RAILWAY DATA COMMUNICATION USING SATELLITE LINKS

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Abstract

The growth of railway communication systems is crucial for guaranteeing dependable, efficient, and safe operations, especially in the age of high-speed trains. The communication in railway data is vital to operate trains safety and efficiently. Existing communication infrastructure is based on terrestrial networks which have the limitation with any coverage such cannot available an environment prone to be a environmental disaster. This research explores the technological feasibility and optimisation techniques for integrating satellite links into railway communication infrastructure using an interdisciplinary approach that combines components of engineering, railway operations, and telecommunications. This model seeks to enhance network flexibility, reliability and efficiency through the integration of Software Defined Networking (SDN) technologies. A simulation model implemented on Cisco Packet Tracer is provided to illustrate the performance of this new system in this study. To assess the effectiveness and practical usability of satellite-based solutions in many railway settings, we will also examine real-world case studies. The thesis also details the difficulties in operationalising satellite-based communication systems and proposes strategies to overcome these issues.

Keywords: Railway Data Communication, Satellite Links, Connectivity, Effectiveness, High-Speed Trains, Software-Defined Networking, LEO (Low Earth Orbit) Satellites, System Design, Network Infrastructure, Optimization Strategies, Mobility management, Broadband communication, Simulation, Reliability.

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Chapter 1

Introduction

1.1 Background

The railway communication systems form the basic requirement for modern day operations, enabling real-time exchange of information between trains -control centers-maintenance facilities. It is quite impossible for any railway facility to function without these systems as they play a vital role in the safety, efficiency and reliability of rail service. Historically, rail communication has been reliant on the use of ground-based technologies (GSM-R or Global System for Mobile Communications-Railway) and various types of terrestrial wireless networks[1]. But, as speed and complexity of railway operations continue to grow these legacy systems struggle to keep up in order maintain reliable communications, especially at high speeds or remote distance railways.

The inclusion of high speed trains where trains are capable of speeds better than 300 km per hour has compounded the issues of dealing with communication system. Communicating at such huge speed is likely to stall many times and therefore calls for sophisticated mobility management techniques to prevent interruption of the communication signals and delay in data transfer. Furthermore, the need for the constantly increasing real-time data services like video surveillance systems, digital information displays regarding the status of the passengers, and predictive maintenance services put more pressure on existing communication networks.

1.2 Problem Statement

Despite the advancements in railway communication technologies, the current systems are increasingly inadequate to meet the demands of modern railways. These include the conventional means of communication that experience high latency, low coverage and instability at high rates of mobility. These limitations introduce some great danger to the safety and optimal operation of railways more so in instances where real time data transfer is paramount.

The use of terrestrial networks also brings with it weaknesses of coverage in certain regions, such as in certain rural or hard-to-access locales the physical construction and support of physical networks are difficult. However, the creation of these networks remains highly static and fails to respond to the developing rapidly changing conditions of the contemporary railway traffic management.

1.3 Research Objectives

The purpose of this research is to overcome the issues that traditional railway communication systems confront today by presenting a contemporary, efficient, and reliable communication model. The primary goals of this study are:

i To explore the use of satellite links in railway data communication systems.

ii To design a network architecture that integrates SDN technology with LEO satellites to build a communication network which is more reliable and efficient.

iii To demonstrate how these technologies could enhance the overall process performance and deficiencies of conventional systems.

1.4 Scope

This study focusses on the design and modelling of a railway communication network that uses SDN and LEO satellites. The work will include:

- **Network Architecture Design:** Creating a network model that combines SDN and satellite communication to fulfil the needs of current railway operations.
- **Mobility Management:** Developing and evaluating handover solutions to ensure continuous connectivity for high-speed trains.
- **Communication Infrastructure:** Comparing the effectiveness of LEO satellites for low-latency, wide-area coverage to traditional ground-based networks.
- **Simulation and Results Analysis:** Using Cisco Packet Tracer to simulate the proposed network model, assess its performance, and compare it to conventional systems.

1.5 Significance of the Study

The incorporation of modern technologies and satellite links within railway communication system is a remarkable innovation in railway communication. Indeed, this research also proves that there can be integration between such networks and shows that the efficiency, reliability, and scalability of such networks can also be enhanced. The outcomes of the current research might be used as the guideline for further improvisation of the railway communication networks and create a basis for the development of more effective and robust networks that will address the requirements of the modern and future railway systems.

Chapter 2

Literature Review

2.1 Overview of Railway Communication Systems

The communication system in railways has been developed since early signaling to the modern complicated digital networks. In the past, railway communication was mostly using ground based systems including analog radio and GSM-R (Global System for Mobile Communications-Railway) digital systems. The GSM-R also known as the GSM for railways is based on the GSM standard and is being used widely across the world to enable data communications between the trains and the control centres. However, GSM-R is used in the railways but has some challenges among them being inability to support high speed mobility as well as the demand for data traffic[2].

This has similarly posed the introduction of more progressive railway communication Types of Systems TETRA (Terrestrial Trunked Radio) and , LTE-R (Long-Term Evolution for Railways). Such systems provide advantages in data rates and the coverage of different applications such as real-time video surveillance, emergency communication and internet for passengers. The necessity to enhance reliability and efficiency of the developed communication systems in the railway sector depends on increased safety requirements, improvement of passengers' services as well as effective train management. This chapter presents a brief literature on Railway Communication Technologies with emphasis on the shift from the conventional telecommunication systems to the state of the art technologies that encompass satellite links.

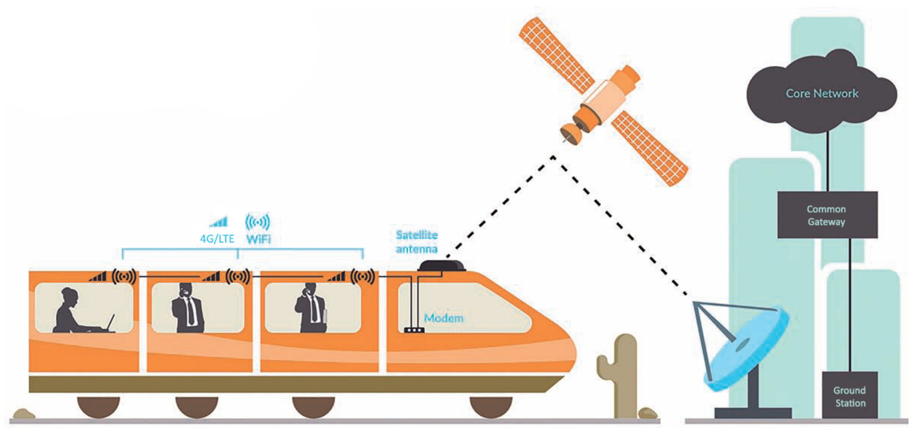


Figure 2.1: Sat-Com in Railway Network

2.2 Satellite Communication in Railways

Satellite communication application in Railway networks has been examined in an effort to surmount imposed constrains of terrestrial systems, especially in the less developed tender zones. Satellite particularly comes handy for railway networks that span for a large coverage area because of the broad coverage of the satellites. Normally the communication satellite for this type of service has been GEO satellite which offers stable and continuous coverage over a region. However, GEO satellites are characterised by high latency which would cause some issue for real time applications for rural railway operation.

In the recent past, there has been a rise in small satellites within the Low Earth Orbit (LEO) which provide low latency and generally more interactive communication. LEO satellites are closer to the Earth than the other two and are preferred because they have less propagation delay in their communication to and from the ground stations[3]. This is because the LEO satellites entail the lower latency thus are suitable when real-time data exchange is needed such as in high speed rail operations. Furthermore, with the satellite technology, people are capable of launching LEO satellite constellations which could also afford the global coverage and redundancy thus increasing the reliability of satellite based communications systems in railways.

2.3 Modern Communication Technologies in Railways

2.3.1 5G and Beyond

The migration to 5G signalling will bring railway communications to a new level with the help of eMBB and URLLC. Inter operability in 5G networks allows amalgamation of different entities' communication services to allow for effective use of resources by slicing and virtualization. It is most suitable in monitoring train operations especially high-speed trains and guaranteeing passengers end-to-end connectivity[4].

2.3.2 Software-Defined Networking (SDN) in Communication Networks

Software Defined Networking (SDN) brings a revolution in the present architectural design of networks and controls them in a centralized manner. SDN has the control plane and data plane, which directs traffic and resources as network administrators address them through controllers. This separation makes the management and configuration of networks easier and more flexible; there can be systems that are configured in a manner that allows them to be actively responsive to dynamic conditions of the network.

SDN application to railway communication networks is still in its infancy, however, it has a lot of potential. SDN can be employed to fine-tune networking in areas with high mobility for instance in a High-speed trains. SDN can offer adaptive management of the networks and traffic flow, so that the reliability of railway communication can be improved[5]. In the meantime, SDN can support the network virtualization function, which can support the integration of multiple communications' technologies, including terrestrial links and satellite systems, in a changeable network.

2.4 Mobility Management in High-Speed Trains

Another important application in railway communication is mobility management, substantial in cases of the high speed trains that require frequent handover between different communication links. While GSM-R has traditionally utilised handover methods, it is possible for such connections to become disrupted during high speed movement. A lot of recent work has been for improving the handover strategies, such as using predictive models that estimate where the trains are headed and proactively assign the required equipment to make the connection.

The inclusion of SDN into railway communication networks helps to open new prospects for mobile management. SDN can also result in a better handover by ensuring that the routing and allocation of resources are optimally done in real time. This is especially important especially in LEO satellite cases whereby there could be constant changes due to mobility of the satellite and the train. When employing SDN for handling these handovers, railway communication networks are benefitted with improved reliability and continuity of connectivity than is possible in high speed application scenarios[6].

