UNIVERSITY OF GREENWICH
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SDN-Based Handoff Management for Hybrid Terrestrial-LEO Satellite Networks in Rural and Disaster Relief Areas

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ABSTRACT

The digital divide between urban and rural areas remains a significant social challenge, exacerbated by the high costs of deploying traditional terrestrial infrastructure in geographically isolated regions. This project investigates the viability of a hybrid network architecture, combining standard terrestrial broadband with a Low Earth Orbit satellite backhaul to provide resilient, continuous connectivity. To manage the routing across this hybrid topology, a Software-Defined Networking approach was utilised. The primary aim was to design, simulate, and evaluate a deterministic handoff management protocol capable of autonomously redirecting user traffic during periods of heavy terrestrial congestion.

Instead of physical hardware, a virtualised testbed was constructed using Mininet to ensure controlled, repeatable testing. Link constraints were configured using TCLink to reflect real-world legislation and proven data, capping the terrestrial link at 10 Mbps and the satellite link at 5 Mbps with an artificial 30 ms delay. A custom Ryu controller was developed in Python to serve as the network's control plane. The algorithm continuously polls port statistics and, upon detecting throughput exceeding a 9.0 Mbps threshold, injects high-priority OpenFlow rules to seamlessly reroute traffic to the backup satellite link.

Testing conducted via UDP traffic floods confirmed the system's reliability and responsiveness, successfully mitigating congestion without manual intervention. While the one-way nature of the handover and the simulated environment present limitations, the findings demonstrate that a lightweight, rule-based SDN protocol is a highly effective, low-cost solution for enhancing disaster relief and rural network infrastructure.

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CONTENTS

1 INTRODUCTION

The ability to setup networks in a rural or disaster areas has never been an efficient process, from getting equipment setup, to calculating the best areas to have access points and ensuring that all nodes have stable connections are just some of the difficulties that have to be overcome in order to set up a reliable network in these difficult environments.(Tirmizi et al., 2022)

A mesh network offers a unique approach to these challenges; a mesh network can group all the available nodes together into a Wide Area Network (WAN). This offers the benefit that in the event one of one nodes on the network fails, it doesn't take the whole chain down, nodes can find other paths instead, greatly improving network resilience. (Karamchand, 2024)

In rural areas, the delivery of a stable and high-quality network connection remains a persistent struggle. Joining and ensuring a fast communication channel with remote communities helps ensure that people who live in remote regions are well connected with the rest of the world and keep them up to date with vital information. (Borgianni et al., 2024)

(Swathi et al., 2024) Suggests that algorithmic approaches are favoured, this is because an algorithm running on a testbed would be able to choose the preferred method of connection Nevertheless, Inter-Mesh link scheduling algorithms need to be investigated more.

(Elbehiry et al., 2025) Investigates using the Bellman-Ford algorithms over something like the Dijkstra algorithm as the end-to-end time is dramatically decreased along with its dynamic nature making it able to find the shortest path while minimising costs. However, the journal also suggests further research is needed since other methods may be more efficient or better suited.

The overall success of this project will be a nodes ability to switch seamlessly between connections to the internet without any effect on the user's end experience. Success will be measured by proving that switching is quicker than remaining on any one network as connection becomes interrupted.

1.1 Background

In modern society digital connectivity is no longer a luxury, it has become a fundamental requirement for, education, remote work and even emergency services. Yet, in rural areas delivering a stable and high-quality internet connection remains a constant struggle. Expanding traditional infrastructure such as laying new fibre-optic cables across miles of inaccessible terrain is often extremely expensive and rarely provides a return on the investment.

A mesh network can offer a highly effective, alternative approach to these challenges. By grouping together nodes in a geographical area such as a rural or disaster relief setup, a mesh topology provides inherent redundancy, if one node fails the network does not suffer a total collapse. Instead, the traffic dynamically finds an alternative route. When a mesh network is paired with a Low earth Orbit (LEO) satellite backhaul, such as those provided by modern mega constellations like starlink, the limitations of geography almost vanish.

Integrating a standard terrestrial link with a LEO satellite introduces complex routing challenges. The overall success of hybrid networks relies entirely on ability to seamlessly switch between the terrestrial link, and the satellite backhaul without any noticeable drop-in service. A highly responsive algorithmic approach is favoured to manage this transition, ensuring that a software controller can accurately monitor congestion and autonomously switch traffic to the most optimal path.

1.2 Aims and Objectives

1.2.1 Aim

This project aims to design, simulate, and evaluate a novel handoff management protocol for a hybrid terrestrial mesh and LEO satellite network to improve connection stability and availability in rural and disaster relief environments.

1.2.2 Objectives

To successfully achieve the aim, this project is broken down into the following measurable objectives:

a) **Literature Review and Project Design**
   i) Conduct a comprehensive and critical review of existing research papers on hybrid mesh networking, LEO satellites, SDN handoff protocols and algorithms.
   ii) Identify the limitations of current hardware and establish the need for a lightweight and deterministic handoff protocol.
   iii) Design the core system and the logic flow for the custom SDN handoff controller, aiming for a highly responsive real-time throughput monitoring system.
   iv) This will deliver Chapter 2, the Literature review, and Chapter 4, the System Design specification.

b) **Product build and Implementation**
   i) Deploy a controlled, visualised network testing environment using Mininet to accurately simulate the physical constraints of rural broadband and satellite backhaul.
   ii) Configure precise network perimeters using TCLink, capping the terrestrial link at 10Mbps and the LEO satellite link at 5Mbps with an artificial delay of 30 ms, to emulate real world conditions.
   iii) Develop the custom SDN controller algorithm using the Ryu framework, programming it to autonomously apply the priority OpenFlow routing rules when terrestrial throughput exceeds the 9Mbps safety threshold.
   iv) This will deliver a working python-based handoff protocol within Mininet.

c) **Project Testing, Evaluation and Final Report**
   i) Conduct appropriate testing by forcing guaranteed network congestion using UDP traffic floods with iperf
   ii) Evaluate the responsiveness and reliability of the SDN controller's handover against the project aims.
   iii) Document all testing results as well as future scalability recommendations within the final report.
   iv) This will deliver a fully working and tested prototype along with a completed dissertation.

1.3 Methodology

To deliver the aims outlines in this project, a simulated network environment was selected as the primary development and testing platform. Originally the decision was a physical hardware deployment using Raspberry Pi nodes, this however, introduced too many uncontrollable variables, such as inconsistent wireless signal strength and physical interference, that would have made it difficult to produce reliable and repeatable results. Therefore, a virtualised approach using Mininet provided a controlled and deterministic environment where network conditions could be customised allowing for repeatability in results.

The network topology was constructed within Mininet, a network emulator that deploys virtual hosts, switches, and controllers on a single machine. Traffic Control Link (TCLink) was used to apply specific bandwidth and latency to each interface. Applying a 10 Mbps cap to the terrestrial link and a 5 Mbps cap to the satellite link, along with an additional delay of 30 ms to the satellite link. These specific values align with both UK broadband Legislation and real-world starlink latency measurements identified during the literature review.

The SDN controller was developed using the Ryu framework, a python based SDN controller that communicates with the virtual switch via the OpenFlow protocol. The controller was programmed to continuously poll port statistics from the Open vSwitch instance every three seconds, calculating live throughput in Mbps using the data from the raw byte count. When the terrestrial link exceeded the 9 Mbps congestion threshold, the controller autonomously injected high-priority OpenFlow rules to divert traffic to the satellite link, executing the handover without any manual intervention.

Testing was conducted using standard Linux networking tools within the Mininet command line, such as the 'pingall' command which was used to verify basic connectivity between all virtual nodes. Also 'iperf' which confirms the bandwidth constraints of each link and stress tests the handover logic by flooding the network with 15 Mbps of UDP traffic, guaranteeing congestion. The success of the handover was measured by observing the controller’s output and confirming that traffic was successfully rerouted.

Due to the nature of this projects testing, data collection was therefore based on quality rather than any statistical output, with the testing evidence being the controller's output and the iperf throughput measurements. This approach made sense given the rule-based nature of the prototype, where the goal was to prove that a handover logic functioned correctly with applied congestion rather than to analyse performance across a wide statistical sample.

1.4 Report Roadmap

This report will be split into 8 chapters, each detailing the research, development, and testing process.

Firstly, this report will investigate prior literature, and how previous research into similar areas is able to achieve similar results and how this project is able to build from those.

Then the report will investigate similar products that exist that are able to be utilised or act as guidance for this project. The research into existing products will build a solid foundation for the direction of this project.

After this, explicit requirements for the product will be laid out, so that the clear expectations and requirements can be understood and met. This section will then also lay out the design that will be used to achieve this project’s goal. The design is a crucial aspect of building a working product and the prior knowledge of research is vital to build this.

