Analysis of Application-based traffic load balancing over Satellite links of divergent performance

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Abstract

The main goal of the thesis is to investigate how to optimize Quality of Experience (QoE) of users using applications over satellite links by application aware load balancing capabilities of SD-WAN. SES (Commercial satellite operator) customers want to use applications over satellite links that have high latency and are often more congested than terrestrial networks which results in lower Quality of Experience (QoE) of users. The applications have been designed and optimized for terrestrial networks, not for satellite networks. Thus, SES wants to use its hybrid (MEO/GEO) satellite network and application aware routing capabilities of SD-WAN to prioritize and steer traffic at the application layer based on intent and business rules and enforced via policy for appropriate QoE.

In the thesis, work is carried out in two parts: Firstly, experiments in lab to perform performance measurement of selected widely used applications over the different satellite links (GEO, MEO & LEO). Then performance of video applications over MEO link in different congestion scenarios (Unidirectional and Bidirectional Congestion) was measured. In order to improve the performance of video applications load balancing mechanism was defined to optimize QoE of the user. Secondly, a simulation model emulating a future SD-WAN scenario on Simulink, which is used to measure QoE of multiple users is designed. A load balancing mechanism which not only optimizes the QoE for multiple users but is also a cost effective alternative to manage the QoE is proposed.

It was concluded that applications belonging to the same category have varied performances in different congestion scenarios on satellite links. Hence, each application has its performance, variation and should be dealt with accordingly. Identifying performance thresholds in different scenarios is essential to derive load balancing mechanisms to improve QoE and optimize the cost. Key applications that drive the behaviour of experience should be identified (which differs in each use case and for different customers) and steered accordingly to the best possible link so that overall QoE could be improved. Recommendations on the designing of policies for different use cases and overall development of SD-WAN as a product have also been presented in the thesis.

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Introduction 1

The Background of the research is presented in section 1.1, importance of SD-WAN in satellite industry in section 1.2. Research Motivation and research relevant literature review in section 1.3, section 1.4 respectively. Based on research motivation and related work Goals of research are defined in section 1.5. Finally sections 1.6 and 1.7 present a high level research approach and outline of the work.

1.1 Background

Satellites are relay stations in the upper space for transmission of voice, video and data communications. They reach multiple sites over a wide area and are suited to provide worldwide communication requirements of military, government and commercial organizations (Figure 1.1).

Satellites provide the capabilities that are not available with terrestrial communication sys-

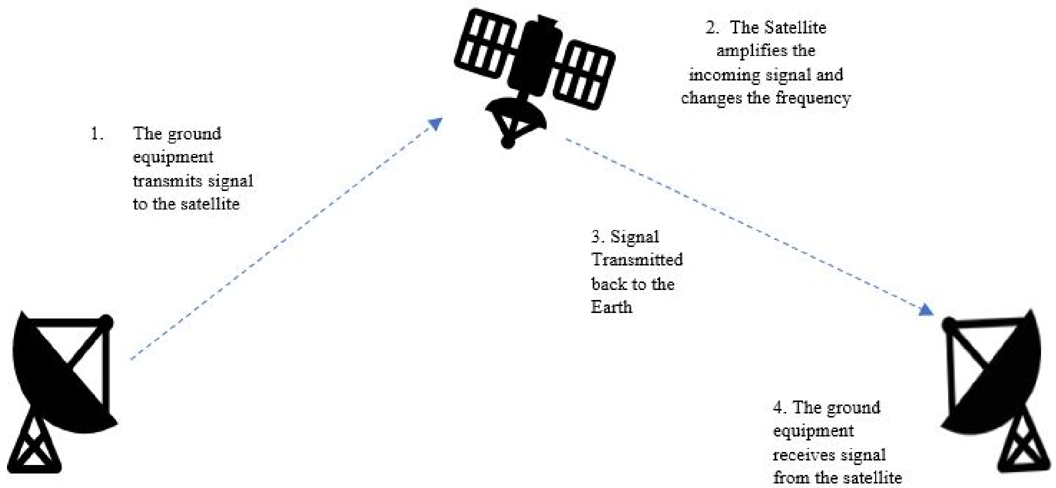

Figure 1.1: Satellite Communication in 4 Steps [11]

tems. They adapt themselves to the needs and requirements of different customers. There is a significant advantage in terms of not having any geographical obstruction, no need to build landlines for a limited population; cost remains independent of distance [11]. There are three types of satellite orbits which are discussed briefly in the current section and which are presented in detail in the next chapter:

1. Geostationary Earth Orbit (GEO): GEO is located 36,000 km above the earth's surface, located at 0-degree latitude, GEO satellite is stationary wrt. earth. The satellites in

this orbit have the highest latency.

2. Medium Earth Orbit (MEO): MEO is located 2,000-30,000 km above the earth's surface.

3. Low Earth Orbit (LEO): LEO is located 200-1,200km above the earth's surface. Satellites in this orbit have the lowest latency due it's distance from the earth's surface.

SES (commerical satellite operator) is the only satellite operator with hybrid satellite network (GEO/MEO) [3]. The current method of managing Wide Area Network connections in SES (Figure 1.2) is based on IEEE 802.1Q or differentiated services code point (DSCP) based traffic prioritization. It does not take into consideration the changing connectivity conditions and is manually controlled. It has inefficient load balancing based on aggregate flows and the service delivers lower level SLA (Service level agreement) metrics.

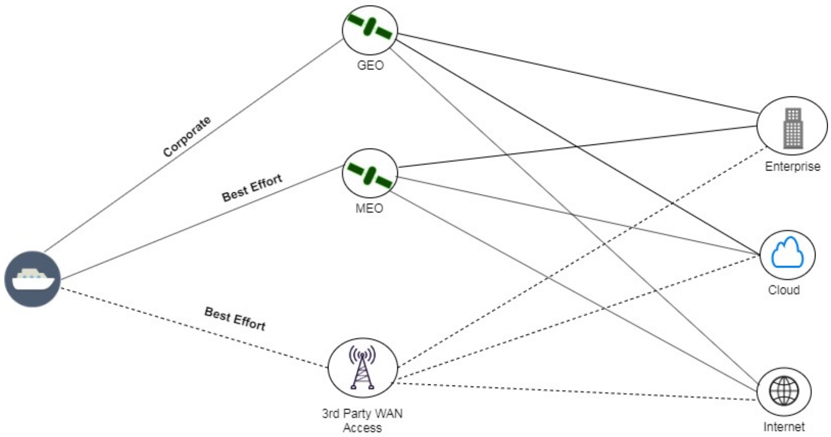

Figure 1.2: Current method of Managing WAN connections

As satellite networks become a more mainstream part for the global, cloud-scale environment, they not only need to have sufficient bandwidth but also intelligence to inspect and prioritize traffic at the application layer to ensure a quality of experience (QoE) and security for the end user. SES is bringing industry-leading application-aware technology SD-WAN [13] and is integrating it to its MEO/GEO satellite network to optimize QoE of its end users during normal operations, times of high demand and in failure scenarios. This will help customers move beyond manually intensive marking requirements to an automated, intent and policy driven QoE [8].

1.2 Addressing the needs of Satellite Industry using SD-WAN

SD-WAN Service operates over existing Underlay Connectivity Services (Figure 1.3) providing a virtual overlay network that enables application-aware, policy-driven, and orchestrated connectivity between two or more subscriber network locations. The SD-WAN (Software defined wide area network) service sits on top of multiple disparate underlay services; it can offer richer and more differentiated service delivery capabilities than traditional WAN Services [12]. SD-WAN provides an effective technique to manage the network to significantly improve network performance. SES has integrated SD-WAN technology [13] into its multi-band, multi-orbit satellite network. The SD-WAN technology provides a virtualized overlay

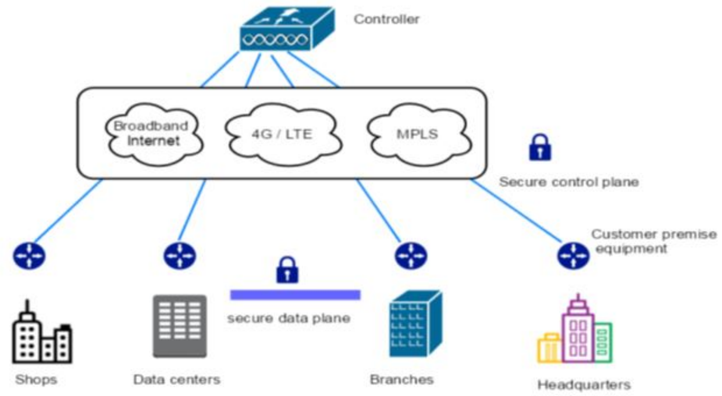

Figure 1.3: SD-WAN solution [45]

of global satellite and terrestrial underlay networks that is application aware. In addition, the technology provides the computational platform to support adding virtualized network functions (VNFs).
The capabilities of SD-WAN bring in a number of key benefits to the satcom industry and take its managed services offerings to the next level, including:

1. Simplified deployment and operation of an overlay network independent of diverse underlay connectivity, whether satellite, cellular, WiFi or terrestrial links.

2. The ability to prioritize and steer traffic at the application layer based on intent and business rules and enforced via policy for appropriate QoE during network demand fluctuations and network failures.

3. Visibility into application usage and performance for continued optimization of the network, including per-application fail-overs based on link performance.

4. Encrypted overlay ensuring consistent security regardless of the underlay path as well as the ability to quickly deploy virtualized firewalls and web filters as VNFs.

5. Simplified deployment of robust security and performance optimization functions with firewall, DDoS detection and mitigation and URL filtering.

6. Intelligent MEO/GEO link-bonding to present simplified overlay connectivity to end-customer and optimized bandwidth utilization.

These key advances in managed satellite network offerings will benefit multiple industries who currently utilize or are considering intelligent satellite connectivity as part of their WAN solution.

1.3 Research Motivation

When communication is on move (e.g. maritime & aero) cruise ship or airline operators have to rely on satellite networks to provide connectivity to their customers. SES customers (cruise ship) using applications over satellite links have to cope with congested WAN circuits which in turn affects the QoE of the cruise ship passengers. The applications (for e.g. Netflix, YouTube, Facebook etc.) have been designed and optimized for terrestrial networks, not for satellite networks. Currently, this issue is dealt with traffic prioritization on the same WAN link but it does not give optimal QoE most of the times. Hence SES customers (cruise ship) are looking for an end to end solution through which they can precisely access the network capacity and can steer and shape traffic to optimize the available resources. SES wants to use its hybrid satellite network and application aware routing capabilities of SD-WAN to improve the Quality of Experience.

1.4 Related Work

Satellites have augmented the need for anytime and anywhere access. As they are becoming a more mainstream part of the global communication system they are facing a high demand for more reliable and faster services with strict QoS requirements. Hence quite substantial work has been done to optimize QoS/QoE over satellite links.
Authors in [36] [22] highlight the importance of QoS and its optimization in satellite networks. Detailed overview of QoS for satellite IP networks with its framework, requirements, objectives and mechanisms is presented in [35]. Authors [40] present an approach to optimize the performance at the application level with prioritizing multiple queues in satellite communications. The paper reflects the importance of adopting the appropriate QoS mechanism. Authors in [43] focus on providing high bandwidth connections in the scenarios where satellite networks complement existing terrestrial infrastructures to achieve similar QoE. The analysis is particularly interesting for commercial satellite operators. Similarly in [23] a QoS routing algorithm is proposed to reduce the inter-satellite handover, it addresses the important aspect of delay in satellites. Video streaming over satellite channels is studied in [30]. The study is aimed towards maximizing the QoS and QoE of the received video over the satellite link. Authors in [20], [31], [19], [41], [18], [25] discuss measures to enhance performance of TCP/IP protocol applications over satellite networks. They briefly address the issues faced by TCP protocol over satellite circuits and propose algorithms/measures to enhance it. Authors in [42] introduce high performance and flexible protocol (HpFP) so as to achieve high throughput for HTS (High Throughput Satellites) even with packet loss. In [44] [50] a load balancing scheme is proposed to distribute traffic in the different satellite layers of a Multi Layer Satellite Network. Certain novel routing protocols [39], [24], [33] have been developed for Multi-Layered Satellite Networks.
SD-WAN provides agility unavailable in traditional Wide Area Network services [51]. The MEF 70 White paper [12] on SD-WAN service attributes and services was released in July 2019 which aims to standardize SD-WAN in the industry . The standard highlights the necessities for an application aware WAN service which would then use policies to determine the application flow over the multiple underlay networks. There some contributions made towards leveraging the benefit of SDN in managing QoS and QoE. In [27], [46] a framework is proposed which forwards the real time Quality of Experience Feedback to the SD-WAN controllers. The effect on QoE was analyzed by using different streaming protocols. In [32] the efficient management of QoE over cloud services is presented. The authors of [37] introduce an SD-WAN architecture to improve the Quality of Service (QoS) of distributed applications. In [29] a fault tolerant reactive routing system for SD-WAN was proposed which keeps track

of the network and monitors packet loss and latency in the SD-WAN. Whereas authors in [38] present a Fast ReRoute QoS protection scheme for bandwidth and probability of packet loss in SD-WAN. The author in [49] presents a solution for the under-utilization of network bandwidth and use the SDN approach together with the Open Flow technology to achieve this. From the industry, perspective Gilat Telecom [2] introduced Gilat Smart Steering (GSS) based on SD-WAN technology allows the Mobile Network Operators (MNO) in Africa to optimise their paths/circuits and helps to route the traffic towards available network elements. The GSS solution is tailor made for particular customer's and specific to that particular network. Communication companies have started to deploy their SD-WAN solution targeting different aspects of their business and geographical locations [16][14].
SD-WAN integration in the satellite industry is a relatively new concept. With NFV and SDN playing a major role in designing of next generation satellite networks [28], [34] there is an increased demand for intelligence in satellite networks to inspect and prioritize traffic at the application layer to ensure a Quality of Experience (QoE) and security of end user. QoE optimization over satellite network using SD-WAN has not been extensively explored. Satellite networks as seen earlier suffer from congested circuits due to increased application traffic which in turn affects the QoE. Each application performs differently in congestion scenarios over different satellite links. Due to the asymmetric bandwidth profiles in satellite industry, it is essential to understand the application performance in each type of congestion in order to optimize the QoE. In the following research, we will measure the performance of different applications over satellite links in different congestion scenarios and then define load balancing mechanisms to optimize the Quality of Experience using SD-WAN. Hence through this thesis, we will extend contributions towards the integration of SD-WAN in satellite use case by utilizing its abilities to optimize the Quality of experience of users.