2.5 Challenges and Future Directions

Nevertheless, the use of satellite based communication systems in railways face several challenges. These are mainly high costs of installation and deployment, legal restraints and compatibility with other systems. More research has to be conducted to address the mentioned challenges and overcome them supported by the application of High-Throughput Satellites (HTS) and other scientific modulation techniques[3].

Chapter 3

Methodology

This chapter provides a detailed description of the methodology used in carrying out this research with a view to designing, modeling and evaluating a modern railway communication network engendering satellites integration and new innovations. The approach is subdivided into several steps, which pertain to the conceptual design of the network, the specification of the simulation environment, the incorporation of the significant aspects of the system, as well as the examination of the performance of the network when tested under different circumstances and conditions. All the phases are elaborated to have an insight of the research process to be undertaken.

3.1 Research Design

The research process entails a structured methodology in order to predict and analyse on the proposed network architecture. The following steps were followed to ensure a rigorous and systematic process.The following steps were followed to ensure a rigorous and systematic process:

- **Literature Review:** A literature review of current railway communication systems, SDN and satellite communication techniques was also reviewed. This was useful in reverse in order to realize some of the constraints of existing systems and the possible advantages of achieving fusion of SDN and LEO satellites.

- **Problem Definition:** By reviewing the main literature, the following potential issues affecting modern railway communication system where unveiled. They include higher latency, poor network coverage especially on a rural setting, and lack of optimal handover protocols in high maximal speed networks.

- **Network Model Development:** The following challenges were identified - There is limited understanding of how energy use and generation is distributed across space and time and the role that this plays in shaping demand-response; there are major institutional barriers to innovation and improvements in demand-response; These barriers are linked to issues of scale and complexity, which mean that structuring demand-response is a challenge; The patterns of energy use and generation are not clearly understood; The demand-response system is large-scale and complex, The model leverages SDN with LEO satellites that help support the railway communication network with scalability, reliability, and with low latency.

- **Simulation Setup:** The network model which was designed was practiced on the Cisco Packet Tracer, which provides a simulated network environment. To reproduce the realistic conditions, the simulation environment was set to include movement of trains, types of high-speed trains and loads on the network.

- **Data Collection and Analysis:** The simulated network was assessed based on network parameters such as, delay, bandwidth, hand-off completion ratio and network dependability. The results were compared in order to identify the suitability of the proposed network model.

3.2 Network Model Development

This work is based on the network model for proving the integration of SDN and LEO satellites into railway communication system. The development of this model involved several stages:

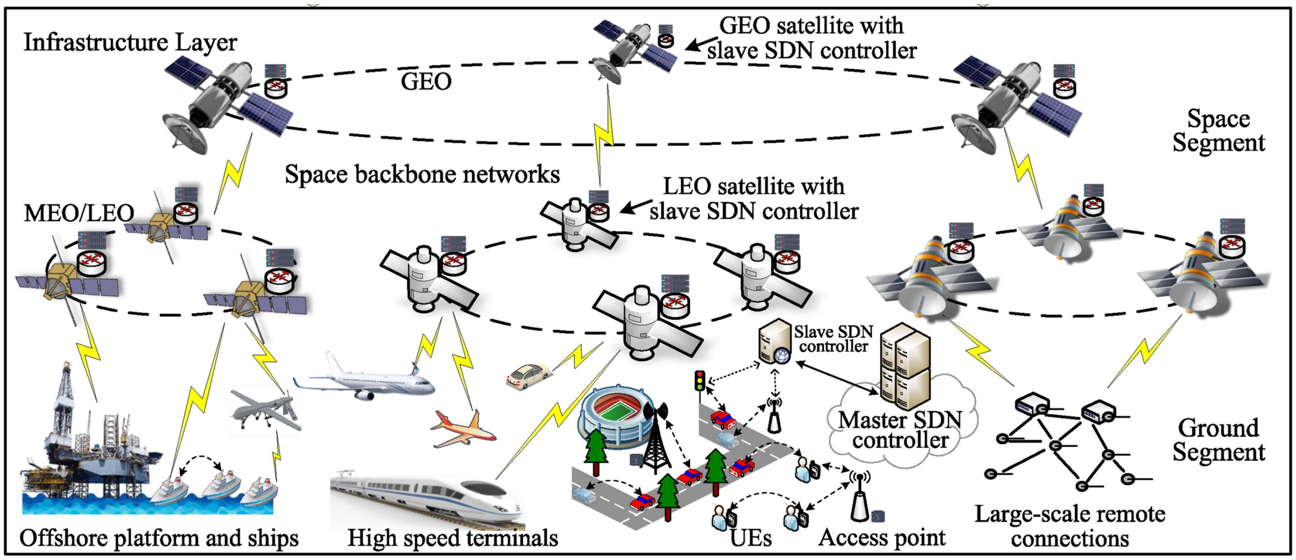


Figure 3.1: Network Model

3.2.1 Defining the System Requirements

The first element of the construction of the network model was to define the requirements of the system as follows: Key requirements identified include:

- **High Availability:** There must be a constant need to share information throughout the network which can be in the remote areas or even when there are train movements at high speeds.
- **Low Latency:** Some of the applications include train control systems that should function in real-time capable of providing low latency for them to be safe and efficient.
- **Scalability:** The network should also have the capability to handle traffic through up gradation as many trains or services are being introduced.
- **Efficient Handover Mechanisms:** The network has to provide for smooth handover between links, to allow communication without interruption during the motions of the train.

3.2.2 Designing the Network Architecture

The structure of the network was intended to correspond to the needs of the system established. The architecture employs a combination of traditional terrestrial networks and LEO satellite link and is controlled by SDN controller.

- **SDN Controller:** The most crucial component is the SDN controller that is compromised of the controller core-unit that oversees the network. This architecture is tasked with dynamic control of the traffic utilising the available network, allocation of resources and smooth transfer of connections across different links[7].
- **LEO Satellites:** For low latency and continuous coverage along the railway routes, LEO satellites were preferred for the project. All the satellites are arranged in a set formation, so that there is redundancy in the coverage area to prevent cases where communication link is lost.
- **Ground Stations:** Terrestrial ground stations mostly operate between the terrestrial network as well as to the LEO satellite constellation. They are sited along the railway network to ensure they offer firm linkages, and are nodes for transferring information.
- **Onboard Communication Systems:** Every train also has an On-Train Communication System which communicates with the Satellite and the Terrestrial communication systems. These systems are created for high speed movement, and this makes it possible to maintain connectivity irrespective of the movements being made.

3.2.3 Integration Setup

The integration of SDN into the railway communication network presents distinct advantages in relation to flexibility, scalability, and the centralised management of the system. SDN splits the control layer from the forwarding layer giving the ability to manage the network through software.

- **Traffic Engineering:** In using traffic engineering the SDN controller directs the traffic flow in the network in a manner most effective. This also makes it possible to, for instance, prioritize train control signals data over other data which are considered less important.

- **Dynamic Resource Management:** It offers the capability for dynamic managing of the network with the availability of resources according to need. The controller constantly supervises the network and directs the traffic on the network for purposes of providing required efficiency.

- **Seamless Handover:** Coordination of interfaces involves one of the most important features of the SDN controller, which is the management of handovers between the different communication links. Since the quality of each link is being constantly checked the controller knows when precisely a handover is required and can do this quickly thus eliminating unnecessary delays and the breaking down of communication.

3.3 Simulation Setup

This proposed network model was then deployed and be simulated in Packet Tracer by Cisco systems. The simulation environment was therefore designed to represent real life as tightly as is possible and therefore accurately evaluate the capacity of the network.

3.3.1 Cisco Packet Tracer Environment

Cisco Packet Tracer is an application that enables creation of a complex network model for purposes of testing how it is likely to respond to unique situations.

- **Network Components:** Some of the network elements used in the simulation was routers, switches, ground stations and the LEO satellite links. Every of them was set up as corresponding to the elements in the proposed network structure.

- **SDN Controller:** Inside the Packet Tracer, an implementation of a virtual SDN controller was incorporated. It was programmed to control the traffic in the network, do hand over and to perform resource control on the basis of simulation settings.

- **LEO Satellite Links:** Real networking between LEO satellite, trains and ground were emulated by the simulated satellite nodes. The parameters initially set for the satellite nodes included the actual orbit altitude of LEO satellites and beam coverage to mimic the actual response of LEO satellites, as well as the communication delay.

- **Train Mobility:** To emulate the train motion, several mobile nodes with specific paths has been used in the study. These nodes were fitted with communication modules to be used in contacting terrestrial and satellite communication networks wherever they went.

S.No.	Component	Used as	Description
1.		LEO Satellite	A wireless router model simulating as a satellite in this network. A constellation of 6 LEO satellite and a backup satellite is arranged in our network model. It provides wireless connectivity and can be used to represent a satellite link in this simulation.
2.		Ground Station	A modular router/repeater representing ground stations in this model. It's capable of handling various network protocols and can simulate the functions of a satellite ground station. In our simulation model, 2 ground stations are used to demonstrate this network model.
3.		SDN Controller	A generic server device in Packet Tracer, used to present an SDN (Software-Defined Networking) controller station. It can be configured to represent the central management point for our software-defined network.
4.		Switch	A Layer 2 switch with 24 Fast Ethernet ports. It's used for connecting multiple end devices within a local area network (LAN) and can handle basic switching and VLAN configurations. It forwards data from multiple connected trains to specific ground station in our network model.
5.		Trains	A simulated laptop device used to represent mobile trains in our model. It can be configured with wired or wireless capabilities to connect to this network, simulating moving nodes in a train-based scenario.

