, running concurrently alongside a standard non-GBR bearer dedicated to background internet data.

4

Simulation Results

This chapter evaluates the proposed UAV operational model through a custom simulation. The first section details the simulation environment and outlines the assumptions, the evaluation metrics and the distinct operational modes tested. The subsequent sections present a detailed analysis of the results, directly comparing the baseline 3GPP standards against the proposed enhancements to quantify network performance, architectural trade-offs and the benefits of autonomous UAV mobility.

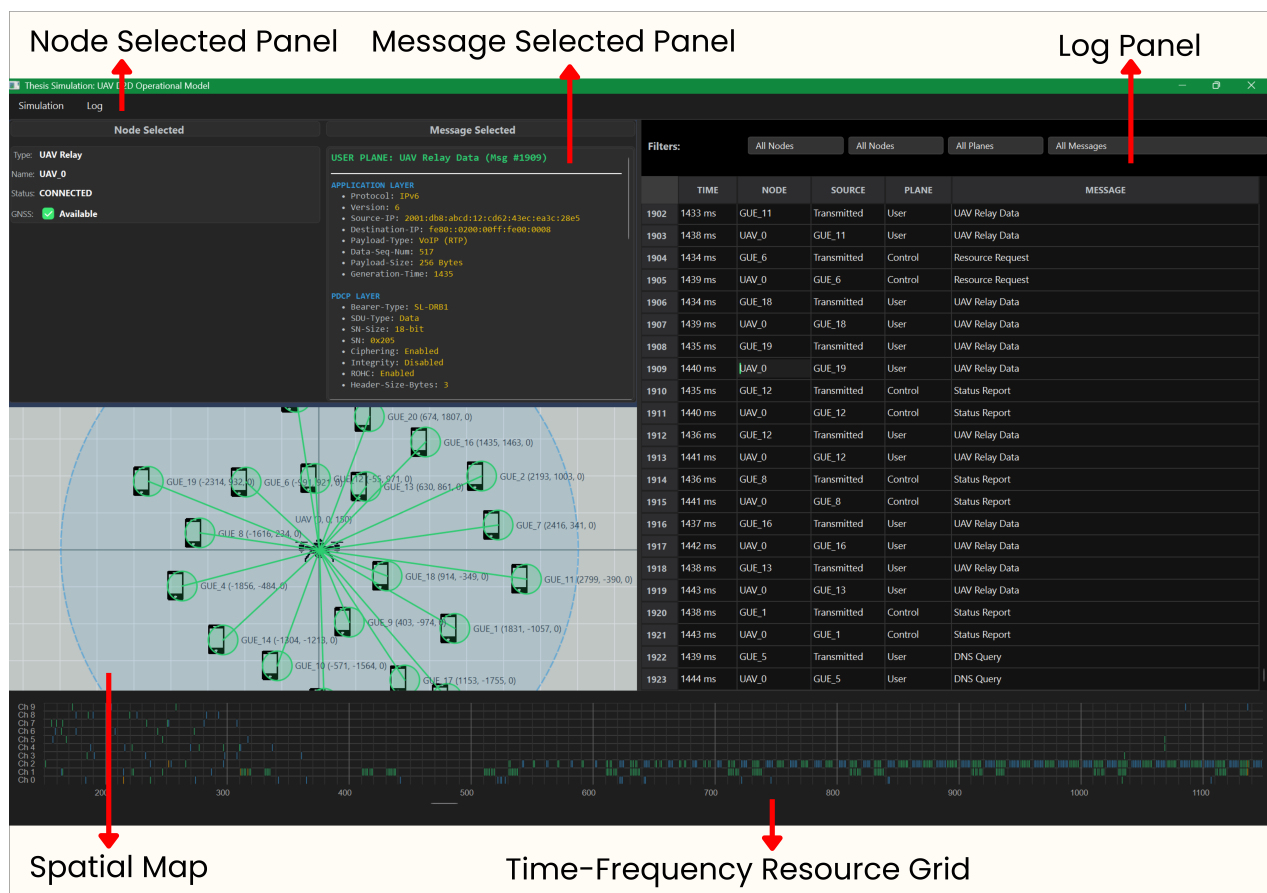


Figure 4.1: Custom Python simulation environment.

4.1. Simulation Setup

Because deploying a physical network of UAVs and 5G devices to test experimental protocols is out of the scope of this thesis due to time constraints and logistical complexity, a custom discrete-event simulation was developed in Python. A discrete-event simulation models the operation of a system as a chronological sequence of distinct events—such as a user initiating a voice call, a data packet arriving at a buffer, or the UAV granting a radio resource. By simulating these events step-by-step, the software creates a controlled, reproducible environment to evaluate how the proposed Sidelink protocols behave under varying degrees of network load. The complete source code for this simulation has been made publicly available and can be accessed via the data repository [47].

To manage the complex, event-driven timing of the network traffic and the underlying protocol state machines, the simulation utilises the SimPy library. Furthermore, the PyQt6 library was used to render a live Graphical User Interface (GUI) for visual analysis. As illustrated in Figure 4.1, the interface features a top-down spatial map displaying the geographical distribution and active Sidelink connections (illustrated by green circles) of the simulated nodes. Selecting a specific node on this map updates the top-left “Node Selected” panel to show its current status. On the right, a message filter logs all transmitted and received network traffic chronologically. When an individual message is selected from this log, the “Message Selected” panel displays the full protocol stack, detailing the specific fields encapsulated within each layer. Finally, the bottom panel provides a real-time visualisation of the time-frequency resource grid, enabling continuous monitoring of the physical spectrum and the resource allocations.

The simulation framework is designed to execute five distinct simulation modes to systematically address the research questions. These include two baseline simulations (U2U and U2N), two proposed model simulations (U2U and U2N), and a mobile UAV simulation. Separating the scenarios allows us to compare the performance of the proposed U2U mode directly against the baseline, as well as the proposed U2N model against the baseline U2N. The fifth mode, the positioning simulation, is explained in Section 4.1.3.

The baseline simulations establish the performance floor by modelling the current 3GPP standard operational mechanisms applied directly to an aerial relay context, specifically drawing from the different “Current 3GPP Sidelink Specifications” subsections in Chapter 3. In these runs, the network relies strictly on standard Mode 2 autonomous resource allocation, providing a baseline metric for Mode 2 performance. In contrast, the proposed model simulations introduce the enhancements designed to resolve the limitations observed in the baseline. These proposed runs implement the UAV-governed resource allocation strategy, as described in Section 3.1.6.

While the simulation provides a detailed evaluation of the 3GPP standards, certain mechanics are abstracted to manage computational complexity. The specific simplifications are outlined below:

1. **Packet Size:** All network traffic is modelled using a fixed packet size of 256 bytes, with the simulation structured such that each packet transmission occupies exactly one time slot (1 ms).
2. **Link Adaptation:** To bypass heavy computation overhead, the simulation does not include adaptive Modulation and Coding Schemes (MCS) or dynamic transmit power control.
3. **Binary Collision Model:** Instead of calculating complex dynamic SINR Ratios, the simulation engine employs a binary collision model. If two transmissions overlap on the exact same time-frequency resource block, both packets are deterministically marked as corrupted.
4. **Channel Sensing:** Standard Mode 2 channel sensing is omitted from the baseline simulations. Because ground devices are geographically dispersed over a large area, with obstacles between them, the likelihood that they can effectively sense each other's transmissions is negligible. Furthermore, Inter-UE Coordination (IUC) is not included in this simulation due to similar physical constraints and the complexity of its implementation.
5. **UAV Mobility:** During the dedicated positioning runs (explained in Section 4.1.3), the UAV's flight speed is artificially increased to 150 meters per second. This is necessary to reduce simulation time, allowing the impact of the UAV's continuous position updates to be observed without prohibitively long execution times.

6. **Guard Bands:** To simplify the time-division modelling, the two 0.5 ms guard periods between the uplink and downlink transitions are combined. The simulation simply reserves the entire first 1 ms slot of every frame as a unified guard band.