1.5 Goals of Research

Based on the research motivation and the related work discussed in the previous section the main research question for the thesis is:

How to optimize Quality of Experience (QoE) of users via application aware load balancing over satellite links using SD-WAN?

The objectives of the thesis can be summarised as follows:

1. Assessment of integration of SD-WAN with the satellite use case in different realistic congestion scenarios and measuring the application performance.

2. Drafting load balancing mechanisms in order to improve QoE in SD-WAN to optimize the performance.

3. Emulating SD-WAN integrated future satellite use case over Simulink which simulates multiple users.

4. Performing intelligent steering to load balance the traffic thus improving QoE of a group of users.

1.6 Research Approach

The high-level approach applied to achieve the objectives described in section 1.5 is as follows:

1. State of the art review of SD-WAN technology and its application in different satellite use cases and thus selecting the Hybrid WAN solution as a reference use case (chapter 2) which would emulated in the lab environment as well as in Simulink.

2. Assuming latencies in the three different types of satellite orbits i.e., LEO (Lower Earth Orbit), MEO (Medium Earth Orbit) and GEO (Geostationary Earth Orbit) and a set of application categories which would be used for testing (section 4.2).

3. Defining congestion scenarios (section 4.3) and metrics to be used for analysis (section 4.4).

4. Template configuration (subsection 4.5.3) of the virtualized SD-WAN environment and traffic profile configuration (subsection 4.5.2) was performed to steer application traffic over different satellite links.

5. Testing selected applications over the unconstrained link (Uncongested) (subsection 4.6.1) which would assist in deciding the link combination.

6. Thorough performance analysis of the selected applications on Unidirectional & Bidirectional congestion (subsubsection 4.6.2.1, subsubsection 4.6.2.2, subsubsection 4.6.2.3).

7. Defining Load balancing mechanism based on application thresholds explicitly marking actions in the algorithm/policy that the application level traffic would take in the scenarios when certain performance thresholds are breached.

8. Now in order to simulate multiple users using different applications which stream on MEO and LEO satellite links (chapter 5) a simulation model was developed in Simulink through which we measure the QoE of a group of users.

9. Defining load balancing mechanism based on application threshold to load balance the traffic.

1.7 Thesis Outline

The remainder of the thesis is as follows: (chapter 2) gives an overview of the SD-WAN technology, its associated components and its integration with Satellite Communications. chapter 3 discusses the strategies in which SES as a satellite provider can use SD-WAN with its next generation satellite constellation to provide better connectivity and Quality of Experience (QoE) to its customers. The main focus of (chapter 4) is to emulate the real life SD-WAN scenario in a lab environment and generate real application traffic to measure QoE of a single user. Load balancing mechanisms to optimize the QoE are suggested in the end. (chapter 5) describes the Simulink model which emulates a group of customers using different applications over SD-WAN. Following which, intelligent load balancing mechanisms have been defined to improve the QoE of a group of users. (chapter 6) Finally, conclusions and recommendations are provided along with Future scope of the work.

Overview of SD-WAN Technology 2

In the current chapter, we discuss in the detail the technologies relevant to the research. Firstly, we discuss the different types of satellite orbits since in later stages they are an important part of our experiments. Then we further move on to discuss traditional wide area network (WAN) and its disadvantages. SD-WAN addresses the disadvantages of traditional WAN; since it's a subset of SDN and NFV we discuss them. SD-WAN and its service components are then introduced which gives us a brief idea about its basic architecture. Finally, we conclude this chapter by presenting the use cases of integrating SD-WAN with satellites.

2.1 Types of Satellite Orbits

We discussed different types of satellite orbits briefly in section 1.1 but here we would present it in detail since they are an important aspect of our research. The Different types of satellite orbits are mentioned below [11]:

1. **Low Earth Orbit (LEO):** LEO is located 200-1200 km above the earth's surface. It takes approximately an hour and a half to circle the earth, the lower the orbit, the higher the speed, the shorter the orbital period. The advantages of LEO are that it requires smaller signal strength to reach the closer satellites and the satellites cost less to build and launch. Ground earth stations must track satellites in this orbit i.e., antennas sweep across the sky following the course of a satellite. LEO is used for earth Observation, military satellites and commercial satellite phone operators.
   Pros: LEO satellites due to its proximity with the earth span the globe and hence it has the lowest latency level. The proximity also means that the launch per satellite is much cheaper and requires much less fuel.
   Cons: Due to the high number of satellites required initially, there is high manufacturing and launch costs. The availability of satellite spectrum for that many satellites and coordinating traffic across them without adding latency are some of the issues that still need to be resolved.

2. **Medium Earth Orbit (MEO):** MEO is located 2000-30,000 km above the earths surface. Typically, communication satellites in the MEO are situated over the North and South Poles and have larger orbits than LEO. Ground Earth Stations must also track satellites in this orbit. MEO is used for Global Positioning Systems (GPS) and military Satellites. Nowadays they provide broadband connectivity to government agencies and enterprises also.
   Pros: Low latency applications are supported due to close distance from the earth. It provides fibre-like services in transmission. Eight MEO satellite can cover the majority of the Earth.
   Cons: Since MEO satellites are not stationary with respect to the Earth. The antennas at ground need to track the satellites in the sky which results in the need for more

complex ground infrastructure. Though they support low latency applications, they cannot reach the levels planned by the LEO operators.

3. **Geostationary Earth Orbit (GEO):** GEO is located 36,000 km above the earth's surface, located at 0-degree latitude, GEO satellites are located above the equator. These satellites have the same angular velocity as the earth and hence remaining stationary over the same spot. The antenna at the ground station can thus point at the same point in the sky. Satellites have station-keeping manoeuvres regularly performed on them to keep them in position and minimize the effects of small variations of gravitational forces due to Moon, forces exerted from the sun, and other influences. They provide services ranging from weather and mapping data to distribution of digital video-on-demand, streaming, and satellite TV channels globally.
   Pros: The antenna design is quite simple since there is no need to track the GEO satellite in the sky. It can support broadband service with a single satellite as their distance from the earth allows them to cast a wider beam. It takes only 3 GEO satellites to cover the majority of the earth.
   Cons: They are not useful in the latency-critical applications. There is also one design consideration that is taken into account which is since the orbit of the satellite is higher it experiences a much greater signal power loss during transmission.

4. **Inclined Orbit:** Inclined Orbits are a subset of GEO orbits. Near the end of GEO satellite life (12-15yrs), station-keeping manoeuvres are reduced and the satellite is then often put into the "inclined orbit". Inclined Orbit satellites are used in some parts of the world for satellite news gathering (SNG) but the majority of SNG operations do not occur on inclined orbit capacity. Uplink and downlink antennas using satellites in an inclined orbit must be regularly adjusted to ensure they accurately point at the satellite. Inclined orbit capacity is sold at a lower price than the stable satellite capacity. This is because it is difficult to track these satellites.

2.2 Traditional Wide Area Network

The traditional WAN connects the multiple local area networks to each other through routers and virtual private networks (VPN) which is beneficial for the organizations, enterprises having more than one location. Traditional WANs use Multi-Protocol label switching (MPLS) (Figure 2.1) which makes it relatively secure and gives the advantage to prioritize the voice, video and data traffic over the network. Most of the time it is run over one carrier-grade circuit connection. Which also makes the MPLS bandwidth expensive [17][4].

Traditional WAN provides a secure connection over MPLS as the packets can only be seen at the destination. However, the backhauling (the transfer of the branch and cloud network traffic to the data centre) to apply the security policies causes latency, congestion in the network and leads to extra cost [15] [17]. There is a high dependency on the data centre wherein the branches are not allowed to have direct access to the cloud; also the prioritization of the application traffic over the VPN is difficult and challenging with traditional WAN [4]. Also, MPLS requires a single provider to access many sites which makes it quite expensive. While even with just bandwidth changes, the manual workflow-based process can take weeks and hence the society which is now transitioned and accustomed to using cloud-based services

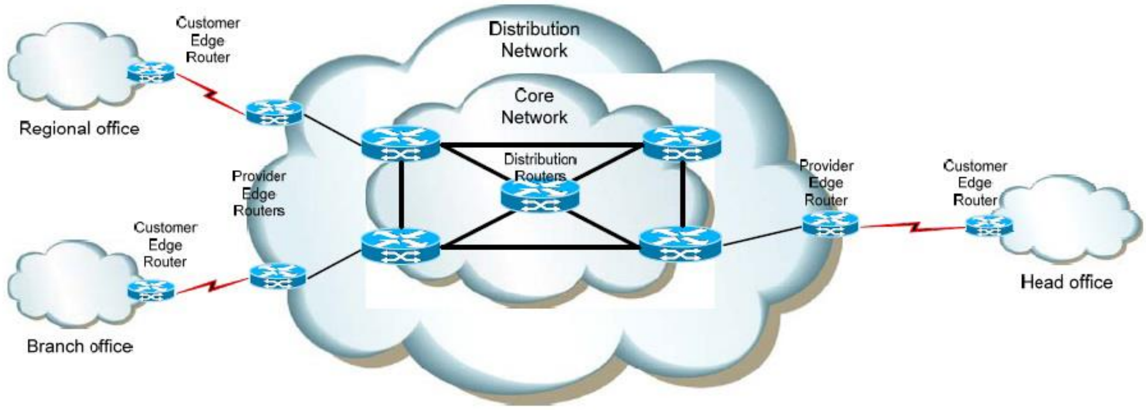

Figure 2.1: MPLS Network [6]

finds this manual workflow based process unacceptable. The devices are with integrated data and control plane and the routing is IP Address (layer 3) specific which needs to be configured at each device. Hence to address all the above-mentioned issues and provide significant advantages, SD-WAN solutions are becoming increasingly popular for different kinds of business.

2.3 Cutting-Edge technologies

Due to the advancements in the technologies, there is a need for new enterprise networking solutions. With SD-WAN being subset of SDN and NFV technologies, it is relevant to have a brief overview of these technologies.

2.3.1 Software-defined Networking

Software Defined Networking (SDN) is a network architecture approach that enables networks to be intelligently and centrally controlled or programmed using software applications. The centralized SDN controller directs the switches to deliver network services wherever it is needed. It is basically where the individual network devices make traffic decisions based on configuring routing tables which is an aberration from the traditional network architecture.
Software networks refers to a shift in the telecom architecture from boxes to functions and from protocols to APIs. It is convergence between telecommunications and IT infrastructure. The main function of these software networks other than reducing the operational costs is also to decouple the network from specialized hardware so that functions are offered as virtualized software elements [21].
SDN enables network behaviour to be controlled by the software that resides beyond the networking devices that provide physical connectivity. SDN has intelligent control and management of network resources since it is built on the logically centralized network topologies. Services and applications running on SDN technology are abstracted from the underlying technologies and hardware that provide physical connectivity from network control. Applications will interact with the network through APIs, instead of management interfaces tightly

coupled to the hardware. The open APIs support a wide range of applications, including cloud orchestration, OSS/BSS, SaaS, and business-critical networked apps. Besides, intelligent software can control hardware from multiple vendors with open programmatic interfaces like OpenFlow. Finally, from within the SDN, intelligent network services and applications can run within a common software environment [10].

2.3.1.1 SDN Architecture

It has three layers (Figure 2.2) application layer, control layer and infrastructure layer [9]. The application layer contains the network applications or functions which can use load balancing or firewalls. Where a traditional network would use a specialized appliance, such as a firewall or load balancer, a software-defined network replaces the appliance with an application that uses the controller to manage data plane behaviour. The Control Layer acts as centralized SDN controller software which is the brain of the SDN. This controller stays at the server and manages the policies and the flow of the traffic throughout the network. The infrastructure Layer is made up of the physical switches in a network. The communication between the layers is done by the northbound and southbound application programming interfaces (APIs).

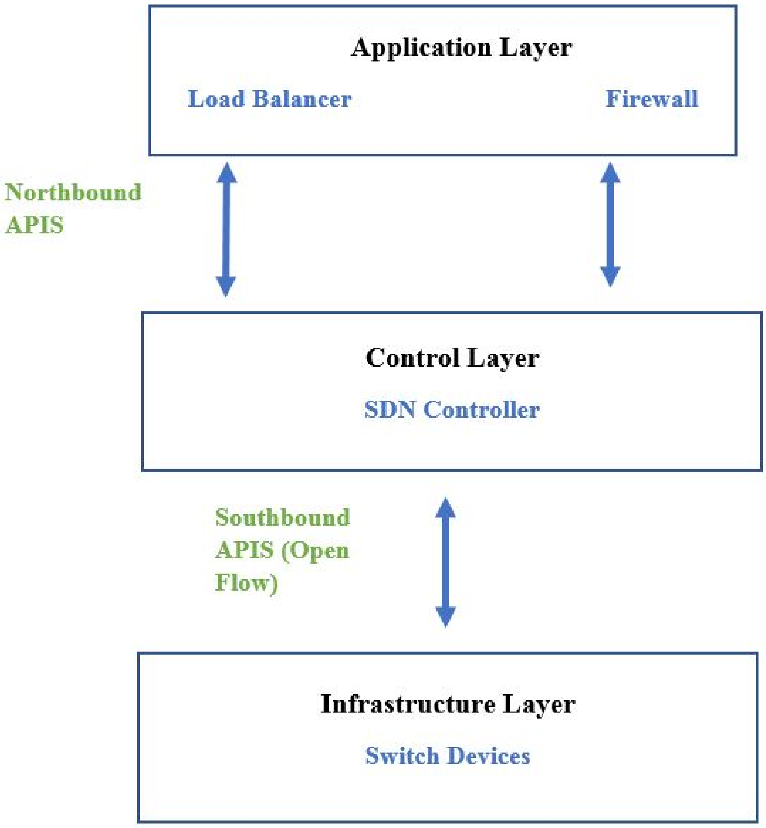

Figure 2.2: SDN Architecture Basic [9]

Like the applications talk to the controller via its northbound interface and switches communicate via the south bound interfaces of the controller like Open Flow.