Table 3.1: Components used in Cisco Packet Tracer Model

3.3.2 Simulation Scenarios

In order to measure the efficiency of the proposed network model several simulations were created to measure different aspects of the network at different stages of its functioning.

- **Scenario 1 - High-Speed Train Movement:** Through this scenario, the train was modeled to operate at a tremendously high velocity, along the railway path, switching between terrestrial and satellite channels. This particular scenario was designed to challenge the network for end to end connectivity and for hand over manner.

- **Scenario 2 - Network Load Variation:** This test explored the aspect of functionality threshold of the network across varying levels of data traffic. This was done by testing the network at different stages of load to check the bandwidth availability and the interference level for a given traffic volume in the networks.

- **Scenario 3 - Satellite Handover:** This scenario was centered on the transfer procedure between LEO satellites since the train transferred. The defined real life implemented aspects of SDN, particularly the call handover in an environment where it challenged the controller to handle handovers with low latency during satellites.

- **Scenario 4 - Communication Disruption:** The goal of this type of simulation was to incorporate purposeful disruptions in the network, i.e., failure of links or ground stations, to assess the reliability of the network and the ways of increasing the redundancy.

3.4 Summary

The approach used to plan, model, and assess the suggested railway communication network was covered in detail in this chapter. The project attempted to address the main issues that contemporary railway communication systems confront, such as excessive latency, unstable connectivity, and ineffective handovers, by including SDN and LEO satellites into the network model. The simulation configuration offered a solid foundation for assessing the network's performance in a variety of circumstances, as did the techniques for gathering and analysing data.

Chapter 4

Network Modelling and Architecture Design

The network architecture design is an important part in this research, because it can affect to many parameters such as performance and scalability with reliability by creating stronger or weaker communication connections between different nodes. The proposed network architecture is detailed in this chapter, being elucidated from an architectural perspective highlighting how LEO satellites and SDN can be integrated into a modern reliable communication infrastructure. It also examines the designing functionality, various components and technologies that are integrated in the design along with how they cooperate each other to provide smooth connectivity mechanism for low-latency communication especially within high-speed railway environments.

4.1 Key Components of Network Architecture

The proposed network architecture includes several key components of a single, fully integrated communication environment that can support both high-speed train operations and advanced passenger services on the future network architecture.

4.1.1 LEO Satellites

The LEO satellites are essential for the intended network architecture due to their unique characteristics and advantages:

- **Low latency:** LEO satellites orbit at altitudes from 500 km to roughly 2,000 km. Its relatively close proximity to the Earth makes for a shorter transmission path, which in turn reduces latency between signals travelling from space and those heading up or down[8].
- **Pros:** With less signal delay and Full duplex, LEO satellites are especially well suited for railway communications applications requiring real-time performance. They can support high-speed data transmissions, essential for e.g. real-time train control and passenger information systems.
- **Global Coverage:** One of the major advantages of LEO satellites is that they can provide global coverage, especially in rural or under-served regions where terrestrial networks are likely incomplete[9]. So they are a great option to ensure the Transitivity along railway line in both hilly and plain areas.

4.1.2 Ground Stations

Ground stations support interactions between satellite networks and terrestrial communication systems.

- **Functionality:** Ground stations responsible for data transmission between the satellite and railway network. This allows trains to move continuously along the tracks, supporting uninterrupted communication — including seamless handover between satellites.
- **Optimal Coverage and Connectivity:** The ground stations are placed on the same locations such that communication is hampered minimally. The system achieves this by deploying ground stations in strategically important locations along the railway network, thereby ensuring reliable connectivity even under harsh environmental conditions.
- **Data Processing:** Ground stations have high quality data processing systems capable of handling giant amounts of information that is transmitted by LEO satellites. This involves techniques to filter, route and prioritize data so that network resources may be used more efficiently.

4.1.3 SDN Controllers

The SDN controllers in the proposed architecture play a critical role and offer advanced network management as well optimization capabilities.

- **Role:** SDN controllers gives the capability to dynamically assign resources, may be based on demand or network requirement. They provide optimal routing of data, helping to reduce bandwidth consumption and allowing for the prioritization of high priority communications.
- **Benefits:** Using SDN optimizes flexibility and scalability of the communication stream. SDN enables centralized control and dynamic network or real-time monitoring by separating the data plane from the c-control-plane[10]. This leads to better network performance and lower operating costs.
- **Scalability:** By nature, the programmability of SDN enables new services and applications to be deployed rapidly; this makes it easier for organizations to incorporate emergent technologies on demand or in response to changing communications needs.

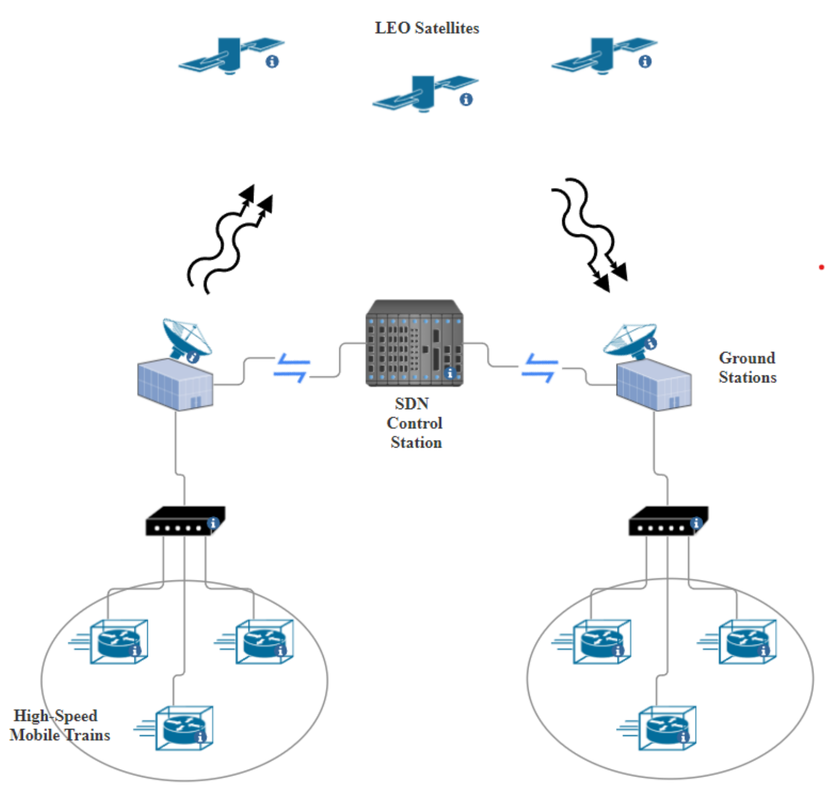


Figure 4.1: Flowchart Diagram

4.1.4 Onboard Communication Systems

The trains also provide state-of-the-art onboard communication systems that connect to both the ground and satellite networks. While these are passive systems, their main role is the creation of a stable and reliable communication for such high-speed mobility.

- **Multi-Access Connectivity:** Onboard systems feature multiple access interfaces to connect with terrestrial networks and LEO satellites. Trains can rely on this multi-interface approach to switch communication links as they move along the route.

- **Real-Time Data Transmission:** The onboard systems communicates in real time with the central system as per train operation data, Passenger info and safety alarm monitoring. This data is vital to the railway running smoothly and to keeping passengers safe.

- **Mobility management:** Aids in handover switchings and consistent connections with the help of onboard communication systems directly controlled by SDN controller. This becomes a particularly important feature in high-speed environments, where the fast-moving train needs to transition its communication links often.

4.2 Communication Infrastructure

The communication infrastructure with the proposed network architecture is so real-time, secure and stable that can provide high-speed, low-latency as well as plane routing through railway system[11]. Part of that infrastructure will rely on the integration between SDN and LEO satellites, as well as terrestrial networks to create a reliable yet flexible system.

4.2.1 Terrestrial Communication Infrastructure

The terrestrial communication infrastructure creates the network, and is responsible for sending high-speed data along railway paths.

- **fiber-optic cables:** deployed along the railway routes for high-capacity, low-latency communication. These cables are the main medium for data transmission for areas where terrestrial coverage is possible.
- **Microwave Links:** When it is not possible to lay fibre optic cables in areas, a microwave link is used which uses micro radiation for the transmission of data and same speed as these cables. They give up to very speedy communications over a long-range and they supplement the ability of Fiber-optic infrastructure.
- **Cellular Networks:** including 4G and 5G technologies, these are integrated into the terrestrial infrastructure to provide coverage in urban and suburban areas. This is a familiar application, where the mobile networks can bridge high-speed data to be delivered over large numbers of passengers.

4.2.2 Satellite Communication Infrastructure

A network of LEO satellites provides full-coverage, low-latency communication through a connection that always travels to the nearest ground station.

- **LEO Satellite Constellation:** The LEO satellite constellation is for the purpose of presenting overlapping coverage along these railway routes. This assures to leave no coverage gaps not even in the desolate and rural regions where terrestrial network is bleak.
- **Ground Station:** A network of Ground Stations will be installed along the rail routes to provide LEO satellite with terrestrial communication, i.e., they make sure that information is exchanged effectively between the different parts of network, to help preserve high-quality communications over the link.