Once the product expectations and design have been laid out, the next chapter will be the implementation. This is where the process of building and implementing the product will be. This section will detail the steps undertaken to build the product and what methods of preliminary testing are used to ensure that the product is working effectively each time.

After the successful implementation, the report will assess the results of testing, and detail how and if the results of testing align with the prior expectations. This chapter will also detail if any anomalies were found during testing along with any constrains that may exist on the product.

The report will also lay out any legal, social, ethical, and professional issues that may be experienced within this project.

Finally, a detailed conclusion summarising the work undertaken and the results. Along with how the project met its aims and with any future work that may be suggested to further the work completed in this report.

2 LITERATURE REVIEW

2.1 Introduction

To identify relevant literature, a series of systemic searches were conducted primarily using Google Scholar with some searches conducted through the University of Greenwich library search. The search strategy involved using keywords such as ‘SDN handoff’, ‘LEO Satellite Network’, ‘Hybrid Mesh’ and ‘Rural Connectivity’. The search was further refined to prioritise papers published after 2022, this was done so that only recent and relevant papers were used as well as the most up to date technologies are included, like LEO constellations such as Starlink. This chapter critically analyses these existing papers, breaking them down in key categories so that a firm foundation can be established for the prototypes design choice.

2.2 Hybrid Network Architectures

As (Karamchand, 2024) says, mesh networking is an essential part of supporting services in rural areas. A mesh network consists of interconnected nodes that route data dynamically, offering a robust and flexible method of networking. This method of redundancy is essentially a self-healing capability, where if one pathway goes down for whatever reason, the network can still maintain its connection to the rest of the network by finding an alternative route. (Tarhouni, Wang and Alouini, 2025)

To further improve reliability in off-grid areas and remote areas recent research advocates strongly for a hybrid network. (Tarhouni, Wang and Alouini, 2025) suggests integrating a traditional terrestrial link with LEO satellites that make use of Free-space Optical (FSO) a communication method that uses laser beams to transmit data at high speeds over long distances, making it immune to electromagnetic interference. However, it does require a line of sight, where the receiving dish is clearly exposed to the sky with no obstructions, this includes any poor weather that may affect the line of sight.

Also (Salem et al., 2023) further demonstrates that LEO satellites significantly enhance baseline connectivity in rural areas. Their research investigated a hybrid system where the LEO satellites made use of a Multiple-Input Multiple-Output (MIMO), allowing users on the network to dynamically associate with either the terrestrial link or the satellite. This provides the benefit of traffic offloading, as if the traffic becomes overloaded during a peak time for example, the satellite link can handle the excess data.

However, the growing rise in LEOM mega constellations introduces new challenges. (Lee et al., 2025) nots that the sheer density of satellites brings forward a heightened inter-satellite interference. To combat this, they propose “satellite cluster networks” where multiple satellite in a specific orbital cluster collaborate and work together to enhance downlink coverage and reduce the signal degradation. This highlights the logistical challenges of satellite downlink connectivity and further instils the need to reliable ground level management.

2.3 Software Defined Networks and Handoff Algorithms

The transition between the terrestrial and satellite link requires a highly responsive control plane. An SDN serves as the core technology for this project, facilitating the algorithmic switch between terrestrial and LEO networks. (Westphal, Han and Li, 2023) explain that SDNs are an emerging domain critical for satellite networking.

An algorithmic approach is a necessity to maintain a reliable, stable network. (Zhou et al., 2023) support this idea by developing a handover utility function to manage decision-making, ensuring connections switch based on maximum capacity, stability, and reliability. Their strategy actively calculates an “available backhaul capacity ratio”, which considers both the feeder link quality and the satellite network state. Importantly, to prevent connection instability caused by repeated switching, (Zhou et al., 2023) introduces a “service time factor” and a “handover control factor”. This uses maths to reduce the overall frequency of handovers, which aims to prioritise long term stability over immediate maximum throughput.

(Borgianni et al., 2024) provides research that almost follows on, where they directly address rural environments by utilising Software-Defined Wide Area Network (SD-WAN) architectures. They evaluate three separate tunnel selection algorithms for switching traffic, particularly across 4G, 5G and satellite links. A baseline random selection tunnel, a deterministic algorithm utilising predefined logic based on traffic data, and an advanced deep Q-learning model. Their findings validate that a deterministic, rule-based algorithm is highly effective for providing a predictable and reliable method of routing constrained traffic in rural areas.

To create accurate SDN triggers, exact parameters of the satellite link need to be understood. To create accurate SDN triggers, (Garcia, Sundberg and Brunstrom, 2025) evaluated starlink’s one-way delay. By analysing over 500 million probe packets, they identified that LEO networks exhibit periodic 15 second reconfiguration cycles that directly impact uplink delays. Their observations of latency confirmed that an artificial delay of 30ms is highly realistic for simulating modern LEO downlinks.

2.4 Artificial Intelligence

Artificial Intelligence (AI) and Machine Learning (ML) are rapidly emerging and disruptive technologies in the networking domain. (Fontanesi et al., 2025) provides a comprehensive survey detailing the increasing integration of deep neural networks into satellite communication. They note that

ML frameworks are currently being deployed to make handoff methods highly dynamic, enabling systems to predict route traffic before a potential threshold is breached.

(Turkmanović et al., 2025) supports this by proposing a distributed AI driven simulation framework designed specifically for evaluating hybrid terrestrial-satellite networks. Their research suggests that implementing AI at the decision-making level leads to a more optimal switching, leading to a more optimised use of resources across the network.

Furthermore, (Han et al., 2024) investigates Deep Reinforcement Learning (DRL), specifically for multipath routing. Their algorithm allows the network to learn and adapt its routing decisions based on continued usage. In specifically terrestrial networks, (Swathi et al., 2024) explores hybrid, problem solving algorithm that optimises network parameters and can focus heavily on energy efficiency.

While AI driven approaches provide high levels of efficiency and predictive capability, they typically require substantial computational resources and extensive training data. As explained by (Borgianni et al., 2024), the processing overhead associated with deep Q-learning can introduce predictive processing delays.

2.5 Key Challenges and Conclusion

Despite the clear benefits of hybrid connectivity, significant challenges remain regarding cost, processing power, and physical infrastructure. While (Salem et al., 2023) showed that hybrid systems can improve rural coverage, their deployment can be costly due to the infrastructure required for both mesh networks and LEO reception. Additionally, (Lee et al., 2025) highlights that satellite downlink connectivity can present logistical challenges, prompting companies to actively work on increasing coverage areas for better resilience.

Therefore, a critical gap exists for a lightweight, deterministic handoff solution. Building on the SDN concepts identified by (Westphal, Han and Li, 2023), this project will develop a Python-based algorithm to manage the handoff based on real-time throughput, rather than just coverage area. By interpretation the SD-WAN ideas proposed by (Borgianni et al., 2024) and the real-world satellite latency data provided by (Garcia, Sundberg and Brunstrom, 2025) , the protocol will utilise a fixed speed limit on a virtual testbed to trigger an immediate switch. This drops the complicated timing rules suggested by (Zhou et al., 2023) in favour of guaranteed, instantaneous data delivery. Ultimately, this creates a fast, and lightweight system that is resilient for rural and disaster relief network infrastructure.

3 PRODUCT RESEARCH

3.1 Introduction

This project investigates similar research done to build a strong base for the project to stand on, the implementation of a mesh network is a documented method of ensuring that networks have a resilient connection, particularly those in rural areas. Different algorithmic methods of switching can show what methods provide a strong and stable connection for all the end users. The methods of providing connectivity are important as they are what the algorithm will use to determine where the best connection is coming in.

3.2 Comparison of Handoff Strategies

(Borgianni et al., 2024) presents three tunnel selection algorithms. These are a random tunnel, used as a baseline to randomly choose a tunnel. A deterministic algorithm that uses predefined logic to determine the tunnel based on traffic requirements and finally a deep Q-learning algorithm, where the system learns to makes decisions based on experience. Additionally, (Zhou et al., 2023) makes use of a similar decision metric, where the link quality is evaluated and a switch is made if deemed to be beneficial. Furthermore, to reduce the frequence of handovers, a Service Time Factor is introduced so that repeat switching back and forth is reduced, meaning stable connections are maintained.

3.3 Terrestrial Communication Methods

The paper by (Borgianni et al., 2024) has a similar operation to the solution planed in this project. It opts for three tunnels consisting of 4G, 5G, and Satellite connection. This provides the various was traffic can be routed so that it is received by the most optimal path.

This paper provides great references for outline; however, the method of this project will aim to use just one algorithm. The papers use of 4G and 5G Wireless technology may have been useful for the scenario outlined, however in this project, there would be either none, or very limited access to such wireless connections, this is why the mesh network connected to terrestrial cables or Free space optical may be used.