2.3.1.2 Working of SDN

SDN focuses on the separation of the control plane and data plane wherein the control plane decides how the packets should flow through the network and the data plane routes packets within the network from one place to another.
The switch (data plane device) seeks guidance from the controller and gives out the information to the controller about the traffic it serves or handles. The packets going to the same end destination are sent through the same path by the switch.

2.3.2 NFV (Network Function Virtualization)

NFV is forming a new set of network functions on-demand and placing them at suitable locations and optimizing and using an appropriate amount of resources. It also provides the orchestration elements to handle the virtualized elements (Figure 2.3).
NFV is seen as a tool to experiment network protocols on production networks without hampering the performance of critical services. Future networks are envisaged to consist of a mixture of wired and wireless physical infrastructure whose resources are absorbed from the virtualized mechanisms hence to get benefit from this progress and integrate into the future networks satellite communications platforms need to adapt to these transformations [26].

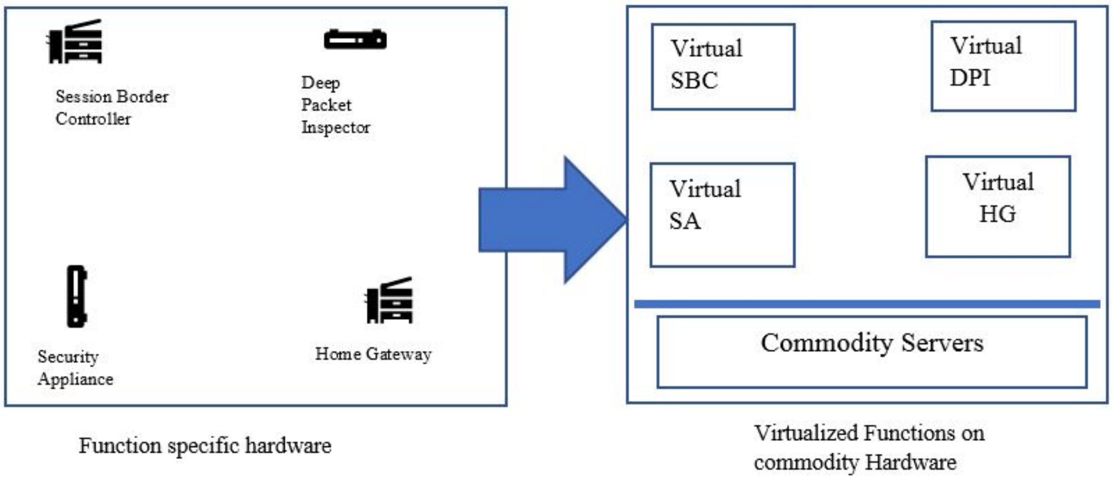

Figure 2.3: Network Function Virtualization concept [47]

NFV represents the virtualisation of the network functions (migration to software-based approach) which in initial concepts was carried out by specialised hardware devices and are deployed on top of its commodity (cloud infrastructure). Combined SDN and NFV based architecture is presented in Figure 2.4
NFV based approaches have several benefits few of them being:

1. Reduction in the OPEX and CAPEX as it leads to reduced hardware equipment investment.

2. Resources are shared between different Network Functions and users.

3. The new Network Functions (NF's) significantly reduce the time to market for new solutions.
4. The downscaling and upscaling of the various resources assigned to each function and promotion of innovation in the field of networking and transforming it to new virtual appliance market which is involved of several Small Medium Enterprises, academia etc.

2.3.2.1 Challenges for NFV

The challenges faced by NFV technology are as follows:

1. Challenging task since it involves the joint management of IT and Networking resources within the same infrastructure.
2. Malfunctioning of a Virtual Network Function (NF) may affect the entire Network Service.
3. The NF should be compatible with the existing OSS and BSS platforms so that there could be a smooth migration.
4. It should support hardware from different vendors and should be generic and universal.
5. The software applications should achieve performance comparable to their hardware peers.

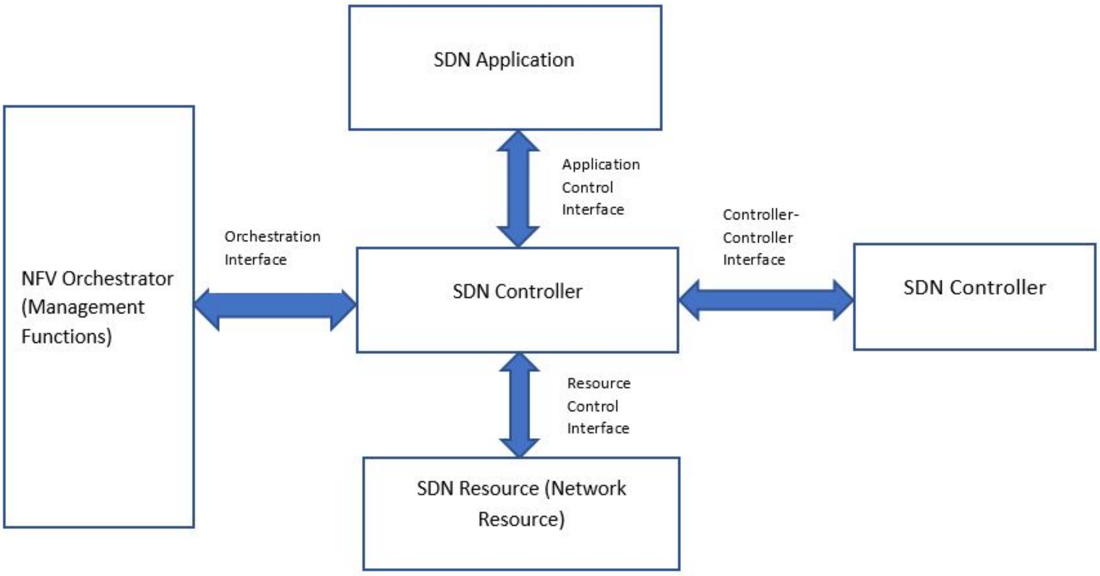

Figure 2.4: SDN NFV Based Architecture

2.3.3 Cloud Computing

Cloud computing is the process of accessing, storing and computing data on data centres (public, private or hybrid) over the internet doing other than our local machines. It gives high computing power, high performance and scalability in their services. Cloud gained popularity due to its high speed and low cost for its services also virtualized networking components can be run on the cloud [45].

2.4 Software Defined Wide Area Network (SD-WAN)

An Software-Defined WAN (SD-WAN) service (Figure 2.5) provides a virtual overlay network that enables application-aware, policy-driven, and orchestrated connectivity between two or more subscriber network locations that are connected to the SD-WAN service provider at SD-WAN user network interfaces. An SD-WAN service operates over existing underlay connectivity services (WANs). Since the SD-WAN service sits on top of multiple disparate underlay services, it can offer richer and more differentiated service delivery capabilities than traditional WAN services [12].
SD-WAN services can provide agility unavailable in traditional wide-area services. This agility can be manifested both in the ability of the subscriber to adjust aspects of the service in real-time to meet business needs and the ability of the service Provider to monitor the performance of the service and modify how packets in each application flow are forwarded based on real-time telemetry from the underlay networks.
Unlike other connectivity services where traffic forwarding decisions are made using network-layer header information, e.g., VLAN ID, MAC address, or IP Address, an SD-WAN service is aware of and forwards traffic based on Application Flows. The Service agreement includes specification of Application Flows that are recognized at the entry to the Service and Policies that describe the appropriate handling of IP Packets associated with the various Application Flows [12] [17]. SD-WAN decouples the physical and virtual devices from the software man-

Figure 2.5: Software Defined Wide Area Network [17]

agement layer to allow companies, business and enterprises to optimize how they route traffic over MPLS, broadband, LTE etc. It dynamically steers the traffic across the best link that is available at real-time which leads to little or no latency and packet loss providing a backup link in case of an outage. Unlike traditional WAN it allows the branches to access the cloud applications and bandwidth customization is performed rather easily. SD-WAN can run on 4G LTE, internet broadband which is cheap when compared to a service delivered via MPLS network. Due to the decoupling of the data plane from the control and management plane, it establishes a central control of network-wide policy and security from the branch to the cloud.
It keeps the data traffic secure by providing end to end encryption over VPN connection and allows to integrate additional security layers. SD-WAN proposes the usage of multiple back-haul available connections between the different locations of the private/enterprise network,

especially to integrate best-effort, internet-like, connectivity. With this, the connectivity between the different locations can be implemented using a mix of resource guaranteed (B2B MPLS networks) and reduced cost best-effort internet connections.SD-WAN usually deploys its software instances as virtual network functions (VNF's) that function on the customer premise equipment (CPE) which gives SD-WAN flexibility in its architecture and makes its deployment quick and easy. Its solutions are mainly provisioned, managed and controlled from software rested in the cloud.

2.4.1 SDWAN service Components

The following service components (Figure2.6) fit into Metro Ethernet Forum (MEF) Life cycle service orchestration (LSO) reference Architecture [17]:

1. SD-WAN Edge- Point of initiation or termination for the SD-WAN tunnel. It performs application-based QoS, security policy enforcement, application forwarding over one or more WAN connections.

2. SD-WAN Controller- It centralizes the control of SD-WAN edge devices. It gives all the physical or virtual device management for all SD-WAN edges and SD-WAN gateways associated with the controller.

3. Service Orchestrator- Service orchestration and policy management for traffic routing and QoS over different WANs. Provides the service management of SD-WAN.

4. SD-WAN Gateway- Enables the sites interconnected via SD-WAN to connect to other sites interconnected via alternative VPN technologies. E.g., CE or MPLS VPNs.

5. Subscriber Web Portal- The subscriber web portal communicates with service providers OSS/BSS applications via the cantata interface (Interface between the customer and OSS/BSS applications shown in Figure 2.6)for functions such as initial subscriber account setup, ensuring a service payment method is available and active and the initial SD-WAN service activation.

2.5 SDWAN for Satellites

With SES being the only hybrid (GEO/MEO) satellite operator in the world, SES would offer SD-WAN as a part of managed network services. Several use cases integrating SD-WAN have been envisioned:

1. **Hybrid WAN solution (Satellite based and application/service steering centric)**- SD-WAN enables unified hybrid WAN connectivity seamlessly managing MEO, GEO and other terrestrial WAN connections to provide single managed service to the customer (Figure 2.7).
   SDWAN is also able to automatically classify traffic based on flow behaviour, which allows enterprise customers to prioritize certain applications, particularly critical cloud-based services. The QoS feature allows enterprises to measure capacity on broadband links and to prioritize workloads to optimize each locations bandwidth usage.

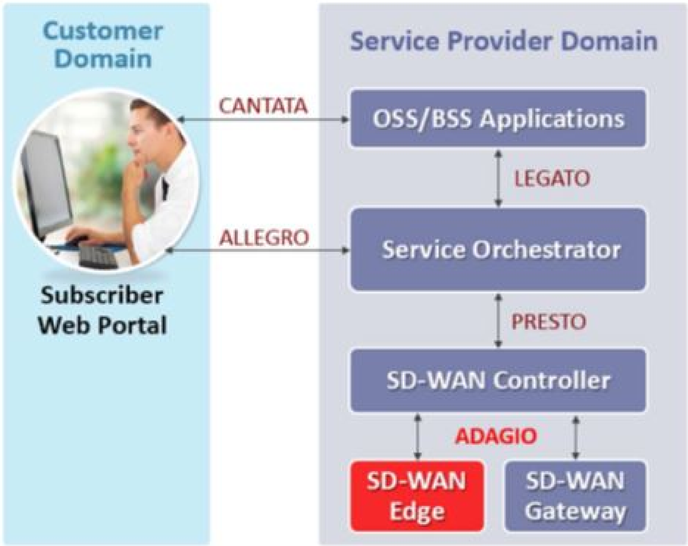

Figure 2.6: SD-WAN service components [17]

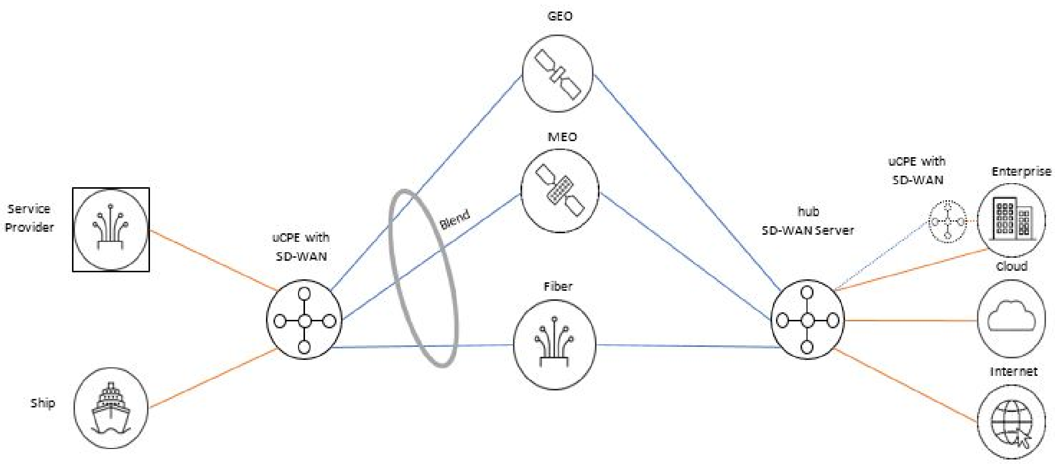

Figure 2.7: SDWAN Services over different connectivity options

It provides application intent-based traffic steering which selects the optimal link for application based on application performance requirements. Also, the High priority applications get the preferential Quality of Experience (QoE) to improve customer experience. Load balancing across multiple MEO, GEO or other connectivity options or combinations of various connectivity options.
There also exists per-packet and per-flow load-balancing options to deliver better load-balancing efficiency compared to routing. It is quite reliable as its always in service with active and backup links. High priority applications get preference on backup link. SD-WAN will play an important role in the satellite industry in the coming years for the trunking scenarios and for the overspill ones as well as for the integration with the industries.