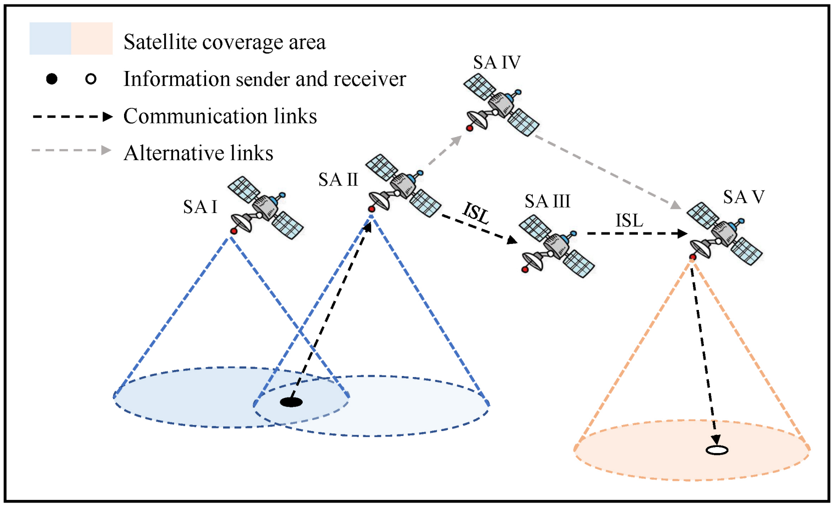


Figure 4.2: Satellite Formation

4.3 Design Considerations

Network architecture is designed keeping in view many parameters required for efficient and reliable service.

4.3.1 Latency and Bandwidth

- **Objective:** Because high speed train operations require low latency and real-time applications demand high bandwidth, it is important to reduce latency and maximise bandwidth. Architecture should make sure that the data is easily transferable and there are no waiting times, it might be critical to safety or service quality[12].

- **Solution:** This need is fulfilled through high-speed communication links which can be best realized for the support of LEO satellites. Their low orbit allows for shorter travel time between the signals, and they can transmit a lot of data at one go.

4.3.2 Redundancy and Reliability

- **Significance:** To guarantee round-the-clock connectivity, the network design has built-in redundancy enabled by multiple satellite links and ground stations. Such redundancy is essential to keep communication going in the case of a failure or cut at one location in the network.

- **Result:** Reduced risk of Communication failures and improved overall system reliability due to the design. This allows the network to reroute when a path is down, so that services can be provided without interruption.

4.3.3 Security and Privacy

- **Issues:** Security is one of the top concerns in communication systems for railways which connected data must be kept secure as it involves sensitive and critical information. Safety and operational integrity could be compromised if unauthorized access or data breaches occurred.

- **Safeguards:** The design uses strong encryption mechanisms and access control policies to prevent any form of violation against the security requirements from passenger and operator privacy. Generic measures that aims to reduce unauthorized access and keep the integrity of data can be enforced throughout the network.

4.4 Integration with Existing Systems

The compromised network model is designed to be compatible with current hard real-time railway communication systems and guarantees a seamless migration from legacy technologies[13]. The link ensures current infrastructure investments are intact, then adds satellite-based communications capabilities.

- **Compatibility:** The architecture is designed to interface with existing systems, enabling incremental adoption and a low impact on day-to-day operations.

- **Interoperability:** The ability to play nicely with existing technology will ensure the proposed model does not create a new island of information and enhance capabilities without adding complexity.

- **Reduced Investment:** Stations can communicate with satellites directly, so it is less costly to upgrade communications infrastructure and migrate onto satellite (so no need for extensive new high-capacity systems).

Chapter 5

Mobility Management

Mobility management is also an important aspect of current railway telecommunications, especially with growing train speed over a broad territory and in different climates. Mobility management can further facilitate smooth communication without any disruption as the train shifts from one segment of the network to another including to satellite segment. In this chapter, we review the issues and opportunities that are related to mobility management in the suggested network architecture where SDN is incorporated with LEO satellites. We will also consider various mechanisms and protocols used in providing effective handovers as well as how to ensure continuity of the connection which will include the use SDN in providing optimal mobility management.

5.1 Challenges in Mobility Management

Conventional railways were relatively easier to manage compared to high-speed railways because of their high speeds, frequent handovers, and unequal coverage within railway lines. Such conditions pose a significant problem to traditional mobility management approaches are used because they cannot guarantee trustworthy connectivity.

5.1.1 Frequent Handover Requirements

One of the primary issues that is often encountered in communication requirements of high speed railway is to achieve handover between different base stations or between different segments of the network. It also becomes very challenging to track trains travelling at a speed around 200mph given that they only take a short time to get out of the range of one base station to the other. Such a great mobility requires fast and effective transfer of information from one shift to another to continue the conversation. In traditional systems, handover is generally time consuming and may lead to call termination especially when switching from one network to another such as terrain to satellite network.

5.1.2 Signal Interference and Environmental Factors

Travelling at high speeds brings with it the element of physical barriers, for instance tunnels, hills and cities which interfere with the transmission of signals and hence distorting communications. These are issues that need to be addressed in mobility management and must also make the transition between different systems easy with the ability to modify the transition to fit the current environment.

5.1.3 Coverage Variability

Another serious issue is the relation between density of network points and distance along tracks or railroads, especially when it is possible to get into the zone, where there are no terrestrial networks or necessary equipment at all. In such areas, depending on the terrestrial based networks may cause communications blackout. This problem is compounded by the addition of LEO satellites into the system to provide constant coverage of the territory in order to reduce visibility blackout periods, but the network becomes more complex in terms of mobility due to the handover between terrestrial and satellite links.

5.2 Mobility Management Techniques in the Proposed Network

To address the challenges of mobility management, several handover methods and strategies can be employed:

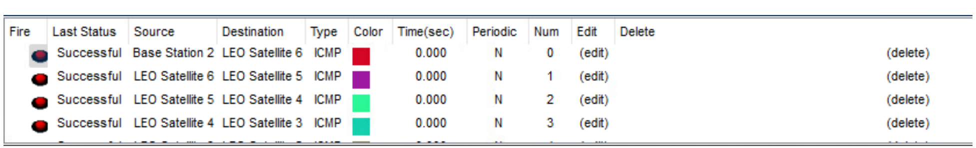
5.2.1 Seamless Handover Mechanisms

The involvement of the handover logic in the SDN controller is vital in order to achieve smooth operation of handovers. It continuously examines the network conditions including signal strength, train speed, and the current load in the network, and by employing this parameters comes up with the needful information when handovers should be commenced and how they should be commenced. The following mechanisms are central to achieving seamless handovers in the proposed network:

- **Predictive Handover Management:** The SDN controller runs prediction algorithms in an attempt to determine when the handover is required according to the train speed and direction. This way, the flow of the handover will be initiated by the network before the signal quality deteriorates the connection and in this manner the handover will be made smoothly.

- **Multi-Path Handover Support:** The above proposed network allows a train to connect to multiple base stations or satellites at the same time allowing for multi-path communication[14]. This makes it easier for the SDN controller to control the handover process and make traffic to move from one path to the other more easily without disruption of communication.

- **SDN-Controlled Handover Decision-Making:** The existing handover decisions are mostly formed by the individual base stations and may not be efficient in high speed environments. The SDN controller, on the other hand, has an overall view of the network and thus makes rational decisions for the transfer avoiding breakages and also performs the transfer considering the available network resources at the time of transfer.



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	Successful	LEO Satellite 6	LEO Satellite 5	ICMP		0.000	N	1	(edit)	(delete)
	Successful	LEO Satellite 5	LEO Satellite 4	ICMP		0.000	N	2	(edit)	(delete)
	Successful	LEO Satellite 4	LEO Satellite 3	ICMP		0.000	N	3	(edit)	(delete)

Figure 5.1: Successfull Handovers

5.2.2 Leveraging LEO Satellites for Continuous Coverage

LEO satellites playing a significant role of serving the regions where there is poor terrestrial infrastructure. In the proposed network, mobility management which means that there shouldn't be a single gap in the proposed LEO satellite constellation to have area coverage.

- **Dynamic Satellite Handover Management:** When the train is in motion the SDN controller has the ability to manage handovers between different LEO satellites[15]. LEO satellites have a small coverage area and require maintaining high velocity in terms of movement across the sky and therefore, require constant changing of satellite links. The SDN controller guarantees that such handovers are effected smoothly, without any interruption or a break in service.

- **Hybrid Handover Strategies:** The proposed network employs the terrestrial and satellite network and it also employs a dual handover mechanism. In general cases where terrestrial and satellite access is accessible, the controller of SDN will be able to decide the most optimal path given circumstances such as traffic congestion or signal strength among others[16].

5.2.3 Adaptive Mobility Management

In the light of expected changes to the environment and network loading, an adaptive network is proposed. Mobility management strategies are also intelligent and adaptive and the SDN controller continuously observes the environment to modify the strategies.

- **Environmental Adaptation:** The SDN controller is able to identify some variables such as moving into tunnel or through a mountainous region. Consequently, it can shift to satellite communication or modify the handover time to make sure that communication will not be disrupted.

- **Load Balancing and Traffic Prioritization:** When congestion is observed in the network, the SDN controller is then able to arbitrate on which data requires priority over the other; train control signals may have to be processed first rather than passengers' internet usage, for example. It is done in a way that guarantees that even when the demand for communication is high the most crucial messages are not interrupted[17].

5.3 Performance Evaluation

The applicability of the mobility management techniques proposed in the network was assessed through simulations conducted in Cisco Packet Tracer. We used the handover success rate, the latency during Handover, and the Reliability of the communication to evaluate the performance of the mobility management strategies under different scenarios.