4.1.1. Simulation Parameters

To rigorously evaluate the scalability and stability of both the baseline and proposed models, the simulation was executed across varying network densities. The network was tested with 20, 40, 60 and 80 GUEs to specifically evaluate the scalability of the resource allocation mechanisms. Each configuration was simulated for a continuous duration of 10 minutes. This timeframe was chosen to ensure the network reaches a steady state after all the nodes are connected to the UAV. Because the simulation relies on random-duration call lengths and a random number of data packets, a 10-minute window allows these traffic models to cycle completely multiple times. Furthermore, every simulation setup was executed five times, and the results were averaged. This smooths out statistical anomalies caused by overly optimal or suboptimal initial random node placements, ensuring that the final evaluation metrics are robust and reflective of the architecture's true performance.

4.1.2. User Traffic Generation

In a disaster zone, mobile device usage shifts away from continuous non-essential background traffic (such as automated application updates and background cloud synchronisation) toward essential, discrete communication tasks. To accurately model this bursty human behaviour, the simulation employs a Poisson arrival process for session initiation. The idle time between a user's communication attempts follows an exponential distribution. This applies uniformly across all traffic types, ensuring that session requests reach the UAV relay randomly and realistically, rather than in an artificial, continuous loop.

Upon the expiration of this designated idle period, a user initiates a "session", which is a distinct period of active communication. The simulation determines the nature of this session by applying a probabilistic split reflecting the specific demands of the network scenario. A session takes one of two forms: a Voice call or a Data session. The duration of these sessions also reflects emergency realities.

1. **Voice Calls:** Modelled as a full-duplex stream where both the initiating user and the receiving user generate a packet every 20 ms. Because emergency calls are typically brief, with only a rare few lasting more than several minutes, their durations are governed by an Exponential holding time. This statistical curve accurately mirrors real-world distributions, capturing a vast majority of short calls accompanied by a long tail of extended coordination calls.
2. **Data Sessions:** Modelled as a short, discrete burst of varying lengths representing SMS, GPS coordinates, or images. These sessions occupy the channel only for the time required to transmit their specific packet burst.

U2U Traffic Generation

In the out-of-coverage U2U architecture, the UAV operates as an isolated local relay without a backhaul connection to the core network. Consequently, ground users cannot access the internet and external data services. Data traffic is therefore inherently restricted to localised SMS, modelled as a short discrete burst of 1 to 5 packets representing texts, GPS coordinates, or status messages. Because external data services are unavailable, mission-critical voice communication naturally dominates the network traffic. The U2U parameters are thus explicitly configured to simulate this voice-primary, localised environment:

- Session Probability: 70% Voice Call / 30% Data Burst (SMS)
- Data Burst Size: 1 to 5 packets (uniformly distributed)
- Mean Voice Call Duration: 60 seconds (exponentially distributed)
- Mean Idle Time: 180 seconds (exponentially distributed)

U2N Traffic generation

In the U2N architecture, the UAV establishes a backhaul link to a functional terrestrial base station, bridging out-of-coverage users to the internet. This external connectivity fundamentally alters user traffic dynamics. Ground users can now access external services and transmit larger data payloads, such

as compressed images of disaster damage and messages to family members outside the affected zone. Consequently, the traffic distribution shifts to a more data-heavy split. Because users actively refresh feeds for evacuation updates or await incoming messages, the idle time between device interactions decreases. Furthermore, when voice calls occur, they tend to last longer as users communicate with relatives located outside the affected zone. The U2N parameters are explicitly configured to simulate this internet-connected, yet emergency-focused environment:

- Session Probability: 40% Voice Call / 60% Data Burst
- Data Burst Size: 5 to 30 packets (uniformly distributed)
- Mean Voice Call Duration: 2 minutes (exponentially distributed)
- Mean Idle Time: 120 seconds (exponentially distributed)

4.1.3. UAV positioning

To evaluate the benefits of autonomous UAV mobility on overall signal link quality, a dedicated positioning simulation was designed. In a disaster response scenario, the geographic distribution of ground users is rarely static or uniformly distributed. To adapt to these conditions, the simulated UAV utilises the geographic coordinates and signal quality metrics (detailed in Table 3.1) that are periodically transmitted by the GUEs within their heartbeats. By processing this data, the UAV continuously calculates an optimal hovering position and physically moves toward it as the simulation progresses.

For this simulation, the UAV employs a simple centroid calculation algorithm, determining its target destination by averaging the coordinates of all currently connected GUEs. While this provides a functional baseline to demonstrate the concept, it represents a simplified positioning algorithm. In a physical deployment, an optimal positioning algorithm would need to account for environmental shadowing and multipath fading. Furthermore, a more advanced deployment could apply weighted factors to the nodes, giving priority to devices that are actively transmitting, or applying heavier weights to edge nodes to ensure they remain safely above the SNR disconnect threshold.

To isolate and measure the impact of this mobility, the simulation was executed in two distinct configurations under identical network conditions and user layouts: one where the UAV remained completely static at its initial deployment location, and one where the UAV dynamically updated its position. Throughout both runs, the physical layer metrics were continuously logged, specifically the average SNR across the entire network and the minimum SNR of the weakest link. The results of these two runs are directly compared and analysed in Section 4.2.3 to quantify the benefits of the mobile aerial relay.

4.2. Results and Analysis

This section presents the evaluation of the aerial relay architecture, analysing the results generated from the previously defined simulations. To assess the network's capabilities, the simulation logs a diverse set of metrics, tracking everything from collision rates to end-to-end scheduling delays. The exact definitions and calculation methods for these metrics are detailed in Appendix C. The raw data from the simulation runs are documented in Appendix D for reference. The following subsections distil these findings, providing a comparative analysis between the baseline and the proposed enhancements, highlighting the key insights and architectural trade-offs observed.

4.2.1. Baseline Analysis

The baseline Mode 2 simulation demonstrates a clear increase in packet collisions as the number of active GUEs grows. In this context, the number of connected GUEs serves as a direct proxy for network load. As the number of connected GUEs increases, the demand on the Sidelink resource pool scales proportionally. As illustrated in Figure 4.2 for both U2U and U2N environments, the network experiences a severe degradation in reliability as the active GUE density scales from 20 to 80 nodes. The total collision rate (indicated by the line graph) exceeds 3% for the scenarios involving more than 20

users. At 3% packet loss, voice call quality degradation becomes noticeable [48].

Analysing the absolute collision count (represented by the bars in Figure 4.2) reveals that the total packet loss is driven by two distinct phenomena: physical collisions and half-duplex (HD) collisions. Physical collisions occur when two or more nodes transmit on the exact same time-frequency block, resulting in both packets being unresolvable at the receiver. Conversely, HD collisions are a hardware-induced limitation of out-of-coverage D2D communications operating within a shared frequency band. Because a Sidelink transceiver relies on a single RF front-end without a duplexer to separate sub-channels, it cannot transmit and receive simultaneously. Consequently, if a node is transmitting a packet in a specific time slot, it cannot receive any incoming transmissions at the same moment, even if the physical resource blocks do not overlap.