2. **Restoration (Satellite based and Trunking centric)**- It could be used as an active backup solution for the underserved regions which mainly rely only on one primary link [5]. It can also be used in the business critical locations in the remote or disaster affected/prone regions. And then in the case of traffic fail over the traffic moves to next available WAN. Currently at SES the managed IP transit services are delivered through its MEO fleet with the advent of SD-WAN in the multi-access environment it can have a more reliable network with primary/main link & a back up connection which could be either be an MEO connection, fibre or any other media, this would trigger to have a better service due to SD-WAN providing load balancing, traffic steering and automatic fall over as shown in Figure 2.8.

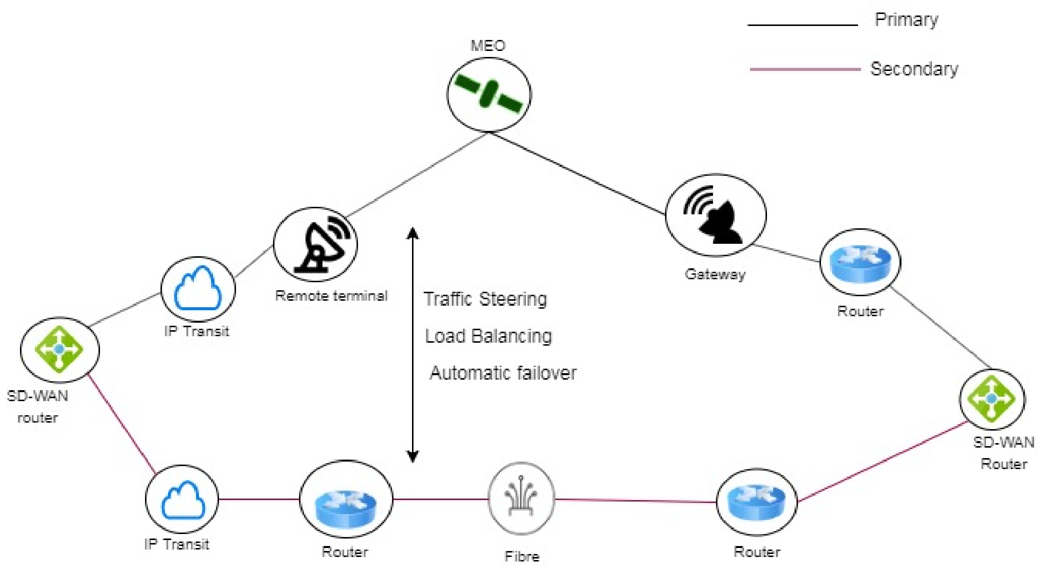

Figure 2.8: SDWAN based hybrid MEO-terrestrial network [5]

3. **Multi-Orbit SD-WAN enabled VPN**- Security is one of the strongest drivers for SD-WAN deployment by end customers [1]. In this use case, the telco or satellite service provider can create a secure link by activating IPsec tunnelling on SD-WAN CPE which steers the encrypted traffic over the satellite links [5]. The service provider (telco) can then configure secure tunnels back to the enterprise headquarters Figure 2.9.

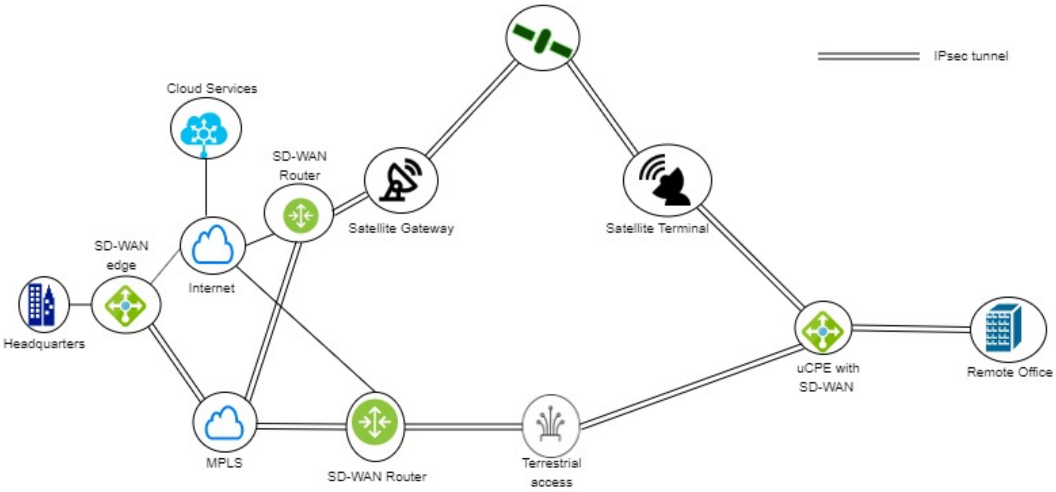

Figure 2.9: Secure enterprise VPN [5]

2.6 Summary

In this chapter, we gave a brief overview of the technologies relevant to our research. Starting from satellite orbits, traditional WAN, SDN & NFV, SD-WAN and its service components and SD-WAN's integration with the satellite. Going further an important point to note here is we would be investigating and conducting experiments considering the Hybrid WAN use case discussed in section 2.5 for the following research.

3 SD-WAN with satellites

The current chapter discusses the strategies in which SES as a satellite provider can use SD-WAN with its next generation satellite constellation to provide better connectivity and Quality of Experience (QoE) to its customers.

3.1 SES Satellite fleet and role of SD-WAN

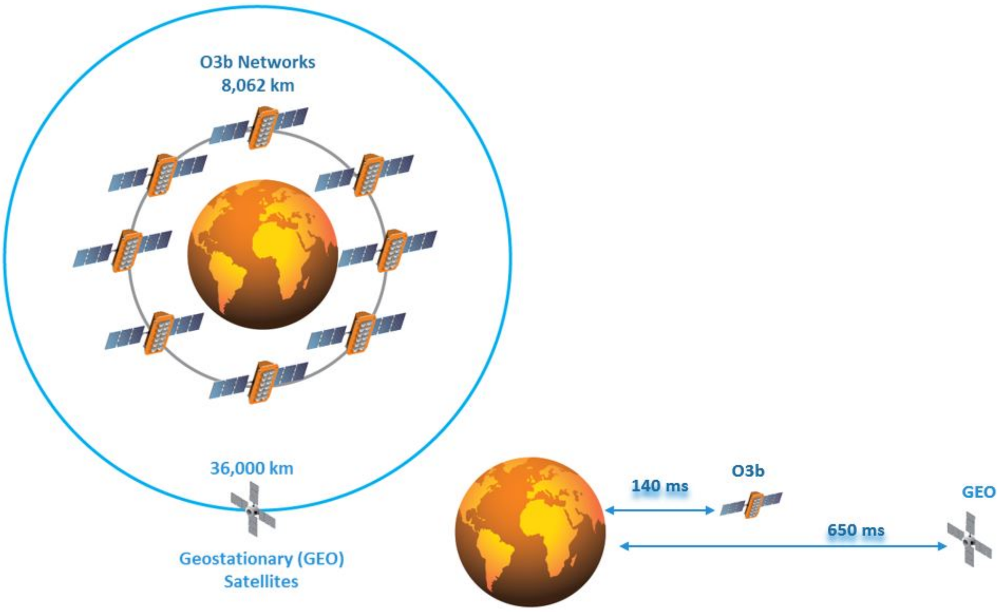

Figure 3.1: SES Satellites

SES is the only satellite operator in the world with a hybrid (MEO/GEO) satellite network. As shown in Figure 3.1, the O3b MEO satellites represent the SES MEO fleet which is situated at 8000 km, while the GEO satellites are situated at 36000 km. The latency of 140 ms from MEO and 650 ms from GEO are two way latency's (round trip). In the present day, cruise customers of SES are served via the O3b MEO satellites. The O3b MEO first generation constellation consists of 12 identical satellites operating in the MEO orbit, out of which nine satellites are operational. Each have 12 mechanically steered beams per satellite which provide 2 Gbps per beam, making roughly 20 Gbps aggregate capacity per satellite [7]. In 2021 SES's O3b mPOWER constellation is scheduled to be launched which would be seven MEO satellites launched in the same orbit of the first generation MEO constellation. O3b mPOWER satellite has 5000 electronically steered beams per satellite and has 10 times a greater capacity, which delivers a 1 Terabit (TB) constellation [8]. MPOWER has a major advantage that allows customers to set optimal capacity levels for fixed or mobile remote sites of any size. When a large number of vessels are at port for the cruise line, the O3b mPOWER can provide localised concentration of bandwidth until each vessel departs to follow its individual route (Figure 3.2). It can also provide gigabits per second of capacity that is needed during the time in port, and then divide and steer that amount of capacity to follow the ships as they embark on voyages. The o3b mPOWER [8] provides an improved and predictable customer experience with its advanced capacity.

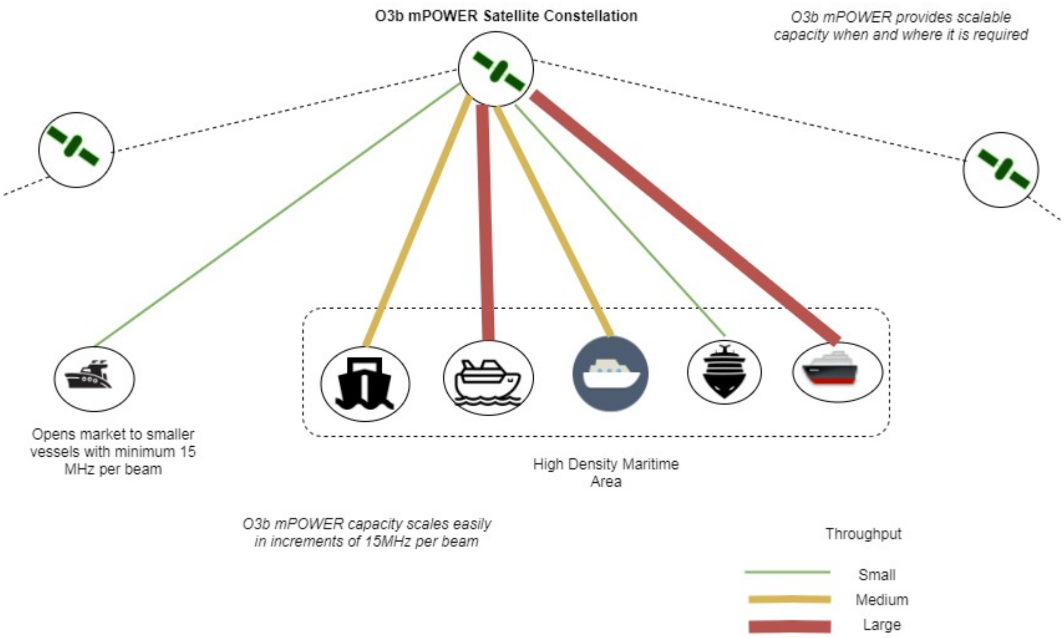

Figure 3.2: O3b mPOWER capacity scaling capabilities

With the integration of SDN and NFV capabilities in satellites, the O3B mPOWER can provide intelligent multiorbit connectivity over satellites, giving freedom to route application traffic over GEO, MEO, terrestrial, and microwave links, thus supporting the introduction of SD-WAN enabled services (Figure 3.3). The O3B mPOWER can strengthen the multiorbit capabilities by providing more capacity and an overall improved network performance of hybrid WAN solutions. O3b mPOWER is backwards compatible with the first generation O3b MEO constellation, as well as with the SES GEO satellite fleet, which enables the existing users to seamlessly transit to the new system in order to meet rising demands. SD-WAN capabilities play a major role in accomplishing this task. mPOWER with SD-WAN provides intent-driven, application aware networking for the customers which improves the Quality of Experience (QoE). Latency and QoE depends on the application, for eg, a lower latency is required for video calls, whereas it is not a critical factor to stream applications. This means that high priority applications get a preferential QoE. Thus, the combination of SD-WAN and mPOWER allows customers to replace expensive private WAN connection technologies like MPLS.