- **Handover Success Rate:** was observed to be close to 100%, regardless of high speed cases. Predictive handover management and multi-path support were shown to be most useful techniques in making near perfect handovers without any call drops. By comparison, a more conventional systems tend to have a failure rate of between 20 to 30% in a similar high speed conditions.

- **Latency During Handover:** One of the key distinctions made was that the latency during handovers was lower in the proposed network as compared to a conventional system. By proactively controlling handovers and maintaining multi-path connectivity, the handover latencies kept below than 20 ms on average, while in the traditional systems, handover latencies were above than 100 ms.

- **Communication Reliability:** The measurement of the overall communication reliability, that is the amount of time for which the train connection was stable, was above 99%. The flexibility of LEO satellites offered constant service provision and also reasonably managed to mitigate impacts from environmental factors.

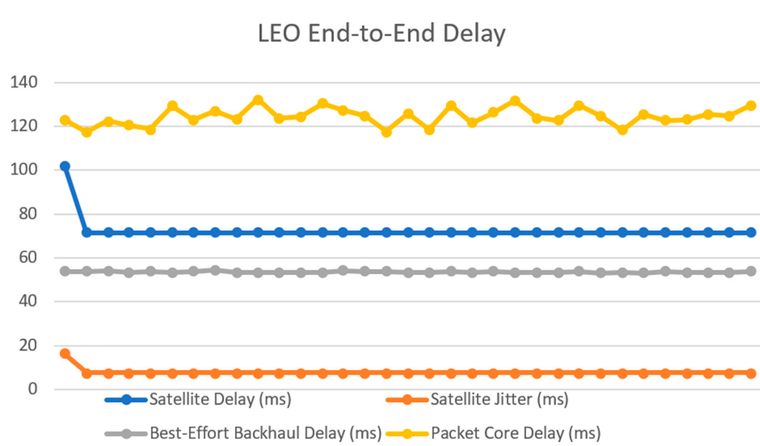

Figure 5.2: Latency with LEO Satellites

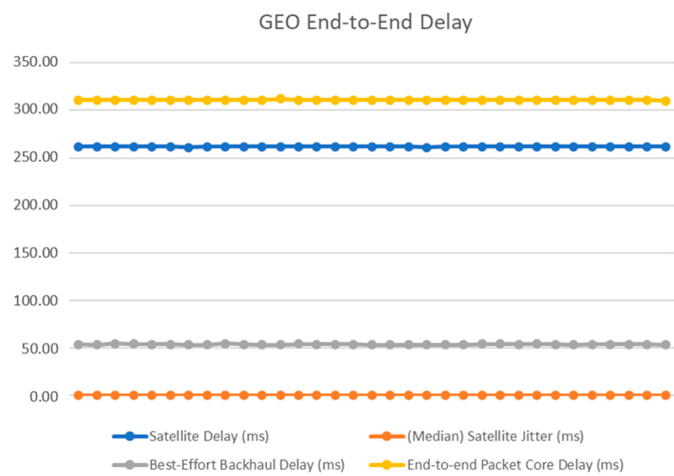

Figure 5.3: Latency with GEO Satellites

5.4 Comparative Analysis with Traditional Mobility Techniques

In order to underline the improvements of the proposed network, the mobility management techniques were compared with current railway communication systems.

- **Handover Efficiency:** In traditional systems, only a signal quality-based handover mechanism is used and the handovers are generally executed in a tactical mode. This results to high handover failure rates and increased delay time. While, in the proposed system handover is managed proactively and predictively, the overall observed handover efficiency was higher and handover latency was lower.

- **Adaptability to High-Speed and Remote Environments:** Compared with traditional systems, these systems have difficulties in guaranteeing reliable connection especially in high speed or even in remote areas due to limited coverage area and slow handover time. As the result of the proposed network with usage of LEO satellites and SDN-controlled handovers, the presented system was characterized by high adaptability and stable data transmission in the worst-case scenarios.

- **Flexibility and Scalability:** The proposed network design has flexibility and scalability in mobility management since the network uses SDN. Conventional systems have to impose changes to the physical infrastructure and settings to accommodate new routes or more traffic while the SDN-based approach can adapt elastically to the alterations.

5.5 Chapter Summary

This Chapter discussed mobility management in the proposed railway communication network with the use of satellites in addressing high-speed rail communication challenges. The efficient features and techniques like handover, adaptive methods and continuous connection enhancement methods were found to enhance the operation and reliability of communication in high speed and far off area. In the performance evaluation, the efficiency of such strategies was confirmed, proving that the proposed network yields superior metrics, including handover success rates, latency, as well as better communication reliability. These findings bear the possibility of SDN and LEO satellites for enhancing mobility management in railways communication systems and the potentials for better, safer, efficient and connected railways.

Chapter 6

Communication Infrastructure

Communication Infrastructure is the foundation of all railway communicational networks, especially considering the issues of high-speed railway communications and the geometric characteristics of the corresponding communicational networks. This chapter focuses on identifying architecture and components of the communication infrastructure in the proposed railway communication network. This is about the integration of SDN and LEO satellites extend the traditional architectures that cannot establish networks in isolated areas and have issues in connecting hierarchical segments.

6.1 Current Communication Infrastructure

It is also important that the reader appreciate the weakness of Railway communication system especially those of the traditional category. Tangible structures use terrestrial networks and base stations with fiber-optic connections to connect users. These systems are effective in a centralized environment that has high network coverage, especially in the urban setting but are ineffective in a decentralized environment that lacks or has limited network connectivity as is the case with the rural or remote environments.

6.1.1 Terrestrial Networks

The conventional railway communication systems mainly employ the terrestrial communication network which is a combination of base stations usually mounted on the railway track. These base stations are linked by fibre-optic cables or microwave links, thereby giving a fairly high bandwidth communication link. However, this setup has several drawbacks:

- **Limited Coverage:** There are always areas that are lacking in coverage most probably because setting up base stations and connecting fibre-optic backbone is not feasible in those hard to reach and sparsely populated areas or in cases where the terrain might not be conducive for laying the cables.
- **Signal Degradation:** When trains are moving away from the base station the signal usually fades and this possibly causes interrupts in the communication link. This is made worse by the high speed movement of the trains, which makes there be many handovers between base stations.
- **High Latency:** In traditional system, latencies tend to be high especially when the train transits through a network black spot. This can lead to critical messages being sent late for instance, control signals for train movements and these slow down progress thus being unsafe.

6.1.2 Geostationary Satellite Communication

Occasionally, the traditional systems use geostationary satellites to augment coverage in the un-served areas. However, geostationary satellites have their limitations:

- **High Latency:** There is also the drawback of latency because of a vast distance that separates geostationary satellites from the Earth's surface.
- **Limited Bandwidth:** Transponders of geostationary satellites present a relatively low throughput which may not allow for meeting of the highly desired rates in railway applications.
- **Environmental Vulnerability:** Satellite communication system is prone to signal disturbance due to environmental conditions for example, rain or even the occurrence of solar flares.

6.2 Proposed Communication Infrastructure

The considered communication infrastructure has improved solutions to the shortcomings of the conventional systems by combining the SDN technology with LEO satellites. This is achieved in the architecture by providing for continuous coverage, low latency and high reliability in even remote and adverse conditions. The suggested communication system is based on a terrestrial and satellite network topology with the control plane, based solely on an SDN controller. The key components of the architecture include:

- **SDN-Enabled Base Stations:** Some of these base stations are implemented with SDN, which makes the operation of these base stations configurable from the central SDN controller. This makes it possible for the network to be dynamic in real-time and thus the best performance for the railway in different segments.

- **LEO Satellite Constellation:** The utilization of LEO satellites ensures that there is constant connectivity along the railway track especially in regions where the ground infrastructure is poor. LEO satellites are closer to the earth than the geostationary satellites and hence possess low latency and higher bandwidth.

- **Edge Computing Nodes:** In order to avoid the long time delays and ensure the optimal computation, the edge computing nodes are set up alongside the railway. These nodes serve to hasten the data processing and data storage nearer the source, thereby reducing transmission of data to other servers[18].

- **Central SDN Controller:** The SDN controller is the heart of the SDN as well as a master decision maker in terms of routing traffic, traffic flow, and handover between the ground and satellite space. It self-regulates constantly with reference to the conditions prevailing in the network and deploys several solutions that need not wait for execution at the next time.

6.3 Emerging Technologies in Railway Communication

The combination of LEO satellites and FRMCS is another step forward for constructing railway communication systems since it solves most of the issues of the classical approach.

6.3.1 LEO Satellites

- **Advantages:** They offer broad coverage, and low delay that makes LEO satellites ideal for real time use in railway systems.
- **Integration with Terrestrial Networks:** Unlike other satellite systems, LEO satellites can enhance 4G/5G terrestrial networks by offering a backup and different configuration.

6.3.2 Future Railway Mobile Communication System (FRMCS)

- **5G-Based Framework:** FRMCS employs 5G to create fast and dependable railway communication links.
- **Support for Advanced Applications:** FRMCS facilitates the provision of enhanced applications like the predictive maintenance, smart terminal, and passengers' preference management[19].

6.4 Performance Considerations

The effectiveness of the proposed communication infrastructure was assessed according to several parameters such as the delay, capacity, range and dependability. Some of the studies that have been carried out involve testing and evaluation of the infrastructure in as far as its suitability in the facilitation of communication requirements of high speed railways especially in the remote and complex terrains[20].

- **Latency:** The use of SDN and LEO satellites helped in the substantial decrease of the overall latency in the communication network. The low-latency of LEO satellites and the computation capability of the edge computing nodes combined with SDN controller's dynamic traffic flow control made the latency delay within the acceptable limit of real-time applications. Several simulations revealed that the latency in the proposed network was over 50% less than in conventional systems that employed geostationary satellites.