(Tarhouni, Wang and Alouini, 2025) explains the positives of using a mesh network, the paper does focus on Free space optical (FSO) methods of meshing networks, this is something that this project will examine in terms of scalability. The paper however does explain why mesh networks are used and why. The paper explains that mesh networks are designed to be redundant, so that any loss of node means traffic can find another path, rather than the whole network. This is beneficial because in rural areas, reliable routes of traffic may be difficult at all hours. Mesh networks are also incredibly scalable, adding in extra nodes is easy and an even improves the reliability of the network, each node that is added. The paper also investigates FSO in satellite communications, which is something that satellite internet providers such as Starlink provide

3.4 Satellite Communication Methods

The use of satellite communications is the backbone of the hybrid system; it is needed to be switched to and from when needed. (Tirmizi et al., 2022) explains how LEO satellites the benefit of global coverage has, there are no geographical limitation on where the rural communities are, they can receive similar connections to that of any customer around the world. Furthermore, as supported by (Casoni et al., 2015) LEO satellites provide a strong disaster resilience, making them vital in disaster relief areas where traditional terrestrial communications may have been damaged.
Additionally, in (Tirmizi et al., 2022) discuss the use of LEO satellites for a backhaul service, the paper explains how these satellites can be used to support local cell towers which can be supported solely by these satellites, providing 4G service to remote rural communities. The use of this to support many endpoints with one satellite connections is a viable method of use to ensure that cost is kept low, while maximising the potential benefits to end users.

3.5 Key Findings

The product research highlighted that mesh networking is a proven and necessary component for delivering necessary digital services to rural communities, primarily for its inherent self-healing redundancy. However, integrating a terrestrial mesh network with a satellite backhaul introduces some complex routing challenges.

The research identified several methods for managing this hybrid connectivity, which can be categorised into baseline random selection tunnels, complex predictive machine learning models, and deterministic Software-Defined Networking

Basic random tunnel selection often relies on a primary connection having a total failure before blindly pushing traffic to a backup node. This reactive approach is great for basic emergency backup, but completely unacceptable when providing quality connections as major packet loss is experienced before the backup tunnel is live and making it unsuitable for continuous, critical services during heavy congestion or disaster scenarios.

Alternatively, a deep neural network implementation would provide a highly proactive approach. These models are designed to learn network states over time so that they can predict when congestion may occur so that traffic can be routed to alternative links before any downtime is experienced. While this method is highly effective for load balancing, these models require a significant amount of computational power along with prior extensive training data. The overhead required for decision making is impractical for the low cost, lightweight deployment that would be expected in rural or disaster relief areas.

Therefore, after evaluating these strategies, it is apparent that the most cost-effective method for this problem is a deterministic SDN algorithm. By utilising predefined logic, hard coded throughput thresholds, the system can trigger a handover the moment congestion is detected. This ensures that the system switches connections before any failure can happen while simultaneously avoiding the delays of a basic random tunnel. Providing an approach that results in a lightweight and highly responsive mechanism for rural infrastructure.

3.6 Conclusion

Based on this evaluation, the best method of implementation is using a SDN algorithm this is to ensure that there is a proactive method of when the system should make the switch compared to a standard roaming method that would switch only when it cannot see its prior connection. Furthermore, in a practical setting, the system can be connected to, if any, a preexisting network link, be it a preinstalled wired connection, a 4G or 5G connection or network over FSO. Finally, the fundamental backbone of the hybrid network is the connection to the LEO satellites, this is an important step to ensuring that there is always the reliable fallback for the network.

4 REQUIREMENTS ANALYSIS AND DESIGN

4.1 Introduction

This Chapter defines the requirements and system design for the hybrid rural network prototype. It establishes the functional and non-functional requirements. These are expectations needed to simulate a realistic rural broadband environment.

4.2 Requirements Analysis

4.2.1 How requirements were determined

The requirements for this project were determined using both current legislation and existing academic literature. The goal was to ensure that the parameters used in the prototype accurately reflected real-world challenges experienced in rural and disaster relief areas.

Rather than deploying physical hardware, which introduces uncontrollable variables like weather and signal interference, the project used a controlled, virtualised approach in Mininet where results were guaranteed reliable and repeatable.

To simulate realistic bandwidth constraints, the terrestrial link was capped at 10Mbps, this perfectly aligns with the UK Government's Universal Service Obligation for a minimum decent broadband connection (The Electronic Communications (Universal Service) (Broadband) Order 2018, 2018). The backup link was restricted to half that, at 5Mbps to simulate an emergency backhaul. Additionally, the backup satellite had a 30ms delay based on modern LEO downlink measurements identified in the literature review (Garcia, Sundberg and Brunstrom, 2025).

Finally, testing the 9 Mbps handover threshold required forcefully flooding the network with UDP traffic generated with 'iperf'. This is a specified functional requirement as the TCP traffic would automatically throttle its transmission speed before tiggering the handover logic.

4.2.2 Assumptions and Constraints

a) Emulation Constraint
The system is constrained to a virtual environment (Mininet). It assumes that the Open vSwitch behaviour within the emulator accurately reflects how physical real-world hardware would react to the controller's instructions.

b) Bandwidth Constraints

The terrestrial link is constrained to 10 Mbps to reflect the rural baseline legislation (The Electronic Communications (Universal Service) (Broadband) Order 2018, 2018), and the satellite link is constrained to 5 Mbps with an artificial delay of 30 ms to simulate real-world limitations. These bandwidth values have been intentionally scaled down for the emulation environment. This allows deliberate network congestion to be triggered reliably without exceeding the processing limits of the virtual CPU.

c) Traffic Assumption

The prototype assumes that the primary stress factor for the network is heavy UDP traffic, simulated via iperf.

4.2.3 Functional Requirements

Functional Requirements of the project are the non-negotiable operations that must be present and performed in the project, these are features are the necessary metrics for a successful running of the program.

a) Constant Monitoring

Firstly, the program must be able to establish a constant connection and run indefinitely. It will be started and continue to run, constantly checking the network traffic without any user input.

b) Congestion Metrics

The system must accurately calculate the congestion on the network in real time. Instead of relying on packet loss metrics, the controller must mathematically calculate the raw byte count from the switch into a live Mbps throughput value.

c) Threshold detection

The algorithm must compare the real-time throughput of the traffic against the 9 Mbps threshold within the code. While the physical link capacity is 10 Mbps, the software must be set slightly lower to account for overhead and prevent packet loss during switching. The algorithm must also be able to ignore any negative values that may be caused by the switch's internal counters.

d) Handoff Execution

Once the throughput has reached the 9 Mbps threshold, the controller must independently handover the connection. It must implement the new OpenFlow rules with a priority of 100 to override the default routing path. Successfully diverting traffic away from the terrestrial link to the backup satellite link.

4.2.4 Non-functional Requirements

The non-functional requirements define the performance, security, and usability of a system, rather than what it does. These have been prioritised using the MoSCoW method so that the importance can be categorised.

a) Must Have
The Controller must have full stability and reliability when under heavy load. The logic must be strict and decisive, meaning that if the program decided a handover is necessary, it must be sure that a switch is beneficial to the network and be able to stand by its decision. This ensures that a consistent network connection is accessible to all users.

b) Should Have
The algorithm should be lightweight. This is so that processing power required by the controller does not introduce any additional latency. The controller is monitoring traffic in real-time, so the more complex the code is, the more power would be required to calculate the throughput.

c) Could Have
The code could be designed and built to support multiple switches on a larger network. The benefit of this would be scalability, where many more users in an area could benefit from their own system.

d) Won't Have
The system Will not use a predictive machine learning model. While machine learning can predict trends on networks, it can come with unnecessary processing delays that would lead to a higher reaction time required for an efficient and effective handover.

4.3 Design

This section will layout the design process of the prototype, laying out the expected topology along with how the program is going to communicate withing its network.

4.3.1 Design Rational

Before defining the specific virtual topology, it was necessary to establish the overarching design of the network. Traditional network routing relies on distributed control, where each individual router contains both its own control plane (decision-making logic) and data plane (packet forwarding). While effective for standard setups, this traditional model is rigid and slow to adapt during sudden congestion, making it unsuitable for the immediate failover required in this hybrid rural network.

Therefore, the core design rational for this prototype was to implement an SDN. This aims to fundamentally shift network management by physically separating the control plane from the data plane. In this design the network is centralised into a single software-based controller.

This design provides two major advantages for a hybrid deployment. Firstly, it allows for monitoring of the whole network, rather than relying on individual nodes to communicate the congestion states. Secondly, it majorly reduces the hardware requirements needed for monitoring. Because routing logic is handled by a centralised software, the switches only need to be simple, low-cost packet forwarding devices. This fulfils the aim of creating a lightweight solution that does not rely on heavy duty and expensive hardware typically required for advanced SD-WAN algorithms.

4.3.2 System Architecture

The architecture of the network was designed in a star topology within Mininet. This topology was chosen because it funnels all traffic through a single central point, making it ideal monitoring the traffic quality.