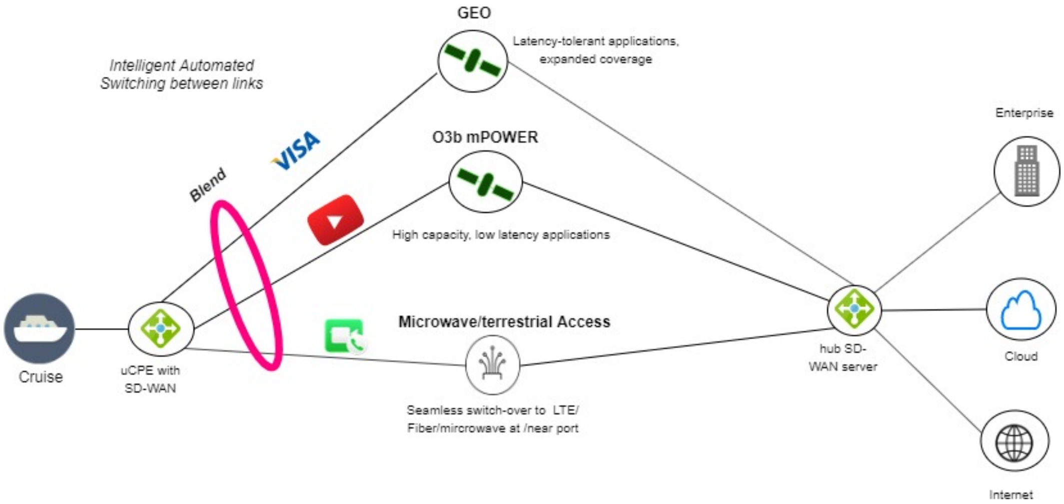

Figure 3.3: O3b mPOWER with SD-WAN

3.2 Future of WAN connectivity

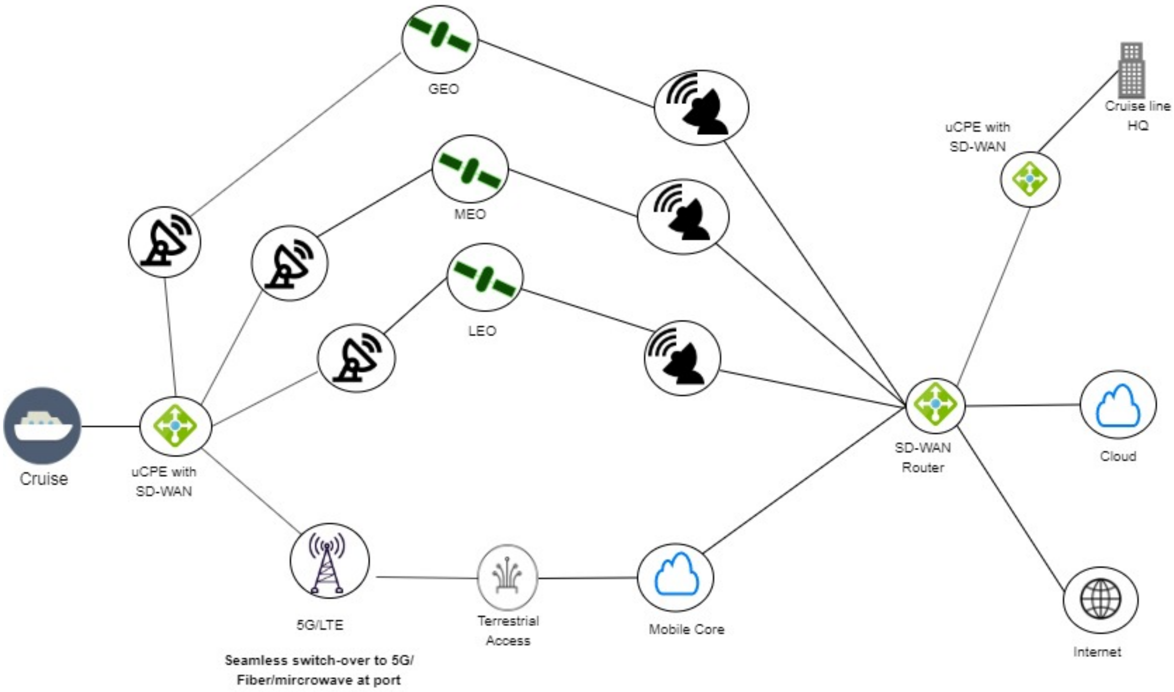

Figure 3.4: Future of WAN connectivity

The future of WAN connectivity seems bright with companies like Telesat LEO, Oneweb, and Starlink announcing their LEO constellation plans as well as nearing 5G rollout. Satellites are becoming more mainstream in global communication systems. Its shift towards virtualization has led to a high demand for more reliable and fast services with better Quality of Experience for users. SD-WAN is becoming increasing popular within the multi orbit solution as it provides an enhanced user experience, application intent-based traffic prioritisation and steering, and optimal resource utilisation. The system function deployed as virtual network function (VNF) is a purpose built, multi-tenant system, which is a highly available distributed virtual network service appliance that delivers software based services. With SD-WAN, VNF function can be hosted on the customer site providing connection to the gateway with the different available WAN connections. The service provider manages different connectivity options through the platform provided by SD-WAN (Figure 3.4). This can combine WAN connections in all three satellite orbits (GEO/MEO/LEO) with 5G/LTE/microwave in future to provide connectivity to their customers.

SD-WAN Measurement Setup Analysis 4

After the overview of SD-WAN technology and its integration with the satellite use case in the previous chapter, the current focus shifts towards emulating the SD-WAN scenario in a lab environment and generating real application traffic to measure the QoE of the user generating traffic. Ultimately, load balancing mechanism which optimize the QoE of the user are defined.

4.1 Objectives

A summarized plan of action of this chapter is presented in the following section. The aim of this chapter is the optimization of the QoE of a single user. The objectives are as follows:

1. Assessing the integration of SD-WAN with the satellite use case in different realistic congestion scenarios, measuring the application performance. The objective will be achieved by:
   (a) Defining the selected assumptions and congestion scenarios for the experiment.
   (b) Introducing the metrics used for experimenting.
   (c) Defining the experimental setup, its components and then configuring the setup.
   (d) Experimenting with the selected applications on uncongested links. Selecting the link to perform congested scenario experiments from the results obtained.
   (e) Performing the experiments using a satellite link in each congested scenario and observing the application performance.
2. Defining a load balancing mechanism in SD-WAN to optimize QoE. The objective will be achieved by:
   (a) Selecting a congested scenario to compare the performance from the previous experiments.
   (b) Defining and applying the load balancing algorithm to the selected scenario to optimize the QoE.

4.2 Assumptions

The assumptions pertaining to this research are as follows:

- *Latency*- The satellite latency's used for the performance of the experiments are displayed in (Table 4.1):

  Satellites are primarily differentiated by latency to distinguish each satellite link. The predominant complexity in a satellite is the latency, because the majority of applications

Links	Latency (round trip)
GEO	650 ms
MEO	140 ms
LEO	28 ms

Table 4.1: Latencies of Different satellite links in the experiment

have been developed for terrestrial networks where the latency is rarely above 100-150 ms.

Figure 4.1 shows that 125ms is required for the data packets to travel at the speed of

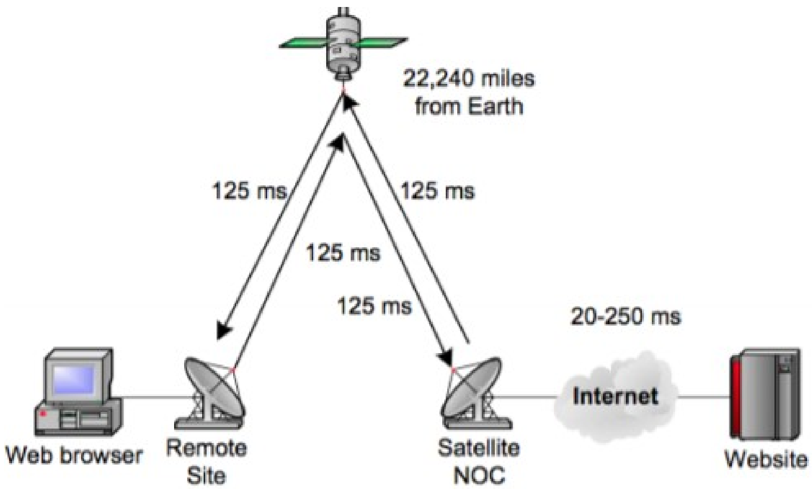

Figure 4.1: Total Round-Trip Time using Broadband Satellite [48]

light from earths surface to any one of the communication satellites positioned over the equator. This implies a minimum RTT (round-trip time), uplink and downlink, between the source and destination of a data session of at least 500ms as depicted in Figure 4.1. So, when things added that are 500ms away in latency, it changes the way protocols behave and this changes the way TCP behaves. Some components can be normalized using TCP acceleration [48], but TCP acceleration does not work for encrypted traffic. Hence, the impact can be minimized, but cannot be eliminated.

Other conditions that create impact are the way satellites are connected to the internet and the way performance characteristics are going to be achieved when connected in different ways. So, if the MEO capacity is landed right above the data centre or landed in the middle of nowhere, there is going to be a difference in performance because of a difference in additional latency being associated with it.

- *Applications*- The key element in this research is the analysis of the performance of video applications such as Netflix and YouTube. Social media applications Facebook and Instagram, and Spotify and Onedrive as background traffic.

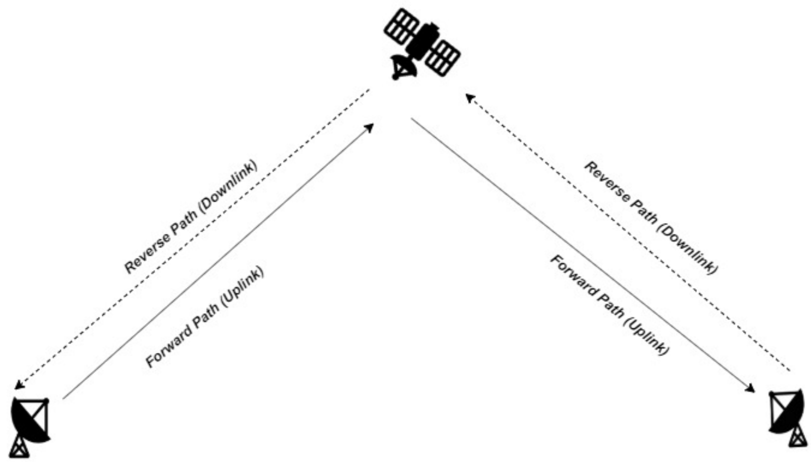

Figure 4.2: Uplink and Downlink in satellite network

4.3 Congestion Scenarios in Satellite Communications

Congestion in a satellite network occurs when the amount of traffic generated, exceeds the available capacity of the satellite link. Satellite networks are becoming more mainstream part for the global, cloud scale environment and increased traffic on the links has triggered the need to analyze the congestion scenarios deeply. Commercial Satellite operators sell bandwidth symmetrically, Uplink and Downlink having the same bandwidth, and asymmetrically with Uplink and Downlink having a different bandwidth. This is because customers require different Uplink and Downlink bandwidth ratio depending on their business needs, e.g. As seen from a customer's perspective, if a YouTube video is streamed the forward path traffic would be very little, and the reverse path traffic is very high because the video is being downloaded not uploaded. In case of Facebook Live, the forward traffic is high and the reverse path traffic low. There are two types of congestion in the satellite networks (Figure 4.2):

1. Unidirectional Congestion
   (a) Forward Path Congestion
   (b) Reverse Path Congestion
2. Bidirectional Congestion

The experiments are performed in each of the above mentioned congestion scenarios to analyze the application performance over the link.

4.4 Metrics for Analysis

The metrics used for the analysis are the following:

1. Delay: The delay of a network specifies the amount of time taken for a packet to travel across the network from one node or endpoint to another node or endpoint.

2. PDU Loss ratio: The ratio of the total number of lost packets in a network (link) to the number of sent packets in a network (link).

3. Total Traffic Generated Rate: This represents the total traffic generated rate (bit/sec) by the applications used for testing.

4.5 Experimental setup

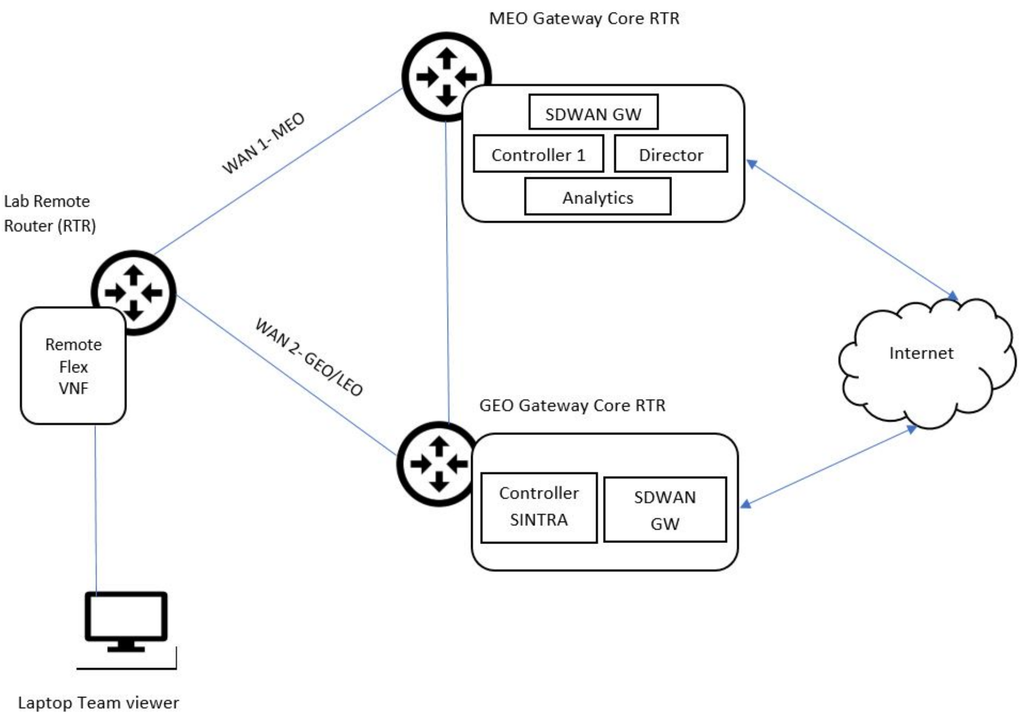

Figure 4.3: Lab Experimental Setup

Figure 4.3 illustrates the SD-WAN setup to demonstrate real-world traffic in a lab environment.This lab is situated in an SES office in Manassas, USA. The lab environment was accessed and configured through a laptop using the Team Viewer software. There are only two WAN links (GEO and MEO) available in the lab, which means that any satellite link as shown in Figure 4.3 could be emulated as a LEO link to perform the experiment. Only the configuration of the latency of the link (Figure 4.5, subsection 4.5.1) is required. The application traffic was generated from a laptop present in the lab which was remotely accessed via Team viewer software. The setup has three main software components which are discussed briefly:

1. FlexVNF- It is a purpose-built multi-tenant system delivering Software based Network Services. It has a distributed architecture with a clean/clear separation of control plane and forwarding plane.