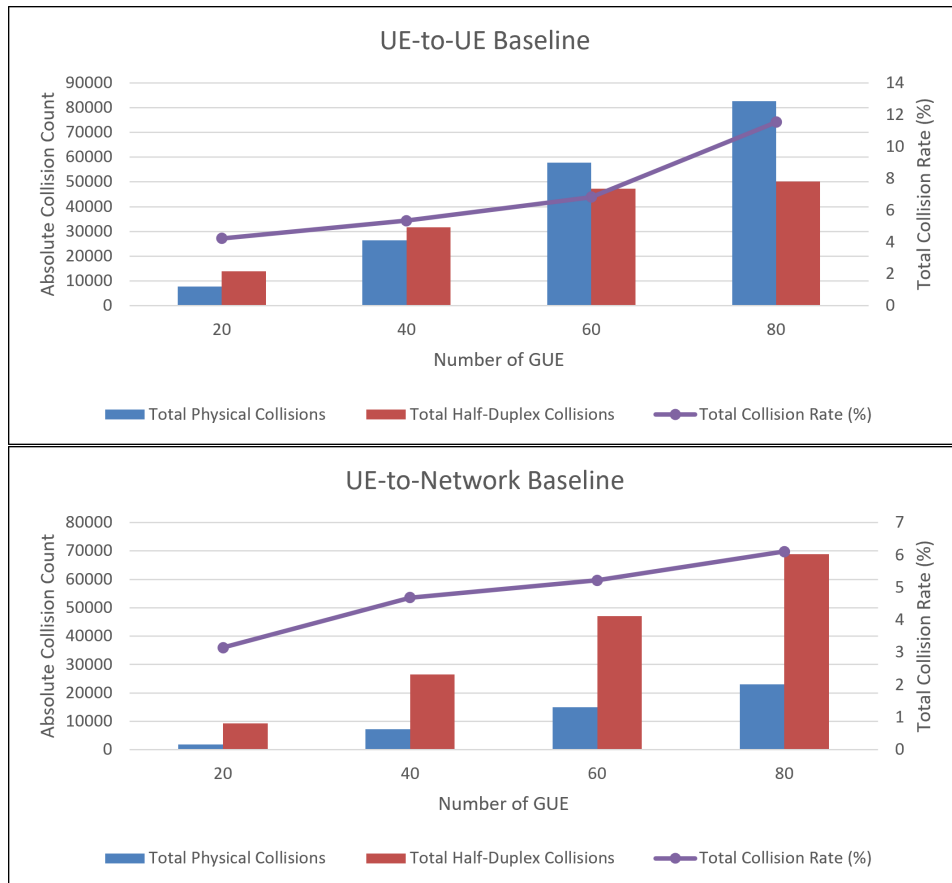


Figure 4.2: Total collision rates and absolute collision breakdowns for U2U and U2N architectures versus the number of active GUEs.

While the overall growth in collisions is driven by the sheer volume of transmissions, it is notable that HD constraints are a dominant driver of network failure. Standard Mode 2 communication (explained in Section 3.1.6) degrades not only due to physical resource contention but also due to pervasive HD collisions. These collisions stem from the inherently flat design of standard D2D protocols, which lack explicit uplink-downlink separation. While traditional D2D networks do not require directional separation, introducing a UAV relay fundamentally shifts the network into a centralised topology, necessitating a distinction between uplink and downlink traffic. To further investigate the impact of the half-duplex constraint identified above, we can deconstruct these specific failures by source of deafness. Specifically, an HD collision can be categorised as either the GUE being deaf while transmitting or the UAV relay being deaf while transmitting.

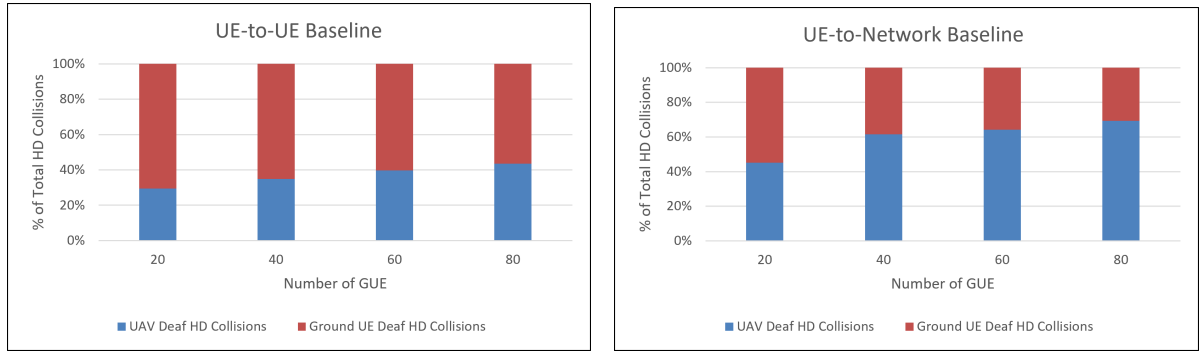


Figure 4.3: Distribution of HD collisions attributed to UAV versus GUE deafness for U2U and U2N architectures versus the number of active GUEs..

As demonstrated in Figure 4.3, the proportion of collisions caused by UAV blindness is significantly higher in the U2N architecture compared to the U2U architecture. In a U2U architecture, the UAV manages localised, intra-cluster traffic between ground peers. In contrast, within a U2N architecture, the UAV functions as the gateway to the broader internet. Consequently, the UAV must receive heavy external data payload traversing the Uu backhaul interface from the base station and continuously relay this payload down through the Sidelink channel. This heavy downlink requirement forces the relay to spend a much larger fraction of its operational time in a transmitting state, leading directly to a higher proportion of UAV blindness.

Furthermore, the data illustrate that as the number of active GUEs increases, the percentage of collisions attributed specifically to UAV deafness scales upward. This trend implies that as network demand grows, the relay is forced to transmit more frequently, thereby blinding itself to incoming uplinks. This confirms that the UAV acts as the primary bottleneck of the system. Ultimately, this exposes a fundamental architectural mismatch in applying the standard 3GPP Sidelink Mode 2 protocol to this architecture. Mode 2 was fundamentally designed for decentralised, peer-to-peer (P2P) communication. These high collision rates confirm that this standard model is fundamentally incompatible with the demands of a centralised UAV-assisted relay network.

4.2.2. Proposed Model Results

Having analysed the baseline performance and identified distributed sensing and half-duplex blindness as a catalyst for the network failure, the proposed operational model shifts to a UAV-governed topology, establishing a strict Time-Division Duplexing (TDD) frame to separate uplink and downlink phases. As illustrated in Figure 4.4, the proposed architecture yields a drastic reduction in total collision rates compared to the baseline. Even under high network load (80 active GUEs), the collision rate for both the U2U and U2N proposed models remains effectively near zero.

To fully understand the operational improvements of the proposed architecture, it is necessary to differentiate between the total collisions recorded during the entire simulation and the subset of post-setup collisions. Total collisions encompass every collided transmission from the moment the UAV is deployed. In contrast, post-setup collisions are a specific subset defined as any collision that occurs after all GUEs have completed their initial handshake with the UAV. Isolating this subset is critical for evaluating the performance of the network during its steady-state operation.

As demonstrated in Table 4.1, the proposed architecture completely eradicates both physical and half-duplex collisions after the setup phase, reducing the count to exactly zero. The minor cluster of collisions recorded in the total count occurs exclusively during the initial connection phase. These initial collisions are a necessary operational reality because, upon deployment, the UAV has no prior knowledge of the ground user population. Consequently, idle devices are forced to rely on standard, uncoordinated Mode 2 to transmit their initial connection requests on a shared channel. However, the moment the UAV processes these requests and issues explicit scheduling assignments, the nodes

enter a fully deterministic schedule. The data proves that once this initial setup is complete, the centralised algorithm guarantees a collision-free environment.

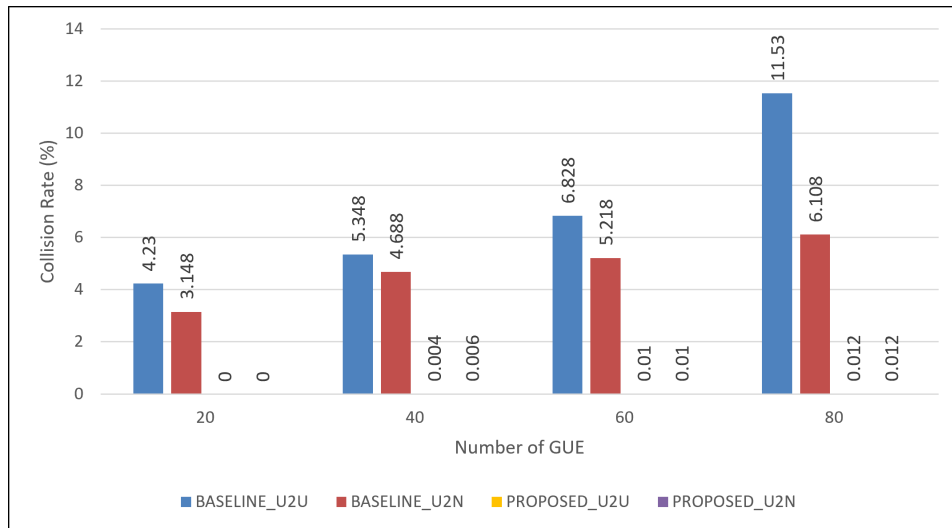


Figure 4.4: Total collision rates for U2U and U2N architectures versus the number of active GUEs.