The architecture is made of three primary components. Firstly, the controller node, this is a custom Ryu SDN controller that acts as the brain of the network, this is where the handover logic and the monitoring take place during regular network usage.

Next is the central switch, this is Open vSwitch instance, that acts as the core router, it communicates directly with the Ryu controller using the OpenFlow protocol which is an interface that allows the controller to manage the data plane of the switch.

Finally, three virtual hosts are connected to the switch. Host 1 is the terrestrial network. This is where the traditional ground connection enters. Then is Host 2, this is the LEO satellite connection, acting as the backup connection for the terrestrial connection. Lastly, is Host 3, this is the user's local device that is used to generate the test traffic on the network.

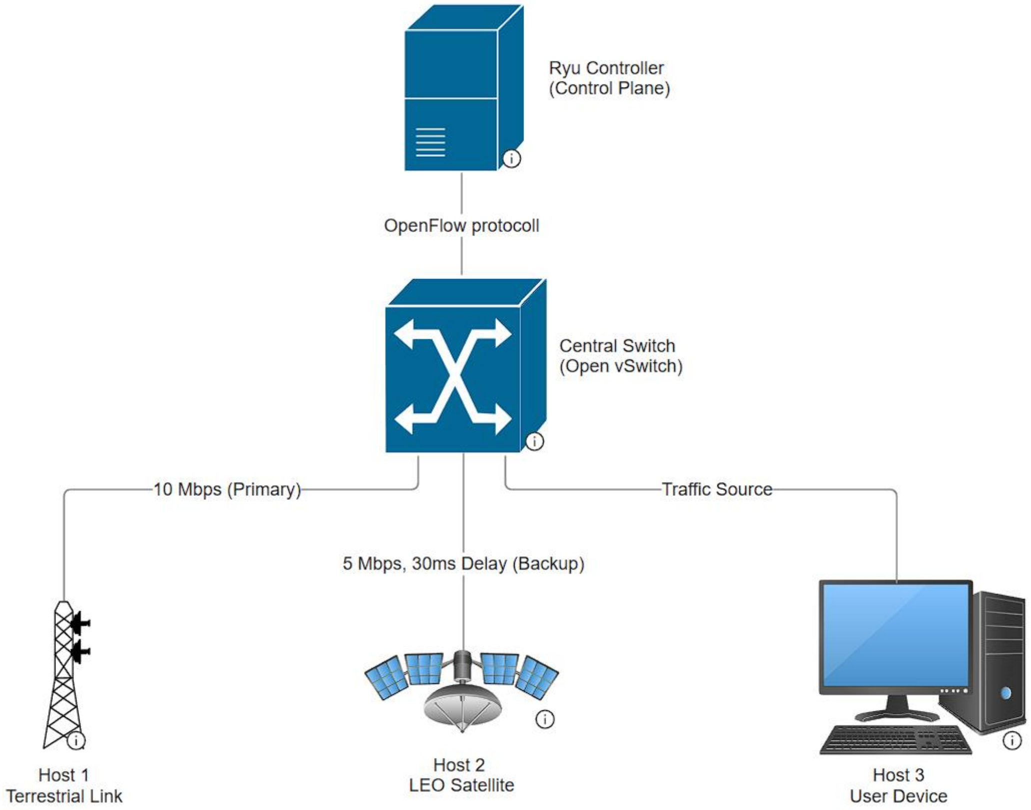


Figure 4.1: Hybrid Rural Network Prototype Architecture

4.3.3 Controller Algorithm and Logic Flow

While the system architecture describes the physical network, the controller algorithm describes the operational logic. As set out in the requirements, the algorithm should take a rule-based approached rather than relying on complex predictive methods.

The controller will run on a continuous loop to monitor the network traffic while keeping processing power low.

Firstly, when the system boots, the Ryu controller finds the Open vSwitch and applies the standard routing rules at a priority 1. This sends all traffic through the terrestrial connection.

Then a Polling loop happens, where the controller pauses for 3 seconds. After the pause the system asks the switch for the latest port statistics.

After, a calculation of the throughput is made, the raw byte count is taken from the switch. This is then subtracted from the previous check and divided by the time passed to calculate the live speed in Megabits per second (Mbps)

The live speed is then checked against the 9 Mbps limit in the code. If the speed is greater than the specified threshold, the controller automatically adds the new routing rule with a 100 priority. Because the priority is so high it immediately overrides the default path and forces the traffic to be routed via the satellite link.

A bi-directional handover could be implemented by extending the monitoring loop to track throughput on port 1, even after the high priority rule is active. Once the throughput on port 1 falls bellow a threshold for two polling cycles, the controller would issue a delete command to the priority-100 rule, reverting back to the default routing rules.

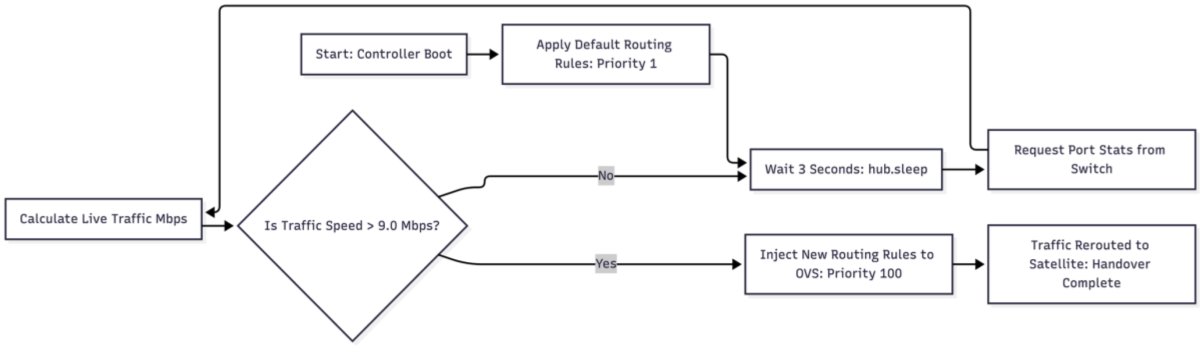


Figure 4.2: Logic Flow Chart

4.3.4 Software Framework Selection

When designing the control plane for this prototype, other frameworks were considered aside from Ryu such as OpenDaylight and POX. OpenDaylight is highly robust controller, however it is Java-based which means there is an additional processing overhead which may take away from the aim of keeping a lightweight deployment. Pox however is a lightweight deployment but primarily supports older OpenFlow versions making it less than ideal for modern testbeds.

Ultimately, Ryu was chosen as the optimal controller. Ryu is entirely python based, making it incredibly lightweight, readable, and fast to deploy. It also offers full native support for OpenFlow 1.3 protocol, which is required for the priority-based routing instructions that this prototype relies on.

For the data plane and topology simulation, Mininet was chosen due to its genuine virtualised Linux networking along with Open vSwitch integration.

This means the Ryu controller interacts with the Mininet simulation exactly as it would with physical hardware switches, ensuring the design remains highly authentic to a real-world deployment while eliminating the unpredictable environmental variables of a physical testbed.

4.4 Conclusions

This chapter set out the core requirements and design choices for the network prototype. By setting out clear bandwidth limits and focusing on UDP traffic, the project created a realistic testbed for a rural network setup. Using a MoSCoW method kept the focus on reliability and low latency, rather than getting restrained by unnecessary predictive features. The requirements outlined in this chapter directly shape the system architecture, resulting in a star topology and a reliable, threshold based SDN controller. Furthermore, the specific selection of the Python-based Ryu framework and the Mininet emulator ensures that this design remains incredibly lightweight while acting as a realistic representation of physical hardware, perfectly setting up the testing environment for the implementation phase.

5 IMPLEMENTATION

5.1 Introduction

This chapter covers the technical implementation and testing of the proposed network solution. It explains how the virtual testing environment was built using Mininet to simulate the physical constraints of rural networking. Following the setup, this chapter also describes the custom Ryu controller algorithm that was created to monitor the network congestion and manage the handover process. Finally, this chapter will detail the testing methods used to validate the system when put under stress. This proves that the core logic of the network works as expected before moving on to the results.

5.2 Virtual Network Topology Configuration

The virtual testing network was needed to construct a large environment. To do this Mininet was utilised. Mininet is a network emulator that can quickly and efficiently deploy virtual hosts, switches and controllers. To accurately reflect physical constraints of real-world architecture, TCLink (Traffic Control Link) was used instead of the standard Link class. This change allowed for custom manipulation of the bandwidth and latency parameters.

The topology used is a star configuration, the network centralised around a single Open vSwitch instance, this was to ensure full compatibility with the OpenFlow protocol.