2. Director- Director is the Virtualized Network Function (VNF) manager that controls a set of FlexVNF software instances running on general-purpose servers. Director is

the brain behind the way services are instantiated, scaled-up and scaled-down and orchestrated to be multi-tenant.

3. Analytics- Analytics allows administrators to perform network planning, traffic/application analysis, network security analytics and behaviour anomaly detection. This provides a complete view into what is happening in the network, what applications are running, and what those applications are doing, combined with what threats are being detected and thwarted.

More detail about each of the software components (section A.1) and the hardware requirements (section A.2) can be found in the appendix.

Test Equipment
These are the test equipment used to conduct the experiments:

1. NetEM tool for latency generation
2. Putty software to access hypervisors
3. Laptop for web browsing and file transfer

4.5.1 Latency Configuration

- There is a hypervisor (Figure 4.4) for each GEO and MEO gateway which contains virtual machines in it. Every hypervisor has separate login details, and the command virtual machine in the Hypervisor can be accessed by typing "virsh list" (which gives the list of the available virtual machines).

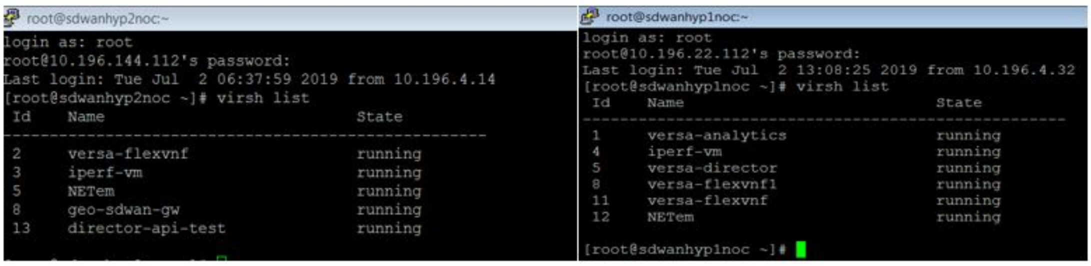

Figure 4.4: The Virtual machines existing at the GEO (left) and MEO (right) hypervisors.

- The latency of different links can be added through the NETem Virtual Machine (Figure 4.5).

- To access any VM in the hypervisor, use virsh console<name-of-vm >. So to access NETem, use virsh console NETem, which then could be used to set up the bandwidth, the latencies and the links. The latencies of the links need to be set up accordingly to set up the configuration.

Before conducting any test in the lab environment, configuration of the traffic profiles is required to direct the links to the path to take for an application type. These profiles can be configured in the Director which can be propagated in the whole network.

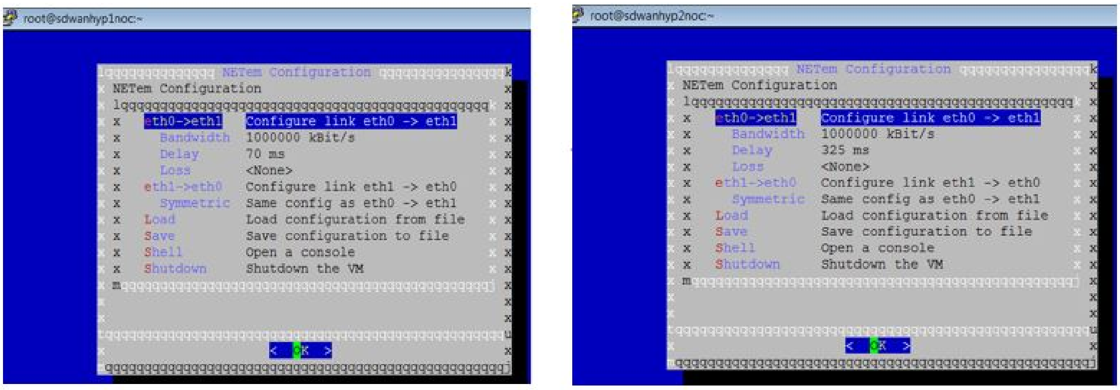

Figure 4.5: Changing Parameters in Hypervisor 1(MEO), Hypervisor 2 (GEO)

4.5.2 Configuring Traffic profiles

Two components are required to be set up to configure traffic profiles:

- Forwarding profile
- Policies

Forwarding profiles suggest a circuit the application traffic needs to take and indicates the minimum SLA thresholds (jitter, packet loss, delay). Policies suggest the type of application the traffic needs to use to forwarding profiles. They have to follow the algorithm which is set by the user wanting to configure the traffic profiles.

1. Firstly, create a forwarding profile name according to the function or task that it performs.

2. Set up an SLA profile. Set and demand the Minimum permissible SLA parameters (Jitter, Packet loss, Latency, Circuit utilisation) in case of the threshold limit being breached, followed by using another WAN circuit.

3. Decide circuit priorities, the most preferred path to route the traffic. Repeat the process of adding circuits until all the possible paths the traffic can take are mentioned in the profile. Top one represents priority 1 and the bottom one has the lowest priority.

4. Circuits/Paths to be avoided for the application traffic can be defined. This is optional.

5. The forwarding profile can be specific to the function that it is designed for, e.g. policy can be created to prefer the MEO link in which circuits that lead to the MEO link should be defined. The SLA parameters are the WAN link parameters.

6. After defining the forwarding profile, a type of application traffic can be assigned to the policy.

7. Policy can be defined, followed by adding rules specific to that policy which are specific to the function they perform.

8. According to the type of traffic (Layer 3, 4 or 7) a match condition can be defined in the rules.

9. Target of the research is Layer 7 traffic, so the applications to be tested are selected and grouped.

10. URL's (e.g., sports and entertainment, websites etc.) can also be used and should be grouped into one category.

11. To conclude, a specific forwarding profile should be assigned to the policy in order to configure traffic profile.

Algorithm 1 gives information about configuring application traffic flow in an SD-WAN setup using forwarding profile and policies. Algorithm 1 indicates the application level traffic-steering based on SLA metrics in the MEO and GEO link configuration.
Forwarding profiles setup are named as Prefer_GEO and Prefer_MEO. Prefer_GEO indicates to go through the prefered GEO link and Prefer_MEO indicates to go through the prefered MEO link. Each Forwarding profile has a path setup through which it is assigned a different priority, e.g. the application traffic level of Spotify being generated, causes the algorithm to use the Prefer_GEO Forwarding Policy, because Spotify initially runs on a GEO link, where subsequently the SLA metrics (Jitter, Packet loss, Forward Packet Loss, Reverse Packet loss, Maximum Latency) are set. Similarly YouTube is selected to stream over a MEO link.

4.5.3 Remote Template configuration

- Set up the logs. This is a basic part of the system configuration like system log, audit log, network configuration log etc., and subsequently enable the Command line interface which assists in testing the system using Command Line Interface.

- Set up the interfaces within the template which defines an interface within the RMT4-DRAGON (the main template for the current experimental setup) and activate the ip address of that particular interface.

- The flow chart in Figure A.1 shows the systematic representation of setting up a template. As mentioned, there are a total of 5 appliances in the lab (section A.2 information regarding the interfaces of appliances are mentioned in section A.3).

After configuring and designing the traffic profile and remote templates, the experiments are ready to be performed on the setup.

4.5.4 Steps to perform the experiment

1. Select the satellite link and configure the latency and bandwidth of the link.

2. Access Director through the Graphical User Interface (GUI) where forwarding profiles and policies would be defined.

3. Select the application and configure the forwarding profile and policy to steer the application on the link.

4. Generate application traffic from the laptop connected to the experimental setup.

5. Confirm the applications running on the desired link by observing the traffic log from the Hypervisor.
6. Access the Analytics tab in Director to monitor the generated traffic which indicates congestion when the generated traffic exceeds the assigned bandwidth.
7. Observe and note down the application performance during different congestion scenarios.
8. Generate Delay, Loss and Total Traffic generated graphs from the traffic and web logs in the analytics tab to compare the performance.
9. A new forwarding profile template needs to be defined to improve the application performance and to steer the traffic to a different WAN link.
10. Update the WAN circuit priority as well as SLA violation threshold to steer the traffic onto the next WAN link in case of a violation.
11. Generate application traffic again from the laptop, observe and note down the application performance. Similarly generate Delay, Loss and Total traffic generated graphs from the traffic logs to compare the performance with previous results.

4.6 Result and Analysis

The structure of the Results and Analysis are as follows. At first, video applications are tested on each uncongested satellite link where two best links are selected. Other applications used as background traffic are also tested to make sure they function on the desired link. Furthermore, a satellite link is chosen to perform the congested scenario tests. The optimization of QoE is performed on the two best satellite links.

4.6.1 Uncongested Link

In this section applications were tested on different satellite links, and their performance was measured in an uncongested network. The link capacity was kept 5 Gbps and each application was streamed one at a time on a satellite link.

1. **Video Applications-** YouTube was tested on different satellite links, concluding that this works well on a MEO link while having the best performance on the LEO link (1080p). Hence, to achieve the best performance it would be suitable to route the video traffic between these two links. The performance of YouTube was the worst on the GEO link in comparison to the other satellite links (Table 4.3), which might degrade further at a high link utilisation. The Quality in the GEO link (leftmost) is worst, while the LEO Link works best here (Figure 4.6). Similar behaviour is observed with Netflix wherein the best performance (1080p) is on a LEO link. In this scenario, Netflix performs better on a GEO link in comparison to YouTube (Table 4.2),while its performance may also degrade at a high link utilisation on a GEO link.
2. **Music-** Spotify was chosen to be tested as the Music application. When tested, it showed good performance on all three links, which matches with its low set of requirements. Hence, Music applications can be best used on a GEO link to balance the traffic on the other links which would ultimately give a better mix of traffic on the other links.

Links	Resolution	Packet Loss	Throughput
GEO	854*480	0.037%	8487 kbps
MEO	1280*720	0.025%	11979 kbps
LEO	1920*1080	0%	27905 kbps

Table 4.2: Metrics for Netflix

Links	Resolution	Packet Loss	Throughput
GEO	854*480	0.18%	3548 kbps
MEO	1280 *720	0.04%	5393 kbps
LEO	1920*1080	0%	8368 kbps

Table 4.3: Metrics for YouTube

Figure 4.6: Quality of YouTube video on GEO, MEO and LEO links respectively

3. **Storage Applications-** OneDrive was chosen to be tested as a test application, showing good performance on all three links because of files and data being uploaded and downloaded. So, while formulating the policies, it would be routed over the GEO link for best performance of the application as well as the network.

4. **Social Media Applications-** Facebook and Instagram were used in the social media application category and these worked perfectly fine on the MEO link. Facebook Video and Instagram Video consumed the most data, but the overall performance of the applications on the MEO link was satisfactory. It is evident that the same applications performed well on the LEO link, since it has a lower latency than the MEO link, whereas videos posted on social media on the GEO link showed degraded performance (lower than 360p). To conclude, Social Media applications work well on GEO, but the videos have a degraded performance.

Table 4.4 is an overview of the application categories and its performance with each link. "Yes" means that the application works on the given link, while "No" means that it does not work on the given link. In this research we focus on the analysis of performance of the video applications Netflix and YouTube. On the basis of the analysis of video applications, it is established that congested scenario experiments would be performed on a MEO link. Video applications performed best on a LEO link, making this the link to load balance the traffic to optimize the QoE in later sections.

Application categories	GEO	MEO	LEO
Video Applications	Yes (lower video quality)	Yes	Yes
Music	Yes	Yes	Yes
Storage Applications	Yes	Yes	Yes
Social Media Applications	Yes (degraded Video playback)	Yes	Yes

Table 4.4: Application categories on different satellite links

4.6.2 Congested Link

The previous analysis established that the MEO link would be used to test video applications YouTube and Netflix in different congestion scenarios. The bandwidth of each congested path is kept 1.5 Mbps (Table 4.5). Facebook and Instagram are used as background traffic, while the main focus was to monitor the video applications Netflix and YouTube.

MEO
Latency- 140 ms (two way)
Congested Path Bandwidth- 1.5 Mbps
Application Mix- YouTube, Netflix, Facebook & Instagram

Table 4.5: Application Mix & Input Parameters

4.6.2.1 Forward Path Congestion

This test resulted in a congested forward path of the MEO link. The red arrows in the figures depict the start and end point of congestion. The congestion in the experiment occurs as the total traffic generated exceeds 1.5 Mbps, which is the capacity link. The time of congestion in this experiment is 15:43 to 15:55. The major traffic generated in forward path was from YouTube live session, Facebook and Instagram video uploads.