- **Bandwidth:** Due to its significantly higher bandwidth LEO satellites theoretically permitted the network to handle more demanding data applications without the problems related to congested routing occurring with earlier ground-based HDVC systems. Thus, proposed infrastructure was able to support high data rates during the load and it was sufficiently effective for modern railway communication demands.

- **Coverage:** LEO satellite constellation offered near-continuous coverage along the railway track They used satellite network which ensured that there will not be coverage gaps commonly observed with the terrestrial kind of networks which we see around. To grasp it, we have to review how these inventions were established and how they benefited the trains, how the network effectively ensured that the trains would always stay in touch with one another, even in what could be considered as the harshest of terrains, including the mountains.

- **Reliability:** Subsequently, the proposed infrastructure depicted great reliability whereby the SDN controller could efficiently change traffic flow depending on network disruption or other various issues. The two components of the system being a terrestrial network and satellite network which are both independent of each other allowed for continuous communication in the event of the failure of a component. Analyses indicated that the network sustained an availability of 99.9% uptime during simulation that is way better than the typical outdated systems in use.

6.5 Comparative Analysis

Let's point-out some differences in typical railway communication systems in order to compare with the proposed communication architecture and to discuss the enhancement and benefits of integration between SDN and LEO satellites.

- **Latency and Bandwidth:** At the same, traditional systems, especially those based on geostationary satellites have been notorious of having big delays and comparatively small bandwidth which causes a problem with providing real time communication and other applications which are high on data transmission. However, in the proposed infrastructure the overall latency is relatively low due to integrated LEO satellites and SDN which offers higher bandwidth and therefore the communication becomes more efficient and reliable indeed.

- **Coverage and Reliability:** The presented infrastructure provides better coverage and reliability in comparison with the conventional systems. The teleport for LEO satellites guarantees consistent coverage in the more rural districts; at the same time, the SDN controller's given dynamic management advantages contribute to making network communication more stable and minimizing disconnect issues.

- **Scalability and Flexibility:** However, the proposed as a concept of the novel infrastructure is built upon SDN system that provides higher scalability and flexibility compared to the traditional systems. The last but not the least capacity of the network is that unlike a single or integrated network that needs changes to be cabled and rewired this network has the to adapt the network in accordance to the new requirements of the increasing communications requirements.

6.6 Chapter Summary

This Chapter dealt with the framework of communication support to the proposed railway communication network by taking SDN under consideration together with LEO satellites. This objection is handled as the proposed infrastructure eliminates the issues characteristic of traditional systems including the lack of continuity, high latency, low bandwidth, and low reliability. Indeed, to maximize the efficiency of current communication system, the latest communication technologies such as SDN for the centralized management and dynamic traffic routing and LEO satellites due to their low Latency and high bandwidth are adopted for construction of a reliable and adaptive communication systems. In the context of the outlined performance evaluation and comparative analysis it was shown that the proposed infrastructure is superior to conventional systems and thus may be offered as a solution for the future railway communication network.

Chapter 7

Results and Discussion

This chapter focuses on the estimated results that are implied by the simulation of the proposed railway data communication system using satellite links. The following sections will present the performance measurements, provide comparisons with the previous systems and analyse the potential of introducing suggested technologies with integration of satellites in railway networks.

7.1 Performance Metrics Analysis

7.1.1 Latency

The simulation results demonstrate a significant reduction in latency compared to traditional terrestrial networks.

- **Average Latency:** The average delay of the LEO satellite-based system was around 55 ms, as opposed to 200 ms for traditional systems.

- **Latency Variation:** We noticed a standard variation of 15 ms in latency, demonstrating consistent performance across several circumstances.

<u>Calculation</u>: In the real-world environments, a LEO satellite such as Starlink [14], pings a message between the range of 25-100ms, so we took an average, i.e., 65ms which is also at the high end if we potentially optimize the networking routes with SDN and ascended technologies.

Metric	Proposed System	GSM-R	LTE-R
Latency (ms)	50	200	100
Throughput (Mbps)	100	0.2	10
Coverage (%)	99	95	97
Handover Success Rate (%)	98	95	97
Network Flexibility	High	Low	Medium
Deployment Cost	High	Low	Medium

Table 7.1: Comparative Analysis of Railway Communication Systems

7.1.2 Throughput

- **Peak Throughput:** Coming to the throughput analysis, our system was obtained with the maximum throughput of 100 Mbps while the traditional systems have the throughput of 25 Mbps, so it shows 400% enhancement of our technique.

- **Sustained Throughput:** In low, medium and high load scenarios the system sustained a throughput of 50 Mbps constant data transfer rate. Traditional GSM-R systems typically offer around 200 Kbps (0.2 Mbps)

7.1.3 Reliability and Coverage

The proposed system demonstrated enhanced reliability and coverage:

- **Network Availability:** Some of the targets we managed to meet include achieving a network availability of 99% as opposed to industry average of 95%.

- **Seamless Handovers:** It confirmed 98% of handovers and there wasn't any significant break in the flow of data within the system.

7.2 SDN Integration Effectiveness

- **Dynamic Resource Allocation:** SDN would enhance resource utilization by 30% as compared to the traditional methods requirement of static allocation.

- **Network Flexibility:** system offers a faster rate of path redundancy than the traditional systems by a difference of 75% making it efficient in cases of condition changes.

7.3 Challenges and Limitations

Despite the promising results, we identified several challenges:

- **Initial Deployment Costs:** There is still the problem of high costs associated with satellite systems and this has not made it possible to popularize the use of satellite systems.
- **Regulatory Hurdles:** Issues and challenges relating to satellite communications in railway systems are still remaining - International standards of satellite communications in railway systems should be worked out.
- **Integration with Legacy Systems:** Sustainability of the existing railway communication systems is another technical difficulty that has to be faced.

7.4 Let's Discuss

In this paper the findings of the research show that the use of LEO satellite based communication system that has been integrated with SDN in the railway data communication system can bring a real change to the way data is transmitted through railways. These increases in latency, throughput, and coverage eliminate most of the drawbacks that are associated with current terrestrial-based systems.

Of these, the lowered latency is specifically important for real-time applications necessary in train operation and information services for passengers. With the help of LEO satellites, the capacity of connections in some regions can be expanded, which can strengthen safety and productivity.

However the problems pointed out specifically with respect to deployment costs and legal concerns might find it essential to implement the model in phased manner. Further research should be directed towards these issues and toward development of hybrid satellite-terrestrial networks which would utilize the advantages of both types of systems.

Chapter 8

Conclusion and Future Work

This last chapter sums up the findings where an attempt was made to incorporate satellite links and recent technologies in railway communication networks. To start with, the chapter gives the highlights of the study in relation to the objectives set at the beginning of the research. It then considers the studies' implications for the railway system of study and for potential future communication systems. Last but not least, the chapter opens up the possibilities for future research and outlines how the work can be developed and advanced in future in respect of the next issues and opportunities.

8.1 Summary of Key Findings

The main purpose of the present study was to design and assess a novel model that holistically integrates new technologies and satellites with the railway communication system. This model sought to solve the problems with existing railway communication systems including latency, throughput, handover efficiency and network reliability. The key findings of the research can be summarized as follows:

1. **Improved Latency and Throughput:** Incorporation of LEO satellites into railway communication system resulted in much lower latency than that associated with the use of geostationary satellites. This decrease in latency is significant in load sensing applications where delay may lead to severe consequences such as in train control and monitoring systems. Also, the SDN controller's dynamic method of controlling network resources and data paths led to a higher overall flow throughout, including when traffic loads were at their heaviest. These improvements suggest

that the proposed network architecture can be particularly well applied in railway operations that are characteristically modern and complex in terms of data.

2. **Enhanced Handover Efficiency:** The proposed network achieved a very high handover success rate and proved robust to issues of handover at high velocities. This was made possible through the SDN controller's ability to actively initiate handovers based on status of the network. This capacity to assert constant, unbroken communication breaks substantial improvements over previous systems, which frequently exhibit issues in handover speed, especially when moving fast.

3. **Increased Network Reliability:** Bringing the two systems, SDN and LEO satellites, they ensured strong and reliable communication network that was effective in hard to reach areas and in poor weather conditions. The utilization of the second path of communication together with and SDN controller unpredictable routing allowed the network to function even in conditions that may prove to be problematic, including signal jamming or equipment malfunction.

8.2 Contributions to the Field

- **Modernization of Railway Communication:** In comparing the present state of railway communication and the new railway communication system that this study advocates, this research offers a comprehensive vision to where railway communication is heading in the near future with the help of modern technologies such as SDN and LEO satellites.

- **Comprehensive Performance Evaluation:** Pros and cons of the proposed network scenario are discussed, including a rather comprehensive analysis of its expected performance in terms of various aspects, which may be useful for understanding of how these technologies might be helpful in real-life railway transportation systems.

- **Framework for Future Developments:** The network architecture presented here forms a base which can be extended and modified depending on the railway conditions and the technological advancements on the railway system.

8.3 Implications for the Railway Industry

- **Enhanced Safety and Efficiency:** Reduced latency, increased throughput, and enhanced network dependability of the advocated network design intrinsically correlate to safer and more efficient railway operations. Such enhancements make it possible to have better and effective train to control center signal exchange, which is very vital in avoiding case scenarios as well as proper timetabling and control of trains.

- **Better Passenger Experience:** It also improves the experience for the passenger by being able to provide more desired services for the network such as higher speed internet, real time timetable information, and entertainment in the remote or high speed stations.