The terrestrial port was mapped to port 1, which had a cap of 10 Mbps, simulating the standard rural broadband connection. This specific threshold was chosen as it aligns with British legislation (The Electronic Communications (Universal Service) (Broadband) Order 2018, 2018)

Port 2 was mapped to the LEO satellite link. This interface was capped at 5 Mbps to simulate a shared backhaul connection. Additionally, a 30ms delay was implemented into Mininet to replicate satellite latency. This specific delay was chosen based on real world measurements of Starlink downlink delays (Garcia, Sundberg and Brunstrom, 2025).

Finally, the user's device was mapped to port 3 to act as the source of the traffic.

5.3 Software Defined Network Controller Algorithm

The network is managed by a custom Software Defined Network (SDN) controller built using the Ryu framework. The controller acts as the brain of the network, where it instructs the Open vSwitch on how traffic should be handled. Upon boot the MAC addresses of connected devices are tracked, and basic routing rules are applied with a priority level of 1.

To manage the handover process, a monitoring loop runs constantly in the background, every three seconds the controller requests a port statistic from the switch. The amount of data passing through port

1 is tracked, this is the terrestrial link. By calculating the change in bytes over these three seconds, the controller can determine the live network speed in Megabits per second (Mbps)

The throughput calculation is done by adding the received bytes (rx_bytes) to the transmitted bytes (tx_bytes) from port 1. This combined byte count is taken away from the previously stored value and then divided by how much time has elapsed since the last interval, giving a result in megabits per second (Mbps). Any negative values are disregarded and treated as 0 to prevent false positives.

The live speed calculation acts as the trigger for the handover. If the terrestrial link exceeds the 9 Mbps limit, the controller detects that the connection is congested. To resolve this, the controller acts on new OpenFlow routing rules and sets the switch to a priority of 100. Because 100 is significantly higher than the standard priority of 1, these new rules instantly override the default routing behaviour. The switch stops sending traffic to the congested terrestrial link and immediately forces all user traffic out through Port 2, executing a physical handover to the satellite link.

5.4 Testing

The Testing phase focused on verifying that links on the network are connected, and working as expected, according to their constraints. The testing included ensuring that the Ryu controller correctly configured the OpenFlow rules under stress. The testing was conducted manually using the Mininet command line interface and standard Linux networking tools such as ping and iperf.

5.4.1 Unit Testing

In the context of network topology, unit testing consists of verifying the individual physical constraints of the Mininet environment before the handover was introduced.

Firstly, basic connectivity was tested using ‘pingall’, this tested the reachability of the virtual nodes, ensuring that they can be communicated with before any traffic is sent. Then basic TCP ‘iperf’ tests were ran between the hosts to prove the TCLink was functioning. This confirmed that the terrestrial link (Port 1) physically could not exceed 10 Mbps, and the satellite link (Port 2) was successfully restricted to 5 Mbps with an active 30ms delay. Verifying these baseline limits was critical to ensuring that following congestion tests were correct.

5.4.2 Integration Testing

Integration testing evaluated the entire system working together, consisting of the Mininet topology, the active traffic, and the Ryu controller monitoring.

The system was tested by sending a deliberate network flood. Using the Mininet CLI, the user’s device (Host 3) was commanded to flood the terrestrial link with UDP traffic using the command ‘iperf -c

10.0.0.1 -u -b 15M -t 10’. This forced 15 Mbps of traffic into the 10 Mbps pipe ensuring a guaranteed congestion.

The Ryu controller was monitored during the flood and successfully observed the congestion and implemented the priority 100 OpenFlow rules, meaning network traffic was successfully shifted from Port 1 to Port 2.

5.5 Conclusion

The testing process successfully validated the core objective of the implementation phase. By using ‘iperf’ to force an artificial congestion state, the testbed proved that the SDN controller could autonomously detect a saturated link and execute a physical handover to a backup satellite connection without manual intervention.

The primary limitation of this testing process is its reliance on a purely emulated environment. While Mininet is highly accurate for testing software-defined routing logic, it does not perfectly replicate the physical hardware limitations or atmospheric interference of a real-world satellite dish. As established by current academic guidance, a logical next step to improve upon these tests would be constructing a real-world testbed with physical nodes.

6 RESULTS AND EVALUATION

6.1 Introduction

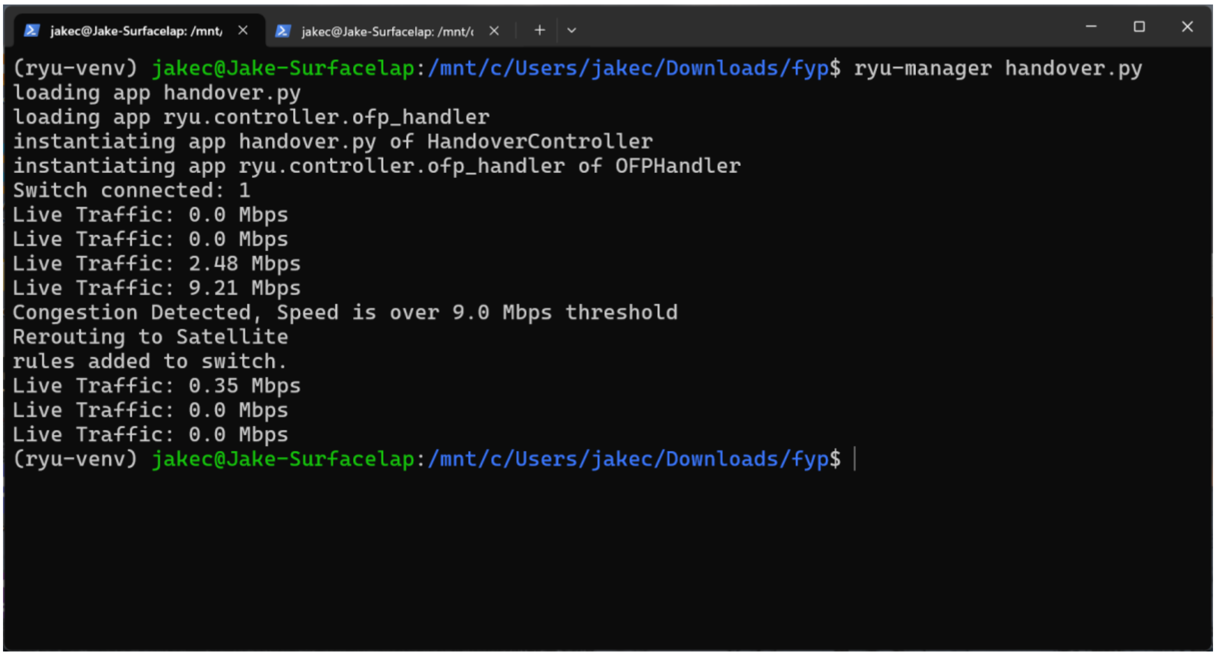
This chapter will present the findings from the Mininet emulation and apply a critical evaluation to the performance of the SDN controller against the aims outlined in Chapter 1. The results show how the system handles heavy network congestion and whether the handover logic successfully maintains a stable connection.

6.2 Results

The prototype in this project was tested using a simulated network flood to see if the controller can independently manage a handover. By forcing 15Mbps of UDP traffic into a 10Mbps tunnel, the system is pushed past its 9 Mbps threshold.

6.2.1 Automated Handover Test

The controller monitored the throughput on the Primary link (port 1) in three second intervals. Bellow shows how the controller reacted when the congestion hit.



```
(ryu-venv) jakec@Jake-Surfacelap:/mnt/c/Users/jakec/Downloads/fyp$ ryu-manager handover.py
loading app handover.py
loading app ryu.controller.ofp_handler
instantiating app handover.py of HandoverController
instantiating app ryu.controller.ofp_handler of OFPHandler
Switch connected: 1
Live Traffic: 0.0 Mbps
Live Traffic: 0.0 Mbps
Live Traffic: 2.48 Mbps
Live Traffic: 9.21 Mbps
Congestion Detected, Speed is over 9.0 Mbps threshold
Rerouting to Satellite
rules added to switch.
Live Traffic: 0.35 Mbps
Live Traffic: 0.0 Mbps
Live Traffic: 0.0 Mbps
(ryu-venv) jakec@Jake-Surfacelap:/mnt/c/Users/jakec/Downloads/fyp$
```

Figure 6.1: Ryu Controller Terminal Output showing Threshold Breach and Rerouting

As seen in the terminal output in Figure 6.1, the system identifies the congestion once the traffic hits 9.21 Mbps, before this threshold is reached, the controller logs normal operation, showing live traffic scaling from 0.0 Mbps up to 2.48 Mbps as the test begins. Once the UDP flood fully fills the link and peaks at 9.21 Mbps, the controller's logic loop correctly identifies that the 9.0 Mbps safety limit has been breached. It immediately outputs "Congestion Detected," followed by "Rerouting to Satellite," confirming that the logic branch has been successfully triggered.