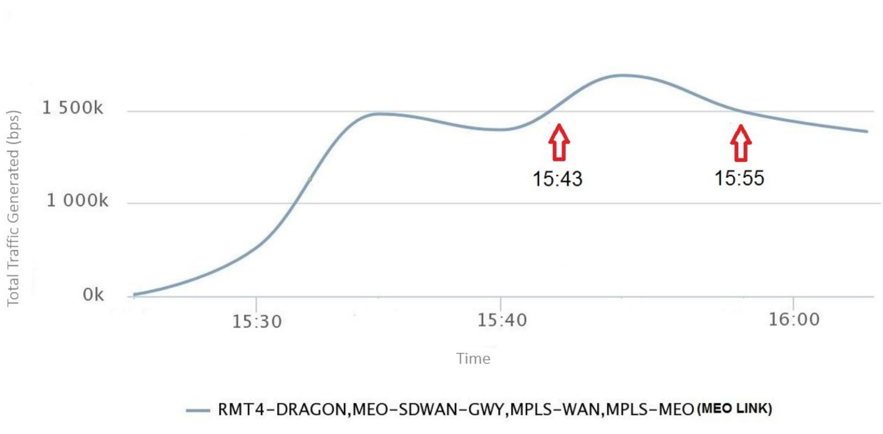

Figure 4.7: Total Traffic Generated Rate (Forward Path Congestion)

- Initially there is a delay at lower traffic which can be explained as follows. As the application traffic is initiated from the team viewer application (it gives access to the

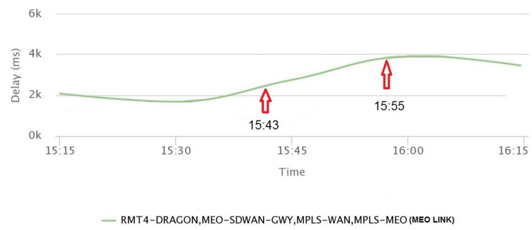

Figure 4.8: Delay (Forward Path Congestion)

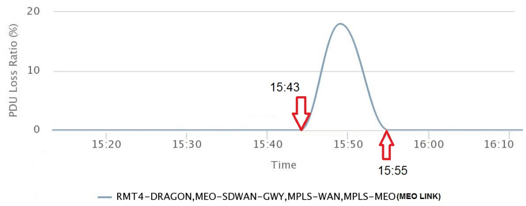

Figure 4.9: PDU loss Ratio (Forward Path Congestion)

laptop in the lab as shown in Figure 4.3) which is connected to WAN via the same interface through which these tests were conducted. So initially there is a team viewer and TCP/video session in the cache or buffer which explains the initial delay.

- The lab environment mimics a customer environment on a remote end of the satellite link so the traffic from team viewer is also classified as management traffic which is inside bandwidth (inband).
- As the total generated traffic increases (Figure 4.7) the delay (Figure 4.8) also varies, but there is no loss (Figure 4.9) observed till congestion (till 15:43) because the applications used in the test are more reverse path centric (more download). Hence, the loss in forward path is almost zero until congestion.
- Delay (Figure 4.8) during the congestion time frame varies from approximately 2200 - 3900 msec at the MEO link.
- PDU loss (Figure 4.9) during the congestion time frame had a spike around 15:48 from 0% - 17% at the MEO link which became zero at the end of congestion around 15:55.
- Due to high packet loss during congestion both YouTube and Netflix stop streaming for some time and they had to be restarted.

4.6.2.2 Reverse Path Congestion

In this test reverse path of the MEO link was congested. The red arrows in the figures (Figure 4.10, Figure 4.11, Figure 4.12) depict the start and end point of congestion. The congestion in the experiment occurs as the total traffic generated exceeds 1.5 Mbps which is the capacity link. The time of congestion in the current experiment is 11:17 to 11:38. The traffic generated in this path was from YouTube and Netflix video sessions.

- The initial delay is again due to team viewer and leftover TCP/video session in the cache or buffer.
- With the increase in the generated traffic delay starts to increase and so is the loss. Loss indicates that there is more queuing and subsequently there would be re-transmission of the packets.

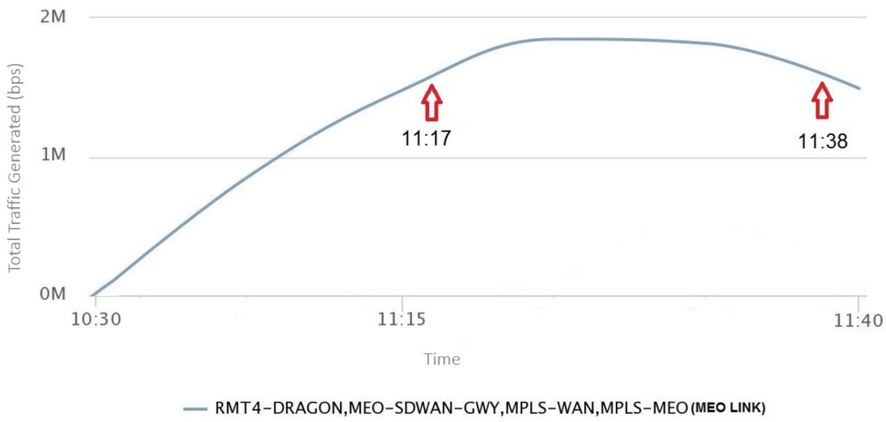

Figure 4.10: Total Traffic Generated Rate (Reverse Path Congestion)

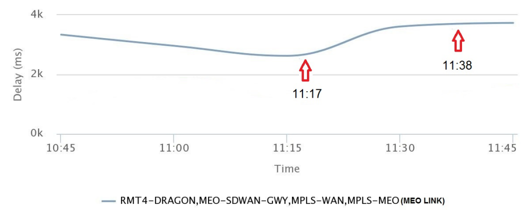

Figure 4.11: Delay (Reverse Path Congestion)

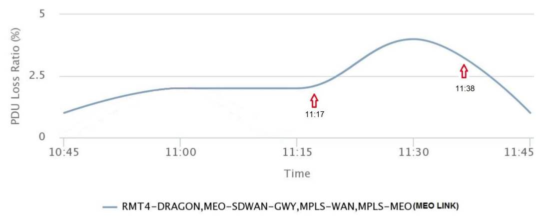

Figure 4.12: PDU loss Ratio (Reverse Path Congestion)

- The applications used for the test use TCP protocol so during congestion (from 11:17) TCP window size decreases to minimize the loss.
- Delay (Figure 4.11) during the congestion time frame (11:17-11:38) varies from 2700 - 3700 msec approximately at the MEO link.
- PDU loss (Figure 4.12) during congestion time frame varies from 2.4% - 3.5% at the MEO link. Netflix stops streaming and crashes during congestion whereas YouTube continues to stream. So, Netflix is loss intolerant application in this scenario.
- TCP has its own inbuilt flow control and manages its own rate limiting. So, when the traffic generated becomes more than the capacity of the link it normalizes and then starts to accommodate in accordance with the available bandwidth.

4.6.2.3 Bidirectional Congestion

In this test both forward and reverse path of the MEO link were congested. The red arrows in the figures (Figure 4.13, Figure 4.14, Figure 4.15) depict the start and end point of congestion. The congestion in the experiment occurs as the total traffic generated exceeds 1.5 Mbps which is the capacity link. The time of congestion in the current experiment is 13:26 to 13:47. The traffic generated in this was combination of forward and reverse path traffic mix namely

YouTube live, Facebook and Instagram video uploads in forward path whereas YouTube and Netflix video streaming in the reverse path.

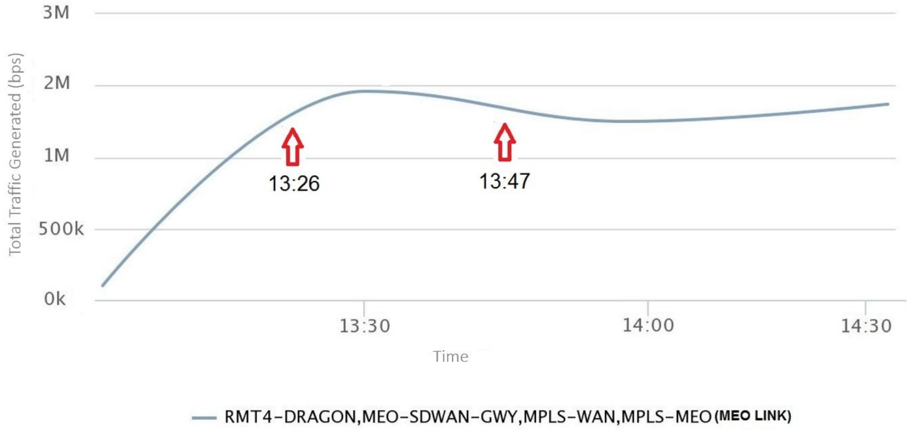

Figure 4.13: Total Traffic Generated Rate (Bidirectional Congestion)

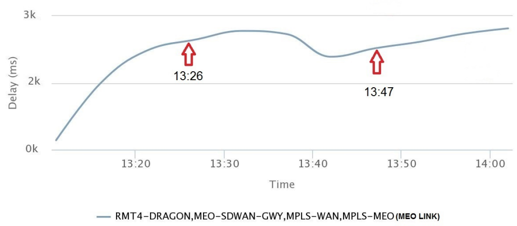

Figure 4.14: Delay (Bidirectional Congestion)

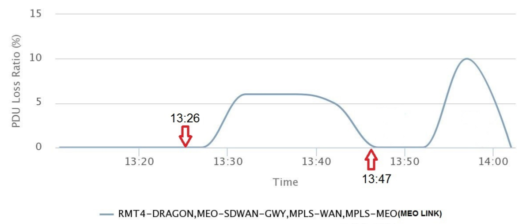

Figure 4.15: PDU loss Ratio (Bidirectional Congestion)

- Delay (Figure 4.14) during the congestion time frame varies from 2600 - 2800 msec approximately at the MEO link.
- PDU loss (Figure 4.15) during congestion time frame had a spike around 15:44 from 0% - 6% at the MEO link. Netflix crashes during congestion whereas YouTube continues to stream.
- In this experiment congestion occurs occurs again around 13:52 (Figure 4.13) also there is slight increment (Figure 4.13) in the traffic generated (which leads to increment in delay) (Figure 4.14) which then further leads to a spike in loss (Figure 4.15) ranging from 0% - 10%. Following which both YouTube and Netflix crash.

Hence, to conclude Objective 1 (section 4.1) has been achieved where assessment of integration of SD-WAN with satellite use in different realistic congestion scenarios has been performed and video application performance has been measured.

4.7 QoE Optimization

After the analysis of video application in different congestion scenarios, in the current section optimization of QoE of video applications is performed using application aware capabilities of SD-WAN. As discussed previously (subsection 4.6.1) MEO and LEO link combination would be used to load balance the application traffic. Application mix with input parameters are mentioned in Table 4.6. Spotify and Onedrive on LEO link, Instagram & Facebook on MEO link is considered as background traffic to emulate a real world scenario and generate additional traffic. In order to compare the performance after optimization Bidirectional Con-

LEO	MEO
Latency- 28 ms (two way)	Latency- 140 ms (two way)
Bandwidth (Tx + Rx)- 1.5 Mbps	Bandwidth (Tx + Rx)- 1.5 Mbps
Applications: Spotify, Onedrive	Facebook, Instagram, YouTube, Netflix

Table 4.6: Input Parameters & Application Mix for Algorithm Testing (MEO & LEO)

gestion scenario (subsubsection 4.6.2.3) is selected. Delay during the congestion time frame varies from 2600- 2800 msecs whereas PDU loss varies from 0% - 6% thus as a consequence Netflix crashes which hampers the QoE of the user.
A load balancing mechanism is defined in algorithm 2 (Load balancing in SD-WAN) where two forwarding profiles of MEO and LEO links with SLA thresholds (delay and packet loss) are defined.

Load balancing algorithm in SD-WAN

- The algorithm states that when Netflix is the application steer it on MEO link initially.
- But if Maximum Delay > 2400 ms or Packet loss > 4 % then steer Netflix to LEO link. The delay threshold is 2400 ms in the algorithm as during Bidirectional congestion the delay varied from 2600-2800 ms and loss threshold is 4% as the loss varied from 0% - 6%. The idea is to steer the application to another link before the threshold is reached.
- Simultaneously if the link utilization of LEO link increases to more than 90% then steer Netflix back to MEO link. It was observed in previous analysis that at high load or high link utilization (more than 90%) the delay and loss increase which affects application performance.

The main idea behind the following optimization is to steer Netflix traffic (which in the current scenario is a loss intolerant application) over to a lower latency LEO link to optimize QoE.

4.7.1 Performance Improvement

In this section Delay and PDU loss charts of With and Without Algorithm are compared to analyze the optimization of QoE.

- As the set threshold (algorithm 2) is breached Netflix traffic is steered to LEO link (Figure 4.22, Figure 4.23).
- When Netflix traffic is steered over to LEO link a sudden spike in delay chart (Figure 4.20) and a small increment in PDU loss chart (Figure 4.21) is observed.