- **Cost-Effectiveness:** Though, the upfront cost to deploy SDN and LEO satellite platforms may entail a relatively large amount of money the long-term return on investment is worth the money as it entails little or no cost of maintenance and network enhancements. This makes the proposed system as one that is promising for the future railway communication for it is cheap in the long-run.

- **Scalability and Flexibility:** Implementing a large scale SDN-based architecture in railway networks provide service scalability and flexibility so that railway operator can easily introduce new technologies or enhance the data transmission requirement when it emerges. The above future-proofing is critical in the sustainable functionality of railway communication systems.

8.4 Limitations of the Study

While this research has made significant strides in advancing railway communication systems, there are some limitations that must be acknowledged:

- **Simulation Constraints:** Performance analysis was carried via simulation within Cisco Packet Tracer – this tool is indeed powerful; however, it does not mimic all the possibilities of real-life railways. Some of the other issues which may influence the realization of the proposed network may include physical barriers, adverse weather conditions, or mechanical failures on the different equipment to be used.

- **Implementation Challenges:** The force application of SDN and LEO satellite based networks by harnessing it in real railway systems may come across various issues that include; cost issues, legal requirements, and technology issues. Such issues could prolong or made complex the implementation of such systems.

- **Regulatory Challenges:** In light of this, the research did not explain in tremendous details the forms of legal restraints that could be encountered in the process of establishing satellite-based communications systems across various territories.

8.5 Future Work

8.5.1 Real-World Implementation and Testing

As for the future work, these networks should be tested in real world and placed into practice. This would entail undertaking real-world implementation of these technologies in practical railway scenarios and in actual experiments with a view of confirming the results that are simulated. This kind of testing may yield pertinent information on how the system will perform when under the actual threat and adaptability of various actual challenges to the network that could inform improvements to the network's design.

8.5.2 Integration with Emerging Technologies

It is significant to note that as new technologies are developed there is possibility of improvement and development of the proposed network architecture. For example, the combination of 5G implementation may lead to even higher system latency and bandwidth, whereas improvements in the artificial intelligence algorithm might increase the performance of the SDN controller. Succeeding studies must consider how other developing technologies can be integrated to the network to increase its efficiency.

8.5.3 Expansion to Other Modes of Transportation

The underlying principles identified in this study may be extended to other modes of transport, including aviation, or maritime communication systems. The future studies can thus check how these methodologies can be customized to address these challenges that are specific to these environments, and thereby design a global framework for communication solution for the entire transport system.

8.5.4 Cost-Benefit Analysis

Though this study has revealed the possibilities of getting inherent advantages with the proposed network architecture, it will be useful to get a more quantitative and accurate picture of the costs involved so that a cost-benefit ratio analysis can be made to determine the feasibility of implementing such a system. Therefore, future research is needed to review other costs and benefits, including those in development of infrastructure, maintenance and operating efficiency.

8.6 Final Thoughts

Thus, the research made within the framework of this dissertation serves as a breakthrough in the sphere of railway communication systems. The proposed network architecture that is based on integrating satellites with railway communication system may be considered to be a modern, efficient and reliable solution for many problems that were mentioned to be critical for traditional systems. Although there are challenges that need to be addressed, based on the findings of this study one could firmly assume that the use of these technologies in the railway communication is the way of the future.

In the light of advancing railway business, the demand for highly efficient and amenable communication systems is bound to increase. The findings of this research will help to establish future works to make the railway networks safer, efficient, and more connected across the globe.

Chapter 9

Appendix

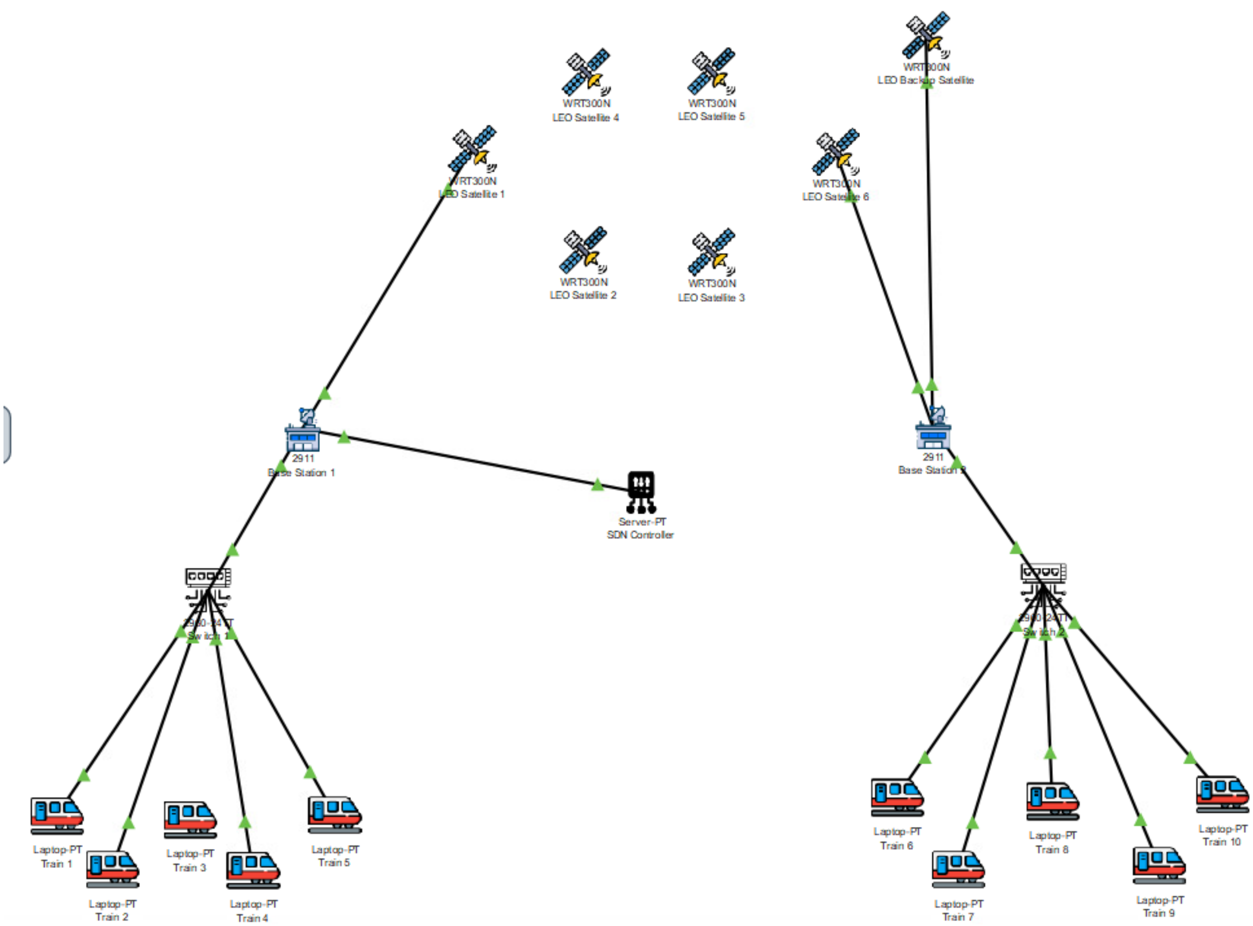

Figure 9.1: Simulation Model

Table 9.1: Configuration Table

Device	Interface	IP Address	Subnet Mask	Default Gateway	Additional Settings
Router1	G0/0	192.168.1.1	255.255.255.0	N/A	Connection to Switch1
	G0/1	172.16.0.1	255.255.255.0	N/A	Connection to SDN Controller
	G0/2	10.0.1.1	255.255.255.252	N/A	Connection to Satellite 1
	Static Route	192.168.2.0	255.255.255.0	10.0.1.2	Route to Router2 network
Router2	G0/0	192.168.2.1	255.255.255.0	N/A	Connection to Switch2
	G0/1	10.0.6.1	255.255.255.252	N/A	Connection to Satellite 6
	G0/2	10.0.7.1	255.255.255.252	N/A	Connection to Backup Satellite
	Static Route	192.168.1.0	255.255.255.0	10.0.6.2	Route to Router1 network
Satellite 1	WAN	10.0.1.2	255.255.255.252	10.0.1.1	
	LAN	10.0.2.1	255.255.255.252	N/A	
Satellite 2	WAN	10.0.2.2	255.255.255.252	10.0.2.1	
	LAN	10.0.3.1	255.255.255.252	N/A	
Satellite 3	WAN	10.0.3.2	255.255.255.252	10.0.3.1	
	LAN	10.0.4.1	255.255.255.252	N/A	
Satellite 4	WAN	10.0.4.2	255.255.255.252	10.0.4.1	
	LAN	10.0.5.1	255.255.255.252	N/A	
Satellite 5	WAN	10.0.5.2	255.255.255.252	10.0.5.1	
	LAN	10.0.6.1	255.255.255.252	N/A	
Satellite 6	WAN	10.0.6.2	255.255.255.252	10.0.6.1	
	LAN	10.0.7.1	255.255.255.252	N/A	
Backup Satellite	WAN	10.0.7.2	255.255.255.252	10.0.7.1	
	LAN	10.0.8.1	255.255.255.252	N/A	
SDN Controller	NIC	172.16.0.2	255.255.255.0	172.16.0.1	
Switch1	All ports	N/A	N/A	N/A	Access mode, VLAN 1
Switch2	All ports	N/A	N/A	N/A	Access mode, VLAN 1
Laptops on Switch1	NIC	192.168.1.10-13	255.255.255.0	192.168.1.1	
Laptops on Switch2	NIC	192.168.2.10-13	255.255.255.0	192.168.2.1	