At the same time, the Ryu controller applies the priority 100 OpenFlow rules to the Open vSwitch. The following polling cycles the show that the handover functioned as intended. The traffic on the primary terrestrial link instantly drops from 9.21 Mbps to 0.35 Mbps, and then back to 0.0 Mbps. This confirms that the data plane is actively using the new control plane instructions, successfully diverting the UDP flood to the satellite link on Port 2.

6.2.2 Network Limit Test

Before running the handover test, it was important to confirm the network was restricted correctly. Using the ‘iperf’ command, the terrestrial link can be confirmed to be stayed at the 10 Mbps limit. The Satellite link was also tested in a similar manner, and that too can be confirmed to be capped at 5 Mbps and shows the expected delay of 30ms. These results prove that Mininet is operating as a realistic simulation of a rural test bed.

6.2.3 Congestion Trigger points

During the 15 Mbps flood, the controller monitored the traffic in real-time. The results showed that as soon as the traffic hit 9.21 Mbps, the controller was able to identify that it was over the limit and injected the new rules. Once the rules were added, the traffic on port 1 dropped to 0.0 Mbps, showing the diversion was successful.

6.2.4 Conclusion

The data gathered during the testing phase demonstrates that the Ryu controller functioned exactly as designed when under heavy network load. The system showed that it can consistently monitor throughput and independently execute an OpenFlow rule modification to divert traffic once a specified threshold is exceeded. These results confirm that viability of the prototype, providing the necessary data to widen the evaluation of its overall performance, limitations and real-world applicability.

6.3 Evaluation

This section critically analysts the data presented in section 6.2, evaluating the prototype against the initial project aims and similar approaches withing the problem domain.

6.3.1 Evaluation Criteria/Metrics

To objectively assess the system, the evaluation is measured in three metrics, The responsiveness, reliability, and the algorithmic efficacy. Firstly, the responsiveness of the controller evaluates the speed at which the controller identifies and mitigates the congestion, this is directly dictated by the three second polling interval. Reliability measures the networking ability to successfully reroute the continuous traffic without any drop in connection during the handover. Finally, the algorithmic efficiency assesses the overheard required to calculate the handover decision, especially when compared to the heavier methods outlines in the literature.

6.3.2 Reviewing the project Aims

The primary aim for this project was to design, simulate and evaluate a handoff management protocol to improve connection stability, this goal was achieved. However, a critical reflection against the original proposal highlights the necessary changes needed during the project's development. The initial objectives proposed deploying a physical hardware testbed using multiple raspberry pi nodes and calculating handover based on packet loss and latency metrics.

During the development, the scope was adapted to focus on a virtualised Mininet environment. This pivot allowed for a highly controlled simulation with physical constraints such as the 30 Ms satellite delay, which would have been difficult to guarantee when using physical hardware. Additionally, the trigger metric was changed from packet loss to active throughput monitoring, this change is beneficial because it enabled the SDN controller to proactively reroute traffic once a threshold is exceeded rather than waiting for severe packet loss to occur. However, the decision to pivot to using simulation was not without limitations. While it did guarantee repeatable results, it also reduced the viability of the results. A physical testbed would have allowed for genuine interference that would contribute to the quality of bandwidth on the network. This means also, that the three second poll works great inside of the simulation, it has not been tested against real-world jitter that a LEO satellite would experience. This is a slight caveat in the response time of the handover.

While the final did not incorporate physical hardware as initially planned, the core objective of delivering a working product that successfully and autonomously switches networks was achieved.

6.3.3 Evaluating against current research

When compared to current literature, this prototype offers an advantage in simplicity and speed. Existing solutions, such as the deep Q-learning tunnel proposed by (Borgianni et al., 2024), required extensive training data along with substantial computer resources that may be too costly or unavailable in proposed environments, just to make routing decisions. Furthermore, while (Zhou et al., 2023) focused on reducing frequent handovers through a "service time factor", this prototype is designed to be an instantaneous disaster resilience, rather than improving overall access performance.

6.3.4 Identified constraints and shortcomings

Despite the success of the project testing, the prototype contains notable limitations. The most significant being the one-way nature of the handover. As the current code stands, the controller will provide a priority 100 routing rule to force traffic over to the satellite link connection indefinitely. This is because the code does not provide a failback. Meaning that even after the congestion is cleared, the traffic will remain routed via the backhaul satellite link until the simulation is cancelled. while this acceptable for an emergency disaster relief scenario, this is an inefficient use of resources for a rural deployment. Additionally, as explained during the testing phase, the reliance on Mininet means the system was isolated from real-world atmospheric interference that physical satellite dishes experience, representing an unrealistic portrayal of a satellite connection in the emulation environment.

6.3.5 Theoretical Scalability

The current single switch star topology was able to demonstrate an autonomous handoff mechanism, however, scaling this for a wider rural deployment will likely make the routing more complex. In its current form, the Ryu controller relies on a deterministic, hard coded port allocation to redirect the traffic from a single the terrestrial link to a single satellite uplink.

However, to scale up this architecture so that a much wider area can be served, it would need to move away from a star topology and move to a multi node mesh network. This would mean that there would be multiple interconnected Open vSwitches, which could potentially have their own satellite connections. This would ensure there was no single point of failure.

In a multi-switch environment such as this, the current rule-based protocol; would not provide enough of a basis to make a beneficial switch. The SDN would need to calculate the most efficient path that may be through several nodes to reach an available backhaul. To do this successfully a dynamic shortest-path protocol would be adopted, such as Dijkstra’s algorithm.

By using Dijkstra’s algorithm, the SDN controller would actively build up a live map of the topology using Link Layer Discover protocol (LLDP) packets. Instead of relying on a static 9Mbps trigger at a single point, the controller would dynamically assign a “cost” to ach of the links within the mesh. A highly congested terrestrial link would be given a high cost while a free satellite link would have relatively low cost. By constantly updating the OpenFlow rules across all switches within the mesh, it is possible that all switches can effectively balance their load across the network.

While implementing Dijkstra’s algorithm would provide much better traffic management for muti-node networks, it does significantly increase the necessary computational power. The controller would require significantly more processing power as it will continuously be calculating the cost of the paths to each node. Therefore, while a dynamic algorithm for routing is essential for future scalability, the deterministic rule-based approach is the most efficient solution for lightweight rural and disaster relief deployment.

6.4 Conclusion

The testing and evaluation phases showed that the SDN handoff protocol successfully meets its main goals. By simulating a network flood, the system proved that it can autonomously detect congestion and divert traffic to an alternative satellite link. These results match the initial expectation that a simple threshold-based algorithm can provide immediate network improvement without heavy processing.

However, the evaluation also highlighted some clear limitations in the prototype, the biggest of which is compared to real-world deployments, the handover is one way. Because there is no failback option, the network stays on the higher latency satellite connection even after the traffic has cleared on the terrestrial link. Additionally, using a virtual Mininet environment meant that the system was not exposed to interference that may be caused by unpredictable weather conditions that a real-world satellite connection my come across.

Furthermore, exploring the systems potential for saleability showed that while a deterministic approach is ideal for a lightweight deployment, expanding it to cover a much larger rural area would require employing a dynamic route such as Dijkstra's algorithm.

Having evaluated the technical performance, limitations, and future scalability of the prototype, Chapter 7 will now examine the legal, social, ethical, and professional issues of deploying this type of network in the real world.

6.4.1 Stress Testing Methodology

A vital design choice during the integration testing phase was the decision to use User Datagram Protocol (UDP) traffic via the iperf -u command, rather than sticking with standard Transmission Control Protocol (TCP) traffic. This decision was critical for successfully evaluating the rule-based handover logic.

If TCP was used to try and simulate the 15 Mbps network flood, the inherent design of the TCP protocol would have completely skewed the results. TCP uses built-in congestion control algorithms such as CUBIC or Reno that rely on packet acknowledgements. As soon as the 10 Mbps terrestrial pipe began to bottleneck, TCP would have noticed the delayed acknowledgements and automatically throttled its transmission window, slowing itself down to avoid dropping packets. This self-throttling would have prevented the throughput from ever reliably breaching the 9 Mbps threshold needed to trigger the SDN controller.

On the other hand, UDP is a connectionless protocol with absolutely no flow control. It just forces packets onto the network regardless of whether the receiving end can handle them or not. By flooding the network with 15 Mbps of UDP traffic, the simulation guaranteed that the terrestrial link would become entirely saturated. This allowed the Ryu controller's throughput calculation to accurately spike past 9 Mbps and execute the handover, proving that the testing methodology was perfectly aligned with what the threshold-based trigger needed to function.