Simulation Mode	Total Physical Collisions	Total Half-Duplex Collisions	Post-Setup Physical Collisions	Post-Setup Half-Duplex Collisions
BASELINE_U2U	138693	66900	121414	62979
BASELINE_U2N	22399	65948	16606	54175
PROPOSED_U2U	90	196	0	0
PROPOSED_U2N	88	185	0	0

Table 4.1: Comparison of physical and half-duplex collisions between baseline and proposed simulation modes (80 GUEs).

U2U Proposed Model Results

To evaluate the practical viability of the proposed architecture, the network must be assessed not just on physical-layer spectral cleanliness, but also on the application-layer QoS experienced by the end user.

Figure 4.5 illustrates the Packet Delivery Ratio (PDR) of the network, defined as the total number of successfully delivered data packets divided by the total number of generated packets. As established in the baseline analysis (Section 4.2.1), an increase in the number of active GUEs increases collisions. This accounts for the degradation in PDR observed in the baseline as network load increases. In contrast, the proposed model maintains a near-perfect PDR across all load conditions. The nominal fraction of packets lost in the proposed architecture occurs exclusively during the connection establishment phase, detailed in Table 4.1.

Transitioning from a distributed scheduling model to a centralised model introduces an inherent architectural trade-off in latency. In the baseline model, a GUE senses the medium and transmits autonomously. In the proposed model, a GUE must first transmit a resource request and wait to receive a dedicated resource grant from the UAV before it is permitted to send user-plane data. This control-plane overhead is captured by the Average Scheduling Delay, which measures the time a GUE waits for a resource grant upon sending the resource request. This metric is inherently zero for the baseline's

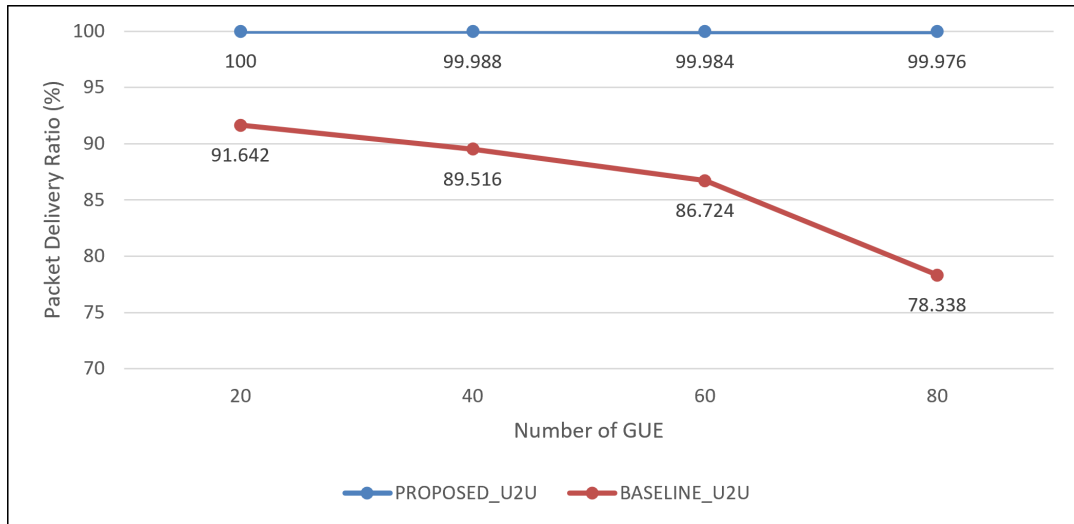


Figure 4.5: Packet Delivery Ratio (%) for baseline and proposed models versus the number of active GUEs.

uncoordinated model. As illustrated in Figure 4.6, the deterministic design of the TDD frame ensures this wait time is highly predictable. Because the network strictly alternates between uplink and downlink phases every 10 ms, the scheduling delay consistently averages approximately 12 to 15 ms regardless of network density.

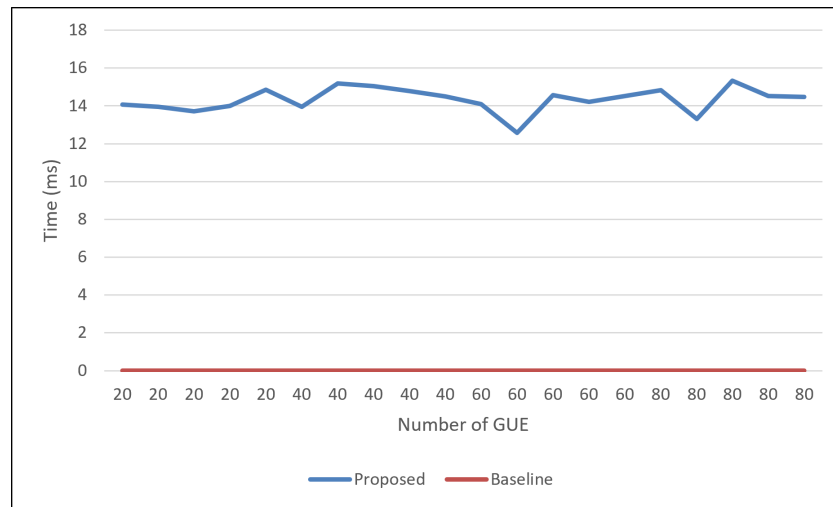


Figure 4.6: Average scheduling delay for U2U architecture versus the number of active GUEs.

To fully contextualise the operational cost of this scheduling overhead, we need to examine the total End-to-End (E2E) delay. This metric measures the true latency experience over the PC5 interface during physical transmission. It is calculated as the time elapsed from the transmission of an aperiodic data packet at the source node, passing through the UAV relay, to its successful reception at the destination GUE, explicitly excluding the scheduling wait.

As demonstrated in Figure 4.7, despite the baseline having zero scheduling delay, its uncoordinated nature forces nodes into collision-induced retransmissions, driving its E2E delay to average over 71 ms. Conversely, the proposed model completely bypasses these retransmissions by guaranteeing a collision-free channel. While the proposed model incurs an initial 15 ms scheduling penalty, its E2E transmission delay is 20 ms, achieving a total delay of 34 ms. By trading a short, predictable wait for a guaranteed, collision-free transmission slot, the proposed algorithm bypasses the retransmission cycle

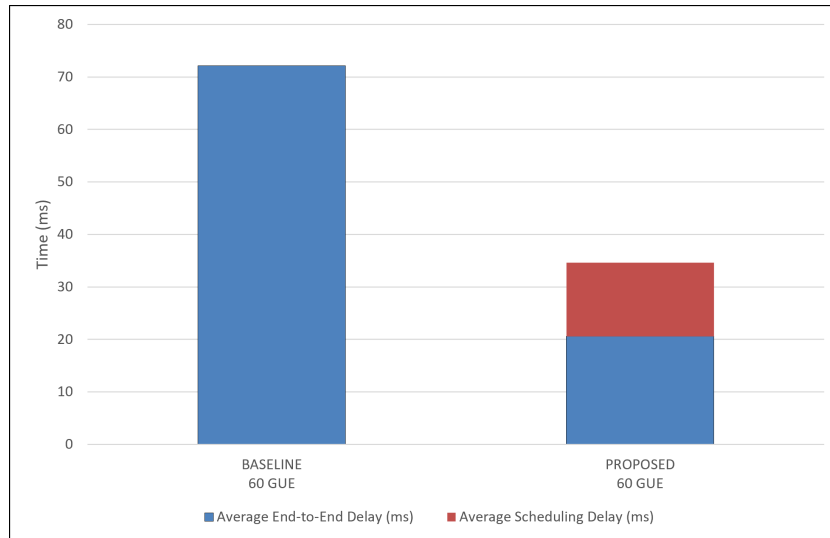


Figure 4.7: Average network latency for the baseline and proposed models for 60 active GUEs.

entirely, resulting in a data delivery pipeline that is two times faster and deterministically stable under heavy network load.