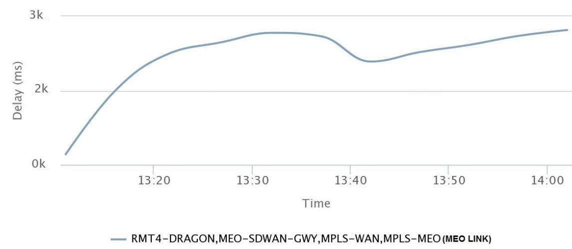

Figure 4.16: Delay at MEO link (Without Algo)

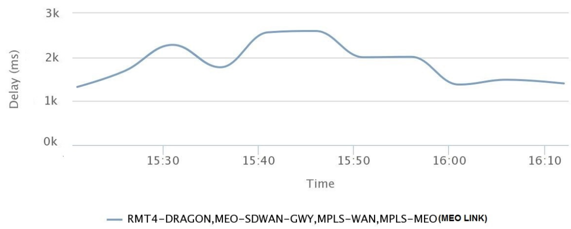

Figure 4.17: Delay at MEO link (With Algo)

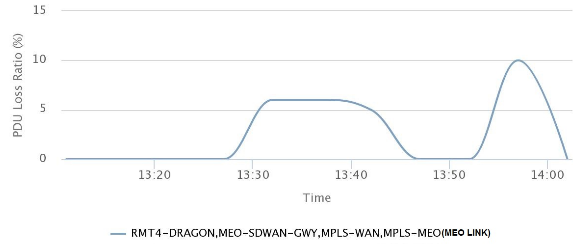

Figure 4.18: PDU loss at MEO link (Without Algo)

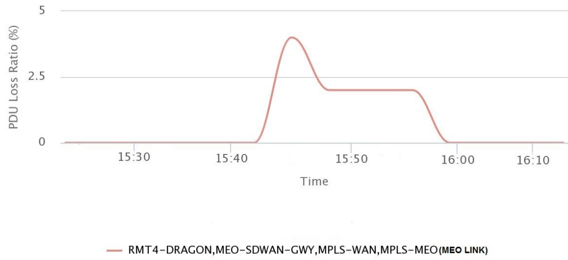

Figure 4.19: PDU loss at MEO link (With Algo)

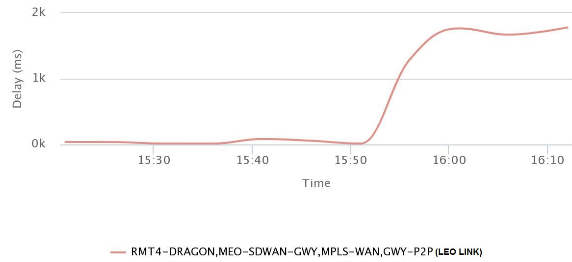

Figure 4.20: Delay at LEO link

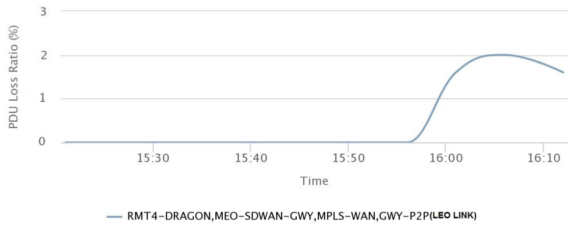

Figure 4.21: PDU loss at LEO link

- Overall delay (Figure 4.17, Figure 4.20) and loss (Figure 4.19, Figure 4.21) is optimized if compared with the performance in Bidirectional congestion scenario (Figure 4.16, Figure 4.18)
- Performance of Netflix improved when it was steered to LEO link which has lower latency. Since, the overall traffic on MEO link is reduced (Figure 4.22) performance of YouTube if compared with the previous analysis was also optimized. Neither YouTube nor Netflix crashed in this experiment.
- From the charts it is concluded that performance of Netflix and YouTube improved which then further leads to optimization of QoE of the user.

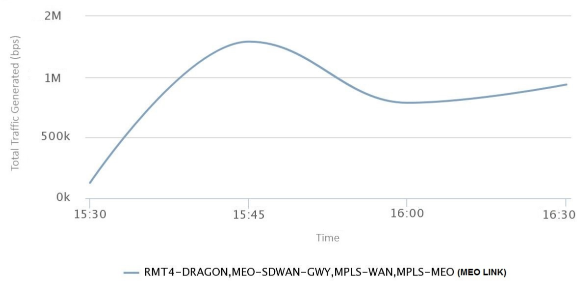

Figure 4.22: Total Traffic Generated Rate MEO link (With Algo)

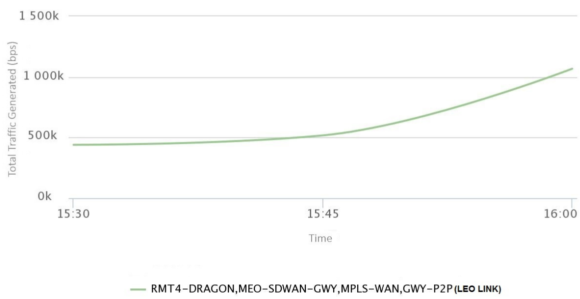

Figure 4.23: Total Traffic Generated Rate LEO link (With Algo)

Hence, to conclude Objective 2 (section 4.1) has been achieved where Quality of Experience (QoE) of one user has been successfully optimized via the application aware capability of SD-WAN.

4.8 Summary

The main theme of the chapter was to optimize the QoE of user using applications over satellite links by SD-WAN. In order to realise this experiments were performed in different congestion scenarios followed by defining the load balancing mechanism to optimize the performance.

1. On uncongested links video applications performed best on LEO link and worst on GEO link so combination of MEO and LEO was chosen for optimization.
2. In different congestion scenarios highest average delay was observed in Reverse path congestion which is understandable as video applications are more reverse path (download) centric hence congestion in reverse path affects them badly.
3. From the analysis in congestion scenarios it is concluded that two applications which fall in the same category have varied performances in different scenarios. E.g. in the current set of experiments Netflix is a fairly loss intolerant application when compared to YouTube.
4. Key applications that drive the behaviour of experience should be identified and steered to the best link. E.g. In this case Netflix is a critical application to optimize QoE and hence is steered to LEO (lower latency link) to improve its performance.

5 Simulation Model Analysis

The focus of the current chapter is to emulate a future use case on Simulink and perform simulations to measure the QoE of multiple users. Ultimately, load balancing mechanism which optimizes the QoE of multiple users is defined.

5.1 Objectives

The objective is to investigate how QoE can be improved with load balancing through simulation in a future use case. This objective will be achieved by:

1. Emulate a future SD-WAN scenario on Simulink software.
2. Measuring QoE of multiple users using applications on Simulink.
   (a) Defining selected assumptions and collecting data for designing the model.
   (b) Designing a simulation model and modelling the data traffic on two levels: Session level (to emulate sessions generation) and Packet level (to emulate application traffic generation).
   (c) Defining a metric (Delay) that will be computed from the packet generation model which will be used as a measure to optimize QoE.
   (d) Performing the experiments over the designed model to compute the QoE of multiple end users.
3. Optimizing the QoE of multiple users of applications by defining load balancing mechanism.

5.2 Use Case

SD-WAN can deliver seamless and high performance experience on cruise ships [5]. E.g. MEO link can be used as a primary/main link when the cruise is in the sea with GEO link mainly providing service continuity and resiliency during times when the ship is beyond the coverage of MEO or when MEO link connection goes down. But during high bandwidth utilization of the main link, with load balancing, the latency tolerant applications can be steered over the GEO link whereas low latency applications on the MEO link. Whereas when the cruise is at the port, SD-WAN can switch to the terrestrial access as shown in Figure 5.1.

As discussed in section 3.2 with the introduction of LEO constellations, satellite connectivity (Figure 3.4) will change in the future. SD-WAN can combine WAN connections in all the three satellite orbits to provide connectivity to customers. In this simulation MEO and LEO links are selected to load balance the traffic to optimize QoE. Figure 5.2 is a representation of the simulation setup of future satellite connectivity model.

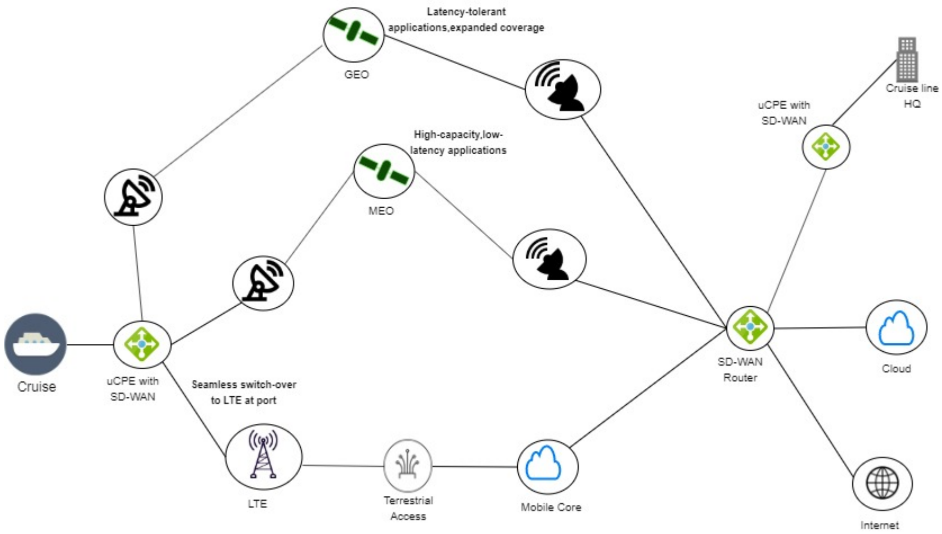

Figure 5.1: SD-WAN based multi-access network on a cruise ship [5]

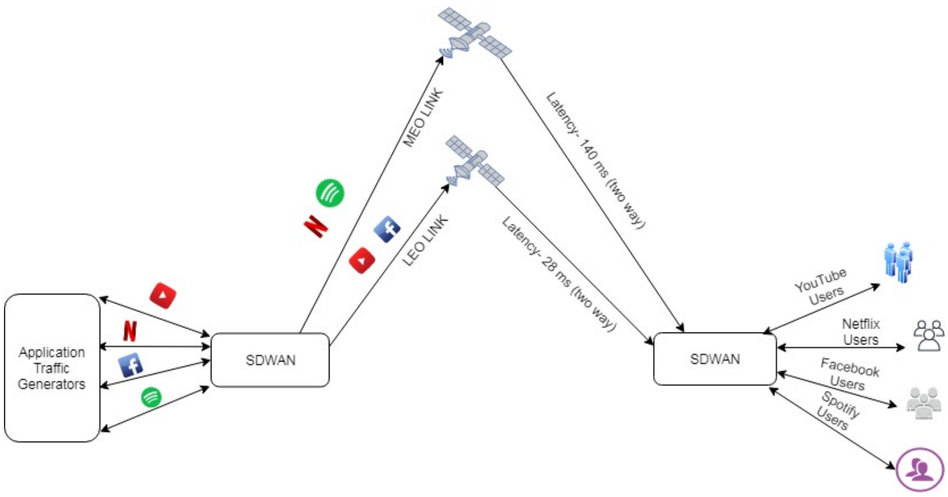

Figure 5.2: Simulation Setup Representation

5.2.1 Data Set

Most used applications (YouTube, Netflix, Facebook and Spotify) on the maritime platform were selected for simulation. Figure 5.3 shows real time cruise ship data of selected applications. The chart shows data consumption of applications (Mbps) on a cruise ship in a day. The consumption varies per hour depending on the amount of usage. For this simulation, busy hour period of each application (YouTube- 2:00-3:00, Netflix- 5:15-6:15, Facebook-18:45-19:45, Spotify- 17:15-18:15) where the amount of data consumed by an application in an hour is maximum over the day is simulated. Average data consumption of the application in the busy hour is calculated from the data set and used in simulation. The data from the cruise ship gives Mbps data consumption for every 15 mins which can be represented as in Table 5.1.

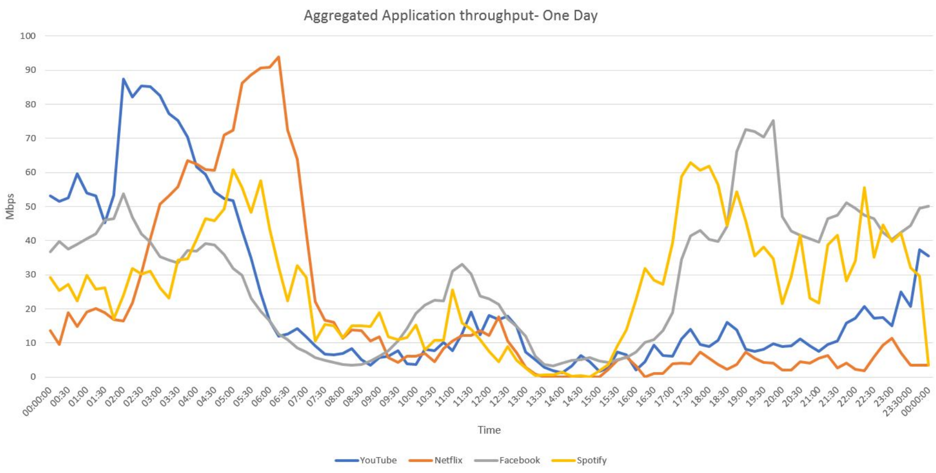

Figure 5.3: Aggregated Application throughput- One Day

00:00	00:15	00:30	00:45
X_1	X_2	X_3	X_4

Table 5.1: Example for sample data representation of cruise ships

The average application throughput ($D_{\text{avg, thr}}$) during the hour is defined as

$$D_{\text{avg, thr}} = (\sum_{i}^{N} X_i)/N(Mbps) \tag{5.1}$$

where:
N= 4
X_i (Mbps) = X_1+ X_2+ X_3 +X_4

5.2.2 Application specific Parameters

Before designing the simulation model application specific parameters are to be assumed or calculated. In Table 5.2 parameters required for designing the simulation model are presented.

Applications	**$D_{\text{avg, thr}}$ (Mbps)**	**Len_{pkt} (bits)**	**$L_{\text{avg, session}}$ (mins)**	**$V_{\text{avg, speed}}$ (Mbps)**
YouTube	84.52	6800	30	5
Netflix	90.18	7000	60	5
Facebook	71.28	1050	15	3
Spotify	60.51	600	10	0.5

Table 5.2: Application specific parameters

Where:
$D_{\text{avg, thr}}$ = Average application throughput
Len_{pkt} = Packet length

$L_{avg,\ session}$ = Average session length
$V_{avg,\ speed}$ = Average speed per user

From Equation 5.1 average throughput for each application can be calculated. Packet length (Len_{pkt}) represents the length of an application packet. Average session length ($L_{avg,\ session}$) is the amount time an application session remains active and average speed per user ($V_{avg,\ speed}$) is the speed assigned to a single user using the application.

5.3 Model Description

In this section a description of the model that is designed on Simulink is presented. In it the data traffic has been modelled on two levels namely session level and packet level. The session level represents the number of active sessions for each application on the cruise ship at any particular time. In the packet level each active session generates data packets according to the specific parameters of the application. The combined data traffic is offered to the SD-WAN and satellite links. While designing the simulation model only overlay network of SD-WAN has been modelled which is an end to end network. The underlay characteristics were not considered and modelled.

5.3.1 Session Generation level