7 LEGAL, SOCIAL, ETHICAL AND PROFESSIONAL ISSUES

This chapter outlines Legal, Social, Ethical and Professional Issues that require considerations during the design, implementation, and future real-world applications of this hybrid network prototype.
When building any kind of network infrastructure, especially systems designed to handle rural communities or disaster relief efforts, the physical code and hardware are only part of the concern.
This chapter outlines the broader Legal, Social, Ethical, and Professional (LSEP) issues that require thoughtful consideration during the design, implementation, and future real-world applications of this hybrid network prototype. Evaluating these factors is critical because deploying an automated failover system in the real world does not just move data around, it directly impacts people's lives, their privacy, and their safety during emergencies.
By stepping back from the technical simulation, this chapter provides a look at the wider responsibilities that come with engineering a public-facing communication network.

7.1 Legal Issues

The main legal considerations for a network-based project such as this would revolve around data protection and authorised access.
This project is based within the United Kingdom and complies entirely with Data Protection act (2018) & UK GDPR. The system was design and tested within a closed, virtualised Mininet environment where all traffic evaluated by the controller is artificially generated using iperf. The project involves no human participants or personal data. Therefore, there is zero risk of any personally identifiable information being leaked.
In addition, to ensure that compliance with the Computer Misuse Act (1990), all development and testing were entirely restricted to locally hosted systems. The SDN controller only manages a virtual switch which is specifically deployed for this project, eliminating any risk of unauthorised access or disruption to real world networks.
If this prototype were to be scaled up into a physical, public deployment, it would also need to be heavily evaluated to ensure the automated switching logic couldn't be hijacked or exploited by malicious actors to intentionally force a network outage on the terrestrial link.

7.2 Social Issues

The motivation behind this project is inherently a social issue, where the goal of bridging a digital divide between rural communities with unreliable infrastructure and the wider world with modern digital services, remote work and emergency alerts remains a strong social issue. By developing an automated handover system that seamlessly switches to the most efficient connection, this project can contribute to improving digital inclusivity to poorly connected communities. Furthermore, in disaster environments where terrestrial lines may be unavailable or severely reduced, an automated hybrid network ensures that critical communication lines remain open providing clear communication channels for responders and affective residents.

7.3 Ethical Issues

Because this research did not include any human participation, interviews or handing of sensitive data, formal ethical approval from the University was not required for this project. However there remains an inherent ethical responsibility relating to rural and disaster relief infrastructure. If a network handoff were to fail during a crisis, the inability to communicate could have severe consequences. Therefore, the ethical focus of this project was on ensuring the testing parameters, such as the 10Mbps cap on terrestrial data and the 30ms delay on satellite data, were honest and realistic metrics. Rather than manipulating constraints to force a successful test result.

7.4 Professional Issues

All work in this project was conducted in accordance with the British Computer Society code of conduct. This code of conduct requires a high standard of integrity, such as academic integrity. Where all third-party literature, existing algorithms and python libraries are properly referenced to avoid plagiarism.

BCS code of conduct also requires transparency, where all limitations of using a simulation over physical hardware are documented in the evaluation. This maintains honestly about the current capabilities of the code.

8 CONCLUSION

8.1 Project Summary and Outcomes

This project aimed to design, create, and evaluate an SDN-based handoff management system for a hybrid terrestrial and LEO satellite network. The main objective of this project was to enhance the stability of network connectivity in rural and disaster relief areas.

The final prototype was able to successfully achieve the goal of providing a handoff system, this was done by deploying a custom Ryu controller within a Mininet topology. The system was able to autonomously monitor network throughput and executed a physical handover to the backup satellite link when the terrestrial traffic exceeded the 9 Mbps limit. The outcome demonstrated that a rule-based algorithm an provide a highly effective method of maintaining network connectivity during high congestion.

8.2 Project Significance and Impact

This project proves the possibility of a simple, rule-based algorithm for maintaining a stable connection in rural and disaster areas. While the literature review highlighted some research that explore more complex methods, such as deep Q-learning or mathematical utility functions, this project shows that a heavy system is not strictly necessary to provide immediate relief of congestion within a network.

By using a lightweight polling loop, that does a check every three seconds, the controller can quickly reroute traffic as soon as the terrestrial link becomes congested. This design priorities the immediate relief rather than complex load balancing methods such as service time factors. This can ensure that vital communication lines remain open.

8.3 Limitations

While the simulation of switching a user's traffic from one connection to another was successful, the project had some limitations. The main issue is the one-way aspect of the handover. In its current state, the code lacks a failback, meaning that traffic stays on the higher latency satellite link even after the primary terrestrial link is no longer congested. In its current form, it works well for immediate relief, but it is an inefficient use of resources for long term rural setups.

Furthermore, using Mininet meant the code was tested in a controlled environment with stable bandwidth limits. In a real-world environment, satellite connections are affected by unpredictable weather and physical interference. Therefore, the protocol has not been tested against the actual packet loss and latency variations that physical satellite hardware would experience.

8.4 Future Work

To address the limitations of the current project, future research into the following areas is recommended.

8.4.1 Algorithm Failback

The logic controller needs a mechanism to switch traffic back to the primary link. This could be achieved by adding a timer to poll the terrestrial connection and remove the 100-priority set previously. This would mean that when the congestion is confirmed to be cleared the priority rule can be removed and traffic can use the terrestrial link again. This would prevent the system from wasting satellite backhaul capacity as well as using a higher latency link.

8.4.2 Physical Hardware Testing

Future additions should be transitioned from Mininet to a physical testbed using several nodes. This will allow the algorithm to be tested on real networking hardware which would show how the code would perform when faced with genuine weather interference, latency spikes and physical processing limits.

8.4.3 Scalability

As evaluated in Section 6.3.5, in its current simulated state, the SDN controller can only handle two network links and a single user. Future scalability would mean that the algorithm must be further tested and refined so that the logic can manage multiple Open vSwitches across a larger mesh network. By implementing the dynamic routing discussed previously, this expansion would allow for a wider rural area to efficiently share and balance traffic dynamically across a central satellite uplink.

8.5 Final Reflection

This project provided invaluable practical experience spanning software-defined networking architectures, OpenFlow protocols, and advanced network emulation techniques. Moving from the initial theoretical research into the final implementation phase highlighted the necessary, and often difficult, trade-offs inherent in network design. Specifically, the choice to prioritise a fast, lightweight, deterministic algorithm over a highly complex, predictive machine-learning model required a shift in perspective. It underscored the engineering reality that the most sophisticated solution is not always the most appropriate one for constrained environments like rural or disaster-stricken areas.

Furthermore, developing the controller in Python using the Ryu framework offered deep insights into how the control plane and data plane interact. Troubleshooting the OpenFlow priority rules to ensure the 100-priority rule successfully overrode the default routing path without causing packet loops or dropping connections was a significant technical hurdle. Overcoming this reinforced my understanding of packet forwarding at a highly granular level.

Additionally, the transition from a proposed physical Raspberry Pi testbed to a virtualised Mininet environment was a critical lesson in project management and methodology. It taught valuable lessons on how to critically evaluate testing parameters and recognise when unpredictable environmental variables threaten the validity of an experiment's results.

Ultimately, this project delivers a working prototype that successfully automates a failover process. The results conclusively prove that a lightweight SDN approach is a highly effective, standalone method for maintaining essential communications when traditional terrestrial networks fail, marking a successful end to this research endeavour.

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APPENDIX A - Project Proposal

UNIVERSITY OF GREENWICH
FACULTY OF ENGINEERING AND SCIENCE
SCHOOL OF COMPUTING AND MATHEMATICAL SCIENCES

COMP1682 Final Year Project Proposal

How a hybrid mesh–satellite system manages handoffs and maintain a stable connection in rural or disaster relief areas?

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Word count: 1,895

November 2025

DECLARATION OF AI USE

Please complete this part when you have used AI during the process of undertaking this assignment to acknowledge the ways in which you have used it.

I have used AI while undertaking my assignment in the following ways:

- To develop research questions on the topic – NO
- To create an outline of the topic – NO
- To explain concepts – YES
- To support my use of language – NO
- To summarise the following articles/resources: – NO
  7.
  8.
  9.
  10.
  11.
  12.
- In other ways, as described below: – YES
  - Create an ordered bibliography to track papers that have been read.

SYNOPSIS

The ability to setup networks in a rural or disaster areas has never been an efficient process, from getting equipment setup, to calculating the best areas to have access points and ensuring that all nodes have stable connections are just some of the difficulties that have to be overcome in order to set up a reliable network in these difficult environments. (Tirmizi, et al., 2022)

A mesh network offers a unique approach to these challenges; a mesh network can group all the available nodes together into a Wide Area Network (WAN). This offers the benefit that in the event one of one nodes on the network fails, it doesn't take the whole chain down, nodes can find other paths instead, greatly improving network resilience. (Karamchand, 2024)

In rural areas, the delivery of a stable and high-quality network connection remains a persistent struggle. Joining and ensuring a fast communication channel with remote communities helps ensure that people who live in remote regions are well connected with the rest of the world and keep them up to date with vital information. (Borgianni, et al., 2024)

(Swathi, et al., 2024) Suggests that algorithmic approaches are favoured, this is because an algorithm running on a testbed would be able to choose the preferred method of connection Nevertheless, Inter-Mesh link scheduling algorithms need to be investigated more.