U2N Proposed Model Results

The U2N architecture exhibits QoS improvements directly analogous to the previously discussed U2U scenario. Because the fundamental centralised scheduling mechanism remains identical, the proposed U2N model maintains near-perfect Packet Delivery Ratios and deterministic End-to-End latency, successfully preventing the collisions observed in the baseline.

However, transitioning from an autonomous distributed protocol to a centralised, UAV-governed architecture necessitates a trade-off regarding signalling overhead. As illustrated in Figure 4.8, the proposed model generates a significantly higher volume of control plane messages compared to the baseline. This explicit signalling is a mandatory requirement for a centralised controller to function, facilitating dynamic scheduling grants and continuous system telemetry. Crucially, this provides the UAV with vital real-time intelligence, including the precise geographical positions of the active GUEs. While this increases the absolute number of transmissions, the operational cost is minimal because control plane messages are extremely low in bandwidth, occupying only a single Physical Resource Block (PRB).

To fully understand the efficiency of this architecture, it is necessary to evaluate the network's physical resource consumption alongside its data delivery. Figure 4.9 illustrates both the aggregate throughput (represented by the bar chart on the primary axis) and the spectrum utilisation (represented by the line graph on the secondary axis). Spectrum utilisation is defined as the total number of occupied time-frequency resource blocks divided by the total number of theoretically available blocks within the resource pool.

As depicted by the line graph, the proposed model consistently consumes a higher percentage of the available physical spectrum than the baseline. However, the bar chart demonstrates that it simultaneously achieves a substantially higher aggregate throughput, successfully transporting vastly more user data. While higher spectrum utilisation is traditionally viewed as a negative metric indicating network saturation, in this operational context, it is a direct indicator of system efficiency. The baseline network consumes a lower percentage of the spectrum simply because it is failing to operate, severe collision rates prevent efficient utilisation of the available spectrum. Conversely, the proposed model utilises more spectrum because it is successfully executing two concurrent tasks: maintaining the control-plane signalling and reliably transporting user-plane data. By guaranteeing a collision-free environment, the proposed algorithm ensures that the spectrum is never wasted on dropped packets.

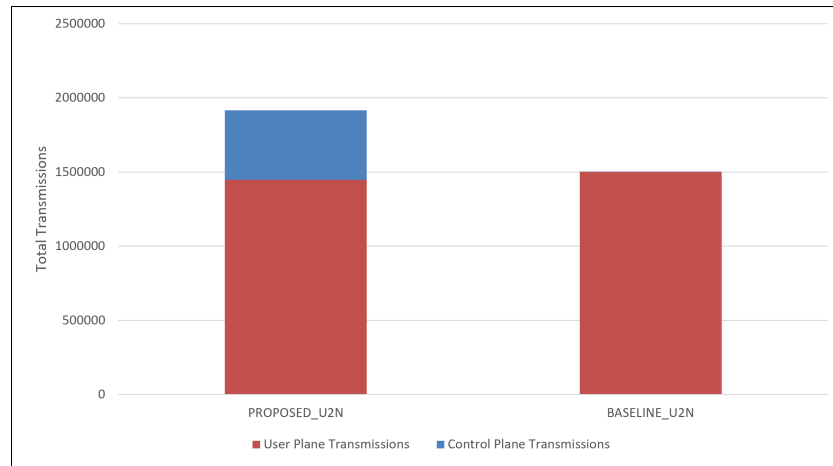


Figure 4.8: Composition of transmissions for the baseline and proposed models for 80 active GUEs.

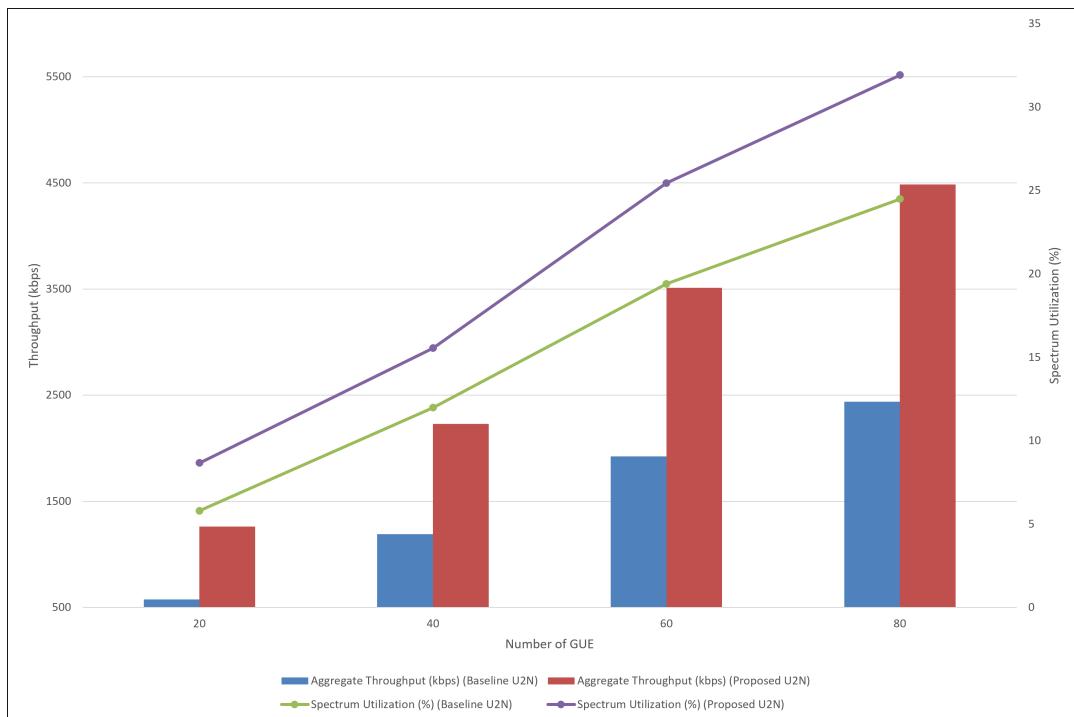


Figure 4.9: Aggregate throughput and Spectrum utilisation for the baseline and proposed models versus the number of active GUEs.

or retransmissions.

4.2.3. UAV Positioning Analysis

In response to Research Question 4, the proposed operational model incorporates a dynamic positioning framework that leverages the control-plane telemetry to physically optimise the network. The methodology of this simulation, wherein the UAV navigates towards the active users, was detailed in Section 4.1.3.

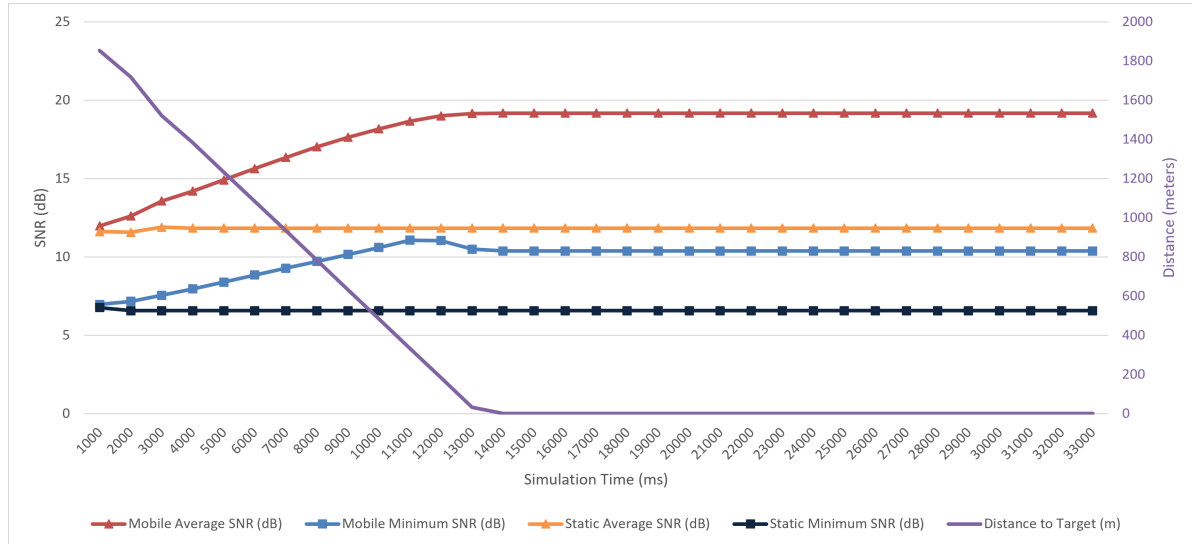


Figure 4.10: Channel quality and trajectory convergence for mobile versus static UAV relays.