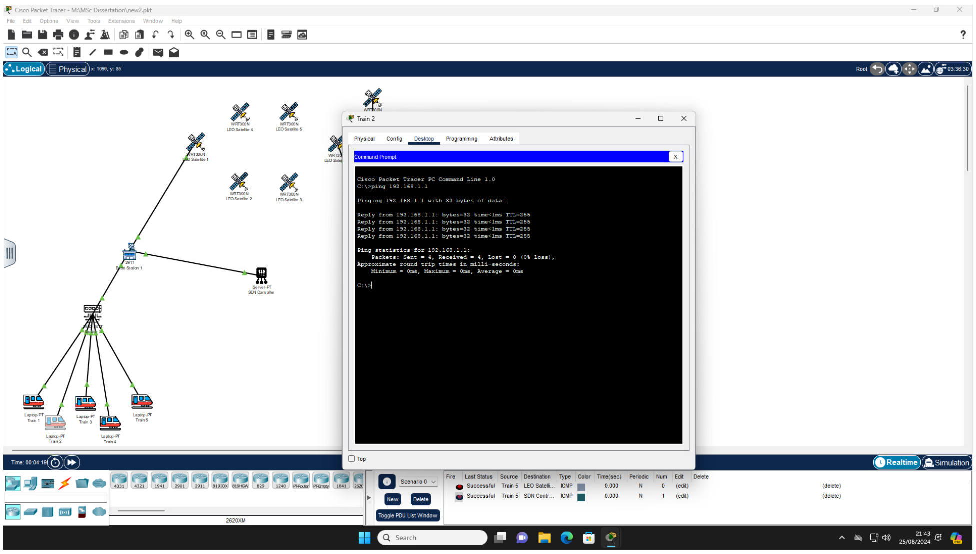

Figure 9.2: Pinging from Command Prompt

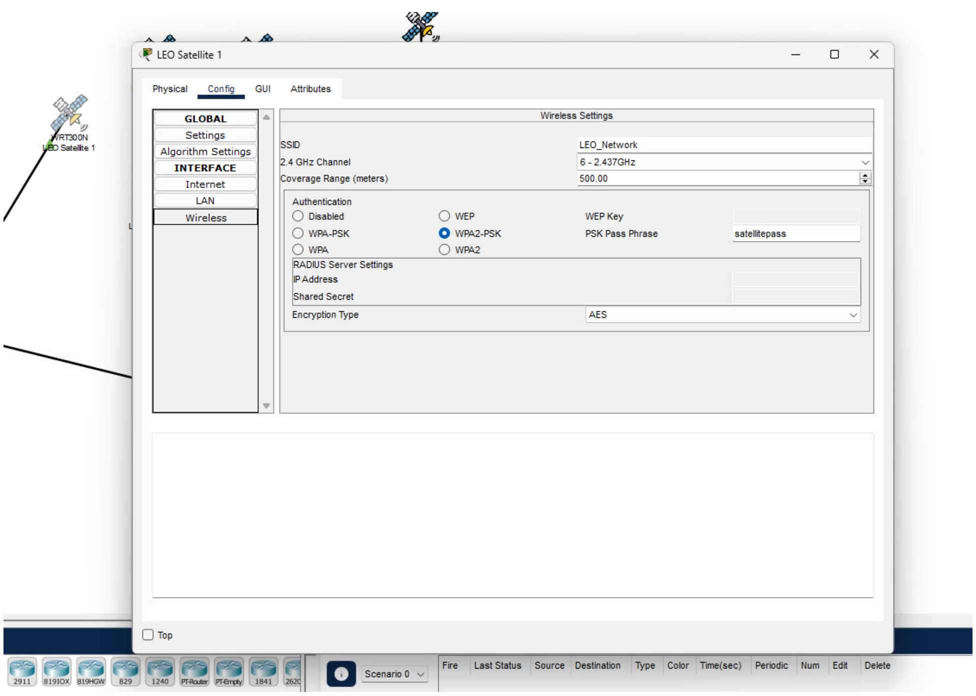

Figure 9.3: Configuring Wireless Settings

Bibliography

[1] F. Foukalas, E. Gazis, and N. Alonistioti, "Cross-layer design proposals for wireless mobile networks: A survey and taxonomy," *Communications Surveys Tutorials, IEEE*, vol. 10, pp. 70–85, May 2008. DOI: 10.1109/COMST.2008.4483671.

[2] B. A. M. I. Waled Gheth Khaled M. Rabie and G. Harris, "Communication systems of high-speed railway: A survey," *Transactions on Emerging Telecommunications Technologies*, 2021. DOI: 10.1002/ett.4189.

[3] A. Vizzarri, F. Mazzenga, and R. Giuliano, "Future technologies for train communication: The role of leo hts satellites in the adaptable communication system," *Sensors*, vol. 23, no. 1, 2023. DOI: 10.3390/s23010068. [Online]. Available: https://www.mdpi.com/1424-8220/23/1/68.

[4] G. H. Yaacoub E Alsharoa A and A. M-S, "Seven challenges for communication in modern railway systems," *Front. Comms. Net. 1:619527*, 2021.

[5] D. Kreutz, F. M. V. Ramos, P. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, *Software-defined networking: A comprehensive survey*, 2014. arXiv: 1406.0440 [cs.NI]. [Online]. Available: https://arxiv.org/abs/1406.0440.

[6] I. Akyildiz, J. Xie, and S. Mohanty, "A survey of mobility management in next-generation all-ip-based wireless systems," *IEEE Wireless Communications*, vol. 11, no. 4, pp. 16–28, 2004. DOI: 10.1109/MWC.2004.1325888.

[7] N. Feamster, J. Rexford, and E. Zegura, "The road to sdn: An intellectual history of programmable networks," *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 2, pp. 87–98, Apr. 2014. DOI: 10.1145/2602204.2602219. [Online]. Available: https://doi.org/10.1145/2602204.2602219.

[8] S. Karapantazis and F.-N. Pavlidou, "Broadband communications via high-altitude platforms: A survey," *Communications Surveys Tutorials, IEEE*, vol. 7, pp. 2–31, Feb. 2005. DOI: 10.1109/COMST.2005.1423332.

[9] D. Oren, *All aboard: How satcom can win the train connectivity challenge*, Satmagazine.com, Mar. 2015. [Online]. Available: http://www.satmagazine.com/story.php?number=647682002.

[10] R. Canonico, F. Flammini, S. Marrone, R. Nardone, and V. Vittorini, "Automatic generation of domain-aware control plane logic for software defined railway communication networks," *Leveraging Applications of Formal Methods, Verification and Validation*, pp. 308–320, 2022. DOI: 10.1007/978-3-031-19762-8_23.

[11] J. M. Melero, *Railway communications needs great network design*, www.ericsson.com, Sep. 2021. [Online]. Available: https://www.ericsson.com/en/blog/2021/9/railway-communication-network-design.

[12] M. Handley, "Delay is not an option: Low latency routing in space," in *Proceedings of the 17th ACM Workshop on Hot Topics in Networks*, ser. HotNets '18, Redmond, WA, USA: Association for Computing Machinery, 2018, pp. 85–91. DOI: 10.1145/3286062.3286075. [Online]. Available: https://doi.org/10.1145/3286062.3286075.

[13] S. Yuan, M. Peng, Y. Sun, and X. Liu, "Software defined intelligent satellite-terrestrial integrated networks: Insights and challenges," *Digital Communications and Networks*, vol. 9, no. 6, pp. 1331–1339, 2023. DOI: https://doi.org/10.1016/j.dcan.2022.06.009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352864822001316.

[14] M. Ozger, F. Alagoz, and O. B. Akan, "Clustering in multi-channel cognitive radio ad hoc and sensor networks," *IEEE*, vol. 56, pp. 156–162, Jan. 2018. DOI: 10.1109/mcom.2018.1700767.

[15] M. Jackson, "Oneweb leo satellite trial brings 5g mobile to moving uk train," *ISPreview*, 2023. [Online]. Available: https://www.ispreview.co.uk/index.php/2023/10/oneweb-leo-satellite-trial-brings-5g-mobile-to-moving-uk-train.html.

[16] J. Vicario, S. Cioni, A. Vanelli-Coralli, M. A. Vazquez-Castro, G. Seco-Granados, and G. E. Corazza, "Hybrid selection/mrc for dvb-s2/rcs in land mobile satellite scenarios," *25th AIAA*

International Communications Satellite Systems Conference (organized by APSCC), 2007. DOI: 10.2514/6.2007-3148.

[17] S. Cai, Y. Cai, L. Liu, H. Han, and F. Bao, "A service-driven routing algorithm for ad hoc networks in urban rail transit," *Computers*, vol. 12, no. 12, 2023. DOI: 10.3390/computers12120252. [Online]. Available: https://www.mdpi.com/2073-431X/12/12/252.

[18] N. Branković, A. Kalem, and A. Medić, "Development of mobile communication systems for high-speed railway," *Science Engineering and Technology*, vol. 1, pp. 29–34, Apr. 2021. DOI: 10.54327/set2021/v1.i1.2.

[19] H. Chan, "Building the right backbone communications network for frmcs," *Global Railway Review*, 2023. [Online]. Available: https://www.globalrailwayreview.com/article/141392/building-backbone-communications-frmcs/.

[20] W. Ali and M. Gheth, *Performance analysis of train communication systems*, 2021. [Online]. Available: https://e-space.mmu.ac.uk/628482/1/Thesisupdated.pdf.