(Elbehiry, et al., 2025) Investigates using the Bellman-Ford algorithms over something like the Dijkstra algorithm as the end-to-end time is dramatically decreased along with its dynamic nature making it able to find the shortest path while minimising costs. However, the journal also suggests further research is needed since other methods may be more efficient or better suited.

The overall success of this project will be a nodes ability to switch seamlessly between connections to the internet without any effect on the user's end experience. Success will be measured by proving that switching is quicker than remaining on any one network as connection becomes interrupted.

Keywords: Handoff Management, Hybrid routing, Mesh Networks, LEO Satellites.

1. AIM AND OBJECTIVES

8.6 Aim

This project aims to design, simulate, and evaluate a novel handoff management protocol for a hybrid terrestrial mesh and LEO satellite network to improve connection stability and availability in rural and disaster relief environments.

8.7 Objectives

8.7.1 Literature Review and Project Design

8.7.1.1 Conduct a comprehensive and critical review of existing research papers on mesh networking, LEO satellites, SDN handoff protocols and algorithms. [10 days].

8.7.1.2 Organise and summarise the key academic papers that contain the relevant research to; mesh networking, LEO satellites and SDN handoff protocols. [5]

8.7.1.3 Design the core functions and the algorithm that the protocol will use, based on metrics of latency and potential packets lost. [10]

8.7.1.4 This will deliver Chapter 2, the Literature review and a System Design specification.

8.7.2 Product build and Testing

8.7.2.1 Building of the product source code will begin to produce the working software that the handoff will run on a hardware testbed of raspberry pi’s. [30]

8.7.2.2 Testing of the software will occur during the build along with the hardware required to make this work, this includes Raspberry Pis that will act as the nodes on the network where the software will run. [10]

8.7.2.3 A complete and working source code will be delivered for the handoff protocol.

8.7.3 Project Evaluation and final report

8.7.3.1 The final report will be completed, and an evaluation of the project will be conducted, measuring the packets lost and the latency. Proving the protocol can seamlessly switch between networks and reflecting the research and work undertaken. [25]

8.7.3.2 Delivered will be a Working product that can successfully switch between networks, greatly improving the connectivity along with the Final report displaying all the research and findings of the project.

2. BACKGROUND RESEARCH AND PROJECT RATIONALE

As (Karamchand, 2024) says, Mesh networking is an essential part of supporting services in rural areas. A mesh network is a network, consisting of interconnected nodes that can route data dynamically. This offers a robust and flexible method of networking. (Karamchand, 2024) Mesh Networks are vital in their ability to provide a stable connection across a network, this is due to their inherent nature of having as many nodes as possible, giving them redundancy. This redundancy is essentially a self-healing capability, where if one pathway goes down for whatever reason, the network can still maintain its connection to the rest of the network. (Tarhouni, et al., 2025) Using a hybrid network to achieve the best possible connection is a step forward in, reliability and stability of rural and off grid networks. (Ben Salem, et al., 2023) This can be provided by satellites in low earth orbit, the local mesh network can be routed via the satellites and use them as another method of redundancy, switching from traditional ground cabling to satellite where needed. (Tirmizi, et al., 2022)

The algorithm this project will provide, aims to be a software defined network (SDN) that is able to algorithmically switch networks between the terrestrial network and LEO satellites. (Westphal, et al., 2023) explains how SDN's are an emerging domain, along with the use of satellite networking. The use of an algorithm to support the network switching is therefore a necessity to maintain a reliable and stable network, as supported in (Zhou, et al., 2023) using a form of handover utility in order to manage the decision making process of switching to a connection with the maximum capacity, stability and overall reliability.

AI is a breaking technology that is being tested in methods like the proposed project, (Turkmanovic, et al., 2025) Suggests that the AI framework can enable an optimal session switching leading to a benefit in optimised resource usages. Machine learning using deep neural networks are attempting to tackle this problem to make the handoff method more dynamic and allow for a more efficient switch mechanism. (Fontanesi, et al., 2025)

Key challenges within the research, these are problems that would be required to overcome to sell the viability of the project. (Ben Salem, et al., 2023) showed that hybrid terrestrial/LEO systems can significantly improve the coverage in rural areas. These however can be costly, as they require a lot of infrastructure to build the mesh network as well as have the facilities to receive network signals from LEO. Satellite downlink connectivity also has shown coverage can sometimes be a logistics challenge, so companies are actively working to have a large coverage to provide the most connected and resilient network coverage which is improved with increasing the coverage area. (Lee, et al., 2025)

This project will use an experimental design method, following an algorithmic and potential machine learning driven approach that has been researched in the literature. (Fontanesi, et al., 2025) (Turkmanovic, et al., 2025) In similar approaches, research have used methods such as complex maths to create models to manage the handoff algorithms. (Han, et al., 2024) Others have created bespoke programmes to handle the management.

3. METHODOLOGY AND TECHNICAL APPROACH

This project will be attempting to create an algorithmic approach which will be run on a central system, in this case a laptop will be used running the algorithm and will use a handover utility function formula to make the best choice of balancing between the terrestrial network and the LEO network. The network will be meshed all linking to each other and linking back to the central system. While the network is running, the connections will be sending information back to the central system consisting of the packets lost and the delay experienced. This data is what will be measured to evaluate the success. The code will be written in python and will connect with the nodes used, for the proof of concept, these will be testing nodes consisting of a raspberry pi and simulated bandwidth delays emulating a LEO satellite as using a satellite such as Starlink is not feasible for this project, a simulated node is of close comparison to its true to life counterpart.

To emulate the realistic network behaviour, Linux based network tools such as ‘tc’ will be used to simulate varying connection qualities. This tool will allow for manipulation in the traffic control settings and add the expected delays that would exist when using LEO connections. Data will be collected via Wireshark, this is so that packet delay, loss and switching response time can be effectively measured.

4. EVALUATION PLAN

The overall success of the product will be judged by the networks ability to seamlessly switch between, terrestrial and satellite when it is deemed beneficial and having little to no effect on the end users experience. The level of success will be measured by the quality of the connection being provenly better than it would have been having remained on either the terrestrial connection or the satellite connection. In addition, the quality of connection will be determined by multiple of factors. Packet loss will provide a clear metric of how stable the connection is, many dropped packets along an excessive number of hops will provide clear evidence that the current connection is poor, or that the network switching algorithm is not efficient. Latency will also be measured, this is a primary metric of the algorithm to determine what the best method of connection is, whether it be over the terrestrial network or the LEO satellite network as having a higher level of latency means regardless of the stability of the network, network speeds are still subpar.

Further evaluation can be undertaken by running an existing algorithm on the same test bed, this will further provide evidence to the benefits or drawbacks of the proposed solution. A pre-existing algorithm may not have a better efficiency comparatively.

5. LSEPI CONSIDERATIONS

This project involves no human participants or personal data, meaning GDPR or consent does not apply to this project. All evaluations will be conducted in a closed network using simulated traffic rather than live user data. Complying with the UK Data Protection Act (2018) and Computer Misuse Act (1990) to avoid unauthorised access or data misuse.

6. RISK ASSESSMENT

The potential risks for this project include, time constraints, hardware constraints technical risks and scope risks. Time constraints of this project can occur due to the nature of building an algorithm from the ground up within the allotted time. This can be mitigated by ensuring that the basics of the software are operating withing the time limit to provide a proof-of-concept idea. Furthermore, hardware constraints can be an issue as the project also requires certain hardware to provide an evaluation of the project, this constraint can be avoided using different hardware. To prove the concept, it is unnecessary that all required hardware is used, simulated hardware or time delays can be added to provide a true to life simulation. The technical risks occur as the project grows, it may become unmanageable, remaining within the scope is important as to further abide by the expected timeline. Finally, the scope risks also link to technical risks as too broad of a scope can balloon the timeline and make the project difficult to complete, remaining within the planned scope and on the expected timeline along with routine meeting with the project supervisor to de-scope some none essential features, if development galls behind is the expected way to mitigate risks on this project.

7. PROJECT PLAN AND TIMELINE

This project will be broken into 3 key parts, consisting of: Part 1 Literature Review and Project Design, Part 2 Product build and Testing and Part 3 Project Evaluation and final report. Beginning in January 2026, running through to April 2026.

TASK	Duration (Days)	START	END
Literature Review and Project Design			
Literature Review	10	12/01/2026	22/01/2026
Organise and Summarise Key papers	5	23/01/2026	28/01/2026
Choose and Design Core functions	10	29/01/2026	08/02/2026
Product Build and Test			
Building of source code	30	09/02/2026	11/03/2026
Testing software on testbed	10	12/03/2026	22/03/2026
Evaluation			
Final Report	25	23/03/2026	17/04/2026

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