Figure 4.10 tracks two distinct sets of metrics to demonstrate the correlation between physical movement and radio link quality. The secondary (right) y-axis tracks the spatial movement of the UAV, defined as the "Distance to target" in meters. This metric represents the physical distance between the UAV's current position and its dynamically calculated optimal position. As the simulation progresses and the UAV actively flies towards this calculated centroid, this distance steadily decreases towards zero. Simultaneously, the primary (left) y-axis plots the corresponding Channel Quality, measured as the Signal-to-Noise Ratio (SNR) in decibels (dB). This axis tracks both the average network SNR and the minimum (worst-case edge user) SNR. To provide a comparative baseline, these identical SNR metrics are also plotted for a stationary UAV scenario.

Figure 4.10 demonstrates a direct improvement in link quality driven by physical mobility. As the simulation progresses, the distance to the target location decreases, and the mobile UAV minimises the path loss between itself and the ground cluster. Consequently, the light blue and red lines representing the mobile UAV's SNR steadily climb. The moment the UAV reaches its ideal hovering position (Distance to Target becomes zero), both the average and minimum SNR stabilise at their new, optimised maximums.

By comparing the mobile metrics to the static baseline, the mobile system yields a tangible link quality improvement of 3.8 dB in minimum SNR and 7.3 dB in average SNR. While the exact magnitude of this dB improvement will naturally vary depending on the UAV's initial deployment coordinates and the specific geographical spread of the ground users, the structural benefit remains consistent. Ultimately, this simulation proves that significant SNR improvements can be achieved simply by leveraging the inherent mobility of the UAV. By physically adapting to the network topology in real time, the mobile aerial relay dynamically mitigates path loss and protects edge users from potential link failure. This highlights a fundamental operational advantage that a mobile UAV holds over traditional, fixed-position cellular infrastructure.

5

Conclusions and Recommendations

This chapter concludes the research on the proposed UAV relay operational model. Section 5.1 outlines the key findings, directly addressing the core research questions defined in Section 1.4. The final section outlines recommendations for future work, identifying specific areas for further research.

5.1. Conclusions

This thesis bridges the gap between theoretical 3GPP terrestrial Sidelink specifications and a deployable operational model for UAV-assisted relays, designed specifically for disaster scenarios. The overarching conclusion of this research is that a UAV-assisted relay network can effectively restore vital communication without relying on terrestrial infrastructure during a crisis. By transforming the UAV into an active network coordinator that integrates centralised resource scheduling with autonomous mobility, the system shifts from a collection of uncoordinated devices into a cohesive, self-optimising aerial network.

Standard terrestrial D2D applications are predominantly designed for network-assisted architectures or for out-of-coverage scenarios where only a limited number of remote UEs connect to a single ground-based relay. In contrast, deploying a UAV as an aerial relay fundamentally alters the network topology. The elevated position of the UAV's provides a privileged LoS footprint, enabling a significantly larger density of ground users to connect simultaneously. This dictates that the underlying communication protocols must be capable of robust scaling, a requirement that existing out-of-coverage standards struggle to meet. As demonstrated by the simulation results, the standard Mode 2 autonomous resource allocation fails to scale effectively, suffering from severe performance degradation as the number of active Ground User Equipment (GUEs) increases.

5.1.1. Revisiting the Research Questions

To provide a structured overview of these findings, this section revisits the research questions and answers them directly based on the results of this thesis.

RQ1: To what extent are the current 3GPP specifications for terrestrial relays suitable for the specific requirement of aerial relaying?

The current 3GPP standards for terrestrial relays provide a mature and robust framework for Sidelink communication and relay operation. The specifications offer different mechanisms for direct discovery, supporting Model A (Announcing) and Model B (Solicitation and Response) discovery, as well as link establishment through both Layer 2 and Layer 3 relay architectures. While these standards are functionally capable of establishing an aerial relay system, the analysis and simulation demonstrated that terrestrial specifications are highly inefficient when directly applied to aerial relaying. Because the standard architecture relies on distributed Mode 2 sensing without a central coordinator, the system suffers from severe scalability issues. As the number of GUEs increases, the network experiences high levels of physical resource contention and HD collisions, ultimately demonstrating that uncoordinated

Sidelink protocols are inefficient for the heavy traffic demands of an aerial emergency network.

RQ2: What needs to be added to the 3GPP standards to fulfil the requirements of an operational model for UAV-assisted relaying based on device-to-device communication?

To transition from a theoretical standard to a functional operational model, certain prescriptive decisions need to be made from the available 3GPP toolbox, such as explicitly choosing Model A (Announcing) discovery over Model B (Solicitation and Response) and mandating a Layer 3 relay architecture rather than Layer 2. Beyond these configuration choices, a few critical enhancements must be integrated into the framework. The synchronisation hierarchy requires a slight modification (as described in Section 3.1.2) to prevent network fragmentation in the event of a total GNSS failure. Furthermore, the architecture necessitates a robust, centralised resource allocation strategy to replace the collision-prone autonomous Mode 2 selection. To leverage the benefits of a mobile UAV, this architecture also integrates telemetry signalling to enable autonomous 3D positioning.

RQ3: What resource allocation strategy can be designed to maximise throughput and mitigate collisions within this aerial relay architecture?

To mitigate the severe collision rates observed when standard Mode 2 is applied to this architecture, this thesis proposes a strictly UAV-governed resource allocation strategy operating within a deterministic TDD framework. By enforcing strictly reserved uplink and downlink phases within the TDD frame, the resource allocation strategy effectively eradicates half-duplex collisions. Furthermore, the algorithm strictly separates the Control Plane from the User Plane, utilising a persistent low-bandwidth control slot alongside an on-demand user plane. This provides a collision-free, periodic control slot for every connected GUE, enabling low-latency control signalling and on-demand user-plane grants without the unpredictability of contention-based sensing.

RQ4: What specific signalling exchanges are required within the operational model to provide the radio environment data necessary for a positioning algorithm to dynamically optimise the UAV's three-dimensional location?

The proposed model leverages the UAV-governed resource allocation strategy to establish a unified telemetry heartbeat mechanism. Instead of relying on heavy application-layer protocols, each GUE transmits a compact status report during its dedicated uplink control slot. This signalling provides the UAV with the exact 3D GPS coordinates of the user alongside critical channel quality metrics, specifically the Sidelink Reference Signal Received Power (S-RSRP), Sidelink Received Signal Strength Indicator (S-RSSI), Channel Quality Indicator (CQI), and Packet Error Rate (PER). This continuous, low-overhead feedback loop serves as the input for the UAV's positioning algorithm, allowing it to calculate an optimal hovering position dynamically.

RQ5: How does the proposed 3GPP-aligned model, inclusive of the resource allocation strategy and signalling support for UAV positioning, perform when evaluated through system-level simulation?

The system-level simulation validates that the proposed operational model significantly outperforms the 3GPP baseline across all key metrics. The implementation of the UAV-governed resource allocation strategy eliminated all steady-state physical and half-duplex collisions, maintaining a near-perfect Packet Delivery Ratio even under heavy network loads. Furthermore, the evaluation of the telemetry-driven positioning algorithm demonstrated substantial gains, yielding an average SNR improvement of 7 dB compared to a static relay. This shows that integrating structural protocol enhancements with autonomous mobility transforms the UAV from a simple relay into a highly efficient, self-optimising aerial network.

5.2. Recommendations for Future Research

While this thesis establishes an operational model for UAV-assisted Sidelink relaying, several avenues remain for future exploration. The following areas are recommended for subsequent research:

- **Advanced UAV Positioning Algorithms:** The current operational model incorporates the specific signalling mechanisms required to serve as input for a dynamic positioning algorithm. Future

research should utilise this input to develop sophisticated 3D trajectory algorithms that account for complex environmental variables such as terrain obstacles, shadowing, and multipath fading. Additionally, these algorithms could incorporate weighted factors to prioritise edge users or devices with active, high-priority data streams.

- **GUE-to-GUE Mesh Networking:** The proposed architecture operates on a strict star topology where all traffic routes through the central UAV. Expanding the operational model to support direct GUE-to-GUE Sidelink communication alongside the aerial relay would facilitate a hybrid mesh network. This would allow ground users to act as secondary relays, significantly extending the communication footprint at the cost of increasing the complexity.
- **Adaptive TDD Scheduling:** While the current static 50/50 TDD frame effectively eliminates steady-state collisions and ensures deterministic latency, it lacks the elasticity to handle highly asymmetric traffic patterns. Future research should explore a dynamic TDD scheduler that adjusts the uplink-to-downlink slot ratio based on real-time traffic volume. This extension must include a robust mechanism to broadcast slot format updates without introducing synchronisation drift or reintroducing collisions.
- **Physical Layer Optimisations:** To manage computational complexity, the current simulation abstracts certain physical layer mechanics. Future evaluations should incorporate dynamic link adaptation, specifically, adaptive Modulation and Coding Schemes (MCS) and closed-loop transmit power control. Additionally, integrating full physical-layer channel sensing for the baseline Mode 2 comparison would provide a more granular representation of RF interference and spatial reuse.
- **U2N Backhaul Optimisation:** This thesis assumes an ideal, unbottlenecked Uu backhaul connection between the UAV and the functional base station. Subsequent research focusing on the UE-to-Network model should evaluate the impact of backhaul congestion at the surviving terrestrial zone. Future work must investigate whether bandwidth enhancement techniques on the Uu interface, such as Carrier Aggregation and EN-DC (E-UTRAN-NR Dual Connectivity), will be sufficient to support the heavy traffic expected between the UAV and the gNB in a disaster scenario.

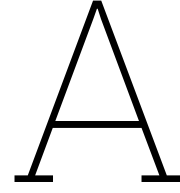
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Literature Summary

Table A.1: Overview of Literature reviewed in this research.

Authors and Reference	Focus
Saif et al. [21]	UAV base station framework
Alsharoa et al. [22]	UAV relay framework
Alsharoa et al. [23]	Multi-UAV relay framework
Ghosh et al. [24]	Multi-hop UAV relay framework
Rani et al. [1]	Sensor-aided UAV base station
Ansari et al. [27]	UAV base station with backhaul connection
Banagar et al. [28]	UAV base station with backhaul connection
Yang et al. [5]	Position optimisation for UAV clusters
Bor-Yaliniz et al. [6]	Position optimisation for UAV base station
Pourbaba et al. [10]	Trajectory optimisation for UAV relay
Selim et al. [7]	Energy and Position Optimisation for UAV base station
Ji et al. [11]	Trajectory optimisation for UAV relay
Sabzehali et al. [8]	Optimizing number and position of UAV base station
Firozjae et al. [9]	Position optimisation for UAV relay
Zhang et al. [12]	Trajectory and transmit power optimisation for UAV relay
Zeng et al. [13]	Trajectory and transmit power optimisation for UAV relay
Barik et al. [14]	Trajectory prediction for UAV relay
Monemi et al. [15]	Link and transmit power optimisation for UAV relay
Nguyen et al. [16]	Transmit power optimisation for UAV relay
Tatar Mamaghani et al. [17]	Transmit power optimisation for UAV relay
Wang et al. [18]	Transmit power optimisation for UAV relay
Wang et al. [19]	Transmit power optimisation for UAV relay
Deng et al. [20]	Transmit power optimisation for UAV relay
Ali et al. [29]	System-level evaluation of NR Sidelink Mode 2
Annu et al. [30]	Survey of resource allocation and RRA challenges for 6G V2X
Wang et al. [31]	Distributed RRA for out-of-coverage D2D communication
Conserva et al. [32]	Performance analysis of RRA for UAV-enhanced Sidelink
Conserva et al. [33]	RRA framework incorporating temporal coupling
You et al. [34]	RRA incorporating energy harvesting and task offloading
Dong et al. [35]	Frequency assignment using radio maps
Zhong et al. [36]	Optimisation of deployment, channel allocation and relay assignment
Pan et al. [37]	Optimisation of UAV number, position, power, velocity and RRA

B

3GPP TS Analysis

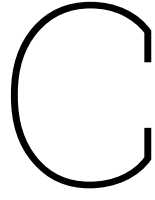
Table B.1: Overview of 3GPP Technical Specifications analysed in this thesis

TS Number	Release	Description
23.256	19	Support of UAS connectivity, identification and tracking; (Stage 2)
23.285	19	Architecture enhancements for V2X services
23.286	19	Application layer support for V2X services; Functional architecture and information flows
23.303	19	Proximity-based services (ProSe) (Stage 2)
23.304	19	Proximity-based Services (ProSe) in the 5G System (5GS)
23.501	19	System architecture for the 5G System (5GS) (Stage 2)
23.502	19	Procedures for the 5G System (5GS)
24.334	19	Proximity-services (ProSe) User Equipment (UE) to ProSe function protocol aspects (Stage 3)
24.501	19	Non-Access-Stratum (NAS) protocol for 5G System (5GS) (Stage 3)
29.343	19	Proximity-services (ProSe) function to ProSe application server aspects (PC2) (Stage 3)
29.344	19	Proximity-services (ProSe) Function to Home Subscriber Server (HSS) aspects (Stage 3)
29.345	19	Inter-Proximity-services (ProSe) Function signalling aspects (Stage 3)
33.303	19	Proximity-based Services (ProSe); Security aspects
33.501	19	Security architecture and procedures for 5G System
36.213	19	E-UTRA; Physical layer procedures
36.214	19	E-UTRA; Physical layer Measurements
36.300	19	E-UTRA and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; (Stage 2)
36.321	19	E-UTRA; Medium Access Control (MAC) protocol specification
36.322	19	E-UTRA; Radio Link Control (RLC) protocol specification
36.331	19	E-UTRA; Radio Resource Control (RRC); Protocol specification
37.324	19	E-UTRA and NR; Service Data Adaptation Protocol (SDAP) specification
38.104	19	NR; Base Station (BS) radio transmission and reception
38.211	19	NR; Physical channels and modulation
38.212	19	NR; Multiplexing and channel coding
38.213	19	NR; Physical layer procedures for control
38.214	19	NR; Physical layer procedures for data
38.300	19	NR and NG-RAN Overall Description (Stage 2)
38.305	19	NG-RAN; Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN
38.306	19	User Equipment (UE) radio access capabilities
38.321	19	NR; Medium Access Control (MAC) protocol specification

Continued on next page...

Table B.1 – continued from previous page

TS Number	Release	Description
38.322	19	NR; Radio Link Control (RLC) protocol specification
38.331	19	Radio Resource Control (RRC); Protocol specification
38.101-1	19	User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone



Evaluation Metrics

C.1. Data Reliability (Drops & Retries)

- **Retransmissions Attempted:** The total number of times the network tried to resend a data packet due to a delivery failure
- **Data Packets Dropped:** The total volume of non-real-time application data permanently discarded by the network. Calculated as an absolute count of packets discarded after exhausting all allowed retransmission attempts.
- **Voice over IP Packets Dropped:** The total volume of real-time voice data permanently discarded. Calculated as an absolute count of failed voice transmissions (which are dropped without retransmission).

C.2. Collision Counts (Absolute)

- **Total Physical Collisions:** The absolute count of instances where two or more nodes transmitted simultaneously on the exact same frequency sub-channel and time slot, corrupting the signal.
- **Total Half-Duplex Collisions:** The absolute count of packets lost because the intended receiver was actively transmitting at that exact moment (hardware deafness).
- **Half-Duplex Collisions (UAV Deaf):** The subset of half-duplex collisions where the UAV missed an incoming packet from a Ground UE, specifically because the UAV was transmitting.
- **Half-Duplex Collisions (Ground UE Deaf):** The subset of half-duplex collisions where a Ground UE missed an incoming packet specifically because that Ground UE was transmitting.
- **Post-Setup Collisions (Physical and Half-Duplex):** The absolute count of physical/half-duplex collisions occurring exclusively during the steady-state data transfer phase, filtering out the initial connection setup "storm."

C.3. Collision Rates (Percentages)

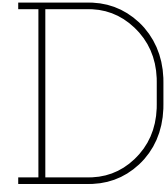
- **Physical Collision Rate (%):** The probability that a transmission is corrupted by concurrent physical interference. Calculated as $(\text{Total Physical Collisions} / \text{Total Transmissions}) * 100$.
- **Half-Duplex Collision Rate (%):** The overall percentage of network transmissions lost to hardware deafness. Calculated as $(\text{Total Half-Duplex Collisions} / \text{Total Transmissions}) * 100$.
- **Total Collision Rate (%):** The aggregate interference rate of the network. Calculated as the sum of the Physical and Half-Duplex Collision Rates.
- **Half-Duplex UAV/UE Deafness Rate (%):** The percentage of network traffic lost specifically to UAV/UE blindness. Calculated as $(\text{UAV/UE Deaf Collisions} / \text{Total Transmissions}) * 100$.

C.4. Latencies

- **Average End-to-End Delay (ms):** The latency experienced over the PC5 interface, evaluated exclusively for aperiodic data packets (excluding voice traffic). Calculated as the average time elapsed from a data packet's MAC-layer generation at the source node, passing through the UAV, to its successful reception at the destination.
- **Average Scheduling Delay (ms)[NEW ONLY]:** A measure of control plane efficiency and network congestion. Calculated as the average time a GUE waits from the transmission of a resource request until the successful reception of a dedicated grant from the UAV scheduler

C.5. System Performance

- **Packet Delivery Ratio (%)**: The probability of successful end-to-end data transfer. Calculated as $(\text{Total Successfully Delivered Data Packets} / \text{Total Generated Application Data Packets}) * 100$.
- **Aggregate Throughput (kbps)**: The raw volume of user data successfully transported. Calculated as $(\text{Total Delivered Data Bits} / \text{Total Simulation Time in Seconds})$. Total Delivered Data Bits is calculated as $(\text{Total Delivered Packets} * 256 \text{ Bytes per packet} * 8 \text{ bits per Byte})$
- **Spectrum Utilisation (%)**: The physical efficiency of radio resource consumption. Calculated as $(\text{Total Consumed Resource Blocks} / \text{Total Theoretical Available Resource Blocks}) * 100$.
- **Implicit Link Failure Rate (%)****[NEW ONLY]**: The rate of connections lost to environmental factors (range or severe interference). Calculated as $(\text{Connections Dropped due to Missed Heartbeats} / \text{Total Connection Attempts}) * 100$.
- **Admission Rejection Rate (%)****[NEW ONLY]**: The rate at which the network denies new users due to capacity exhaustion. Calculated as $(\text{Rejected Connection Requests} / \text{Total Connection Attempts}) * 100$.



Simulation Results

Table D.1: Detailed simulation metrics for U2U scenarios across scaling network loads.

Metric	PROPOSED U2U				BASELINE U2U			
	20	40	60	80	20	40	60	80
Total Transmissions	703511	1228442	1915226	2547850	511743	1088554	1543584	1571620
Control Plane Transmissions	116377	230890	342699	457314	90	215	376	560
User Plane Transmissions	587133	997552	1572526	2090536	511653	1088339	1543208	1571060
Total Generated Data Packets	293487	498625	786065	1045035	259277	554862	792822	814055
Successful Decodes	703501	1228379	1915053	2547517	490002	1030361	1438532	1438860
Signal to Noise Ratio Failures	0	0	0	0	0	0	0	0
Retransmissions Attempted	0	0	0	0	2	9	16	23
Data Packets Dropped	0	0	1	2	1	6	13	13
Voice over IP Packets Dropped	3	32	106	216	21727	58140	104935	132567
Total Physical Collisions	2	18	50	96	7731	26459	57722	82646
Total HD Collisions	7	45	123	237	14009	31734	47331	50115
HD Collisions (UAV Deaf)	7	45	123	237	4126	11076	18756	21770
HD Collisions (Ground UE Deaf)	0	0	0	0	9883	20658	28575	28345
Post-Setup Physical Collisions	0	0	0	0	7716	25654	53457	67855
Post-Setup HD Collisions	0	0	0	0	13990	31342	45931	46579
Physical Collision Rate (%)	0	0	0	0	2	2	4	8
HD Collision Rate (%)	0	0	0	0	3	3	3	4
Total Collision Rate (%)	0	0	0	0	4	5	7	12
HD UAV Deafness Rate (%)	0	0	0	0	1	1	1	2
HD Ground UE Deafness Rate (%)	0	0	0	0	2	2	2	2
Average End-to-End Delay (ms)	21	21	21	21	71	72	72	74
Average Scheduling Delay (ms)	14	15	14	14	0	0	0	0
Packet Delivery Ratio (%)	100	100	100	100	92	90	87	78
Aggregate Throughput (kbps)	1002	1702	2683	3566	811	1695	2348	2947
Spectrum Utilization (%)	12	20	32	42	8	18	25	32
Implicit Link Failure Rate (%)	0	0	0	0	0	0	0	0
Admission Rejection Rate (%)	0	0	0	0	0	0	0	0

Table D.2: Detailed simulation metrics for U2N scenarios across scaling network loads.

Metric	PROPOSED U2N				BASELINE U2N			
	20	40	60	80	20	40	60	80
Total Transmissions	520086	933029	1527201	1915756	350680	729224	1184537	1501263
Control Plane Transmissions	117428	234946	352386	469051	98	237	456	814
User Plane Transmissions	402658	698082	1174815	1446705	350581	728987	1184081	1500448
Total Generated Data Packets	369987	653322	1029313	1314216	311570	673326	1063728	1364172
Successful Decodes	520070	932972	1527051	1915506	339496	695522	1122610	1409394
Signal to Noise Ratio Failures	0	0	0	0	0	0	0	0
Retransmissions Attempted	0	0	0	0	60	215	417	741
Data Packets Dropped	13	13	37	40	3	19	57	112
Voice over IP Packets Dropped	7	27	76	126	11114	33437	61355	90790
Total Physical Collisions	4	16	42	73	1863	7261	14906	23051
Total HD Collisions	12	40	108	176	9320	26442	47021	68817
HD Collisions (UAV Deaf)	12	40	108	176	4206	16244	30148	47633
HD Collisions (Ground UE Deaf)	0	0	0	0	5115	10198	16873	21184
Post-Setup Physical Collisions	0	0	0	0	1790	6759	12715	16427
Post-Setup HD Collisions	0	0	0	0	9141	25400	42975	56236
Physical Collision Rate (%)	0	0	0	0	1	1	1	2
HD Collision Rate (%)	0	0	0	0	3	4	4	5
Total Collision Rate (%)	0	0	0	0	3	5	5	6
HD UAV Deafness Rate (%)	0	0	0	0	1	2	3	3
HD Ground UE Deafness Rate (%)	0	0	0	0	1	1	1	1
Average End-to-End Delay (ms)	24	25	24	25	71	71	71	71
Average Scheduling Delay (ms)	15	14	15	14	0	0	0	0
Packet Delivery Ratio (%)	100	100	100	100	55	52	53	52
Aggregate Throughput (kbps)	1263	2230	3513	4485	575	1191	1924	2440
Spectrum Utilization (%)	9	16	25	32	6	12	19	24
Implicit Link Failure Rate (%)	0	0	0	0	0	0	0	0
Admission Rejection Rate (%)	0	0	0	0	0	0	0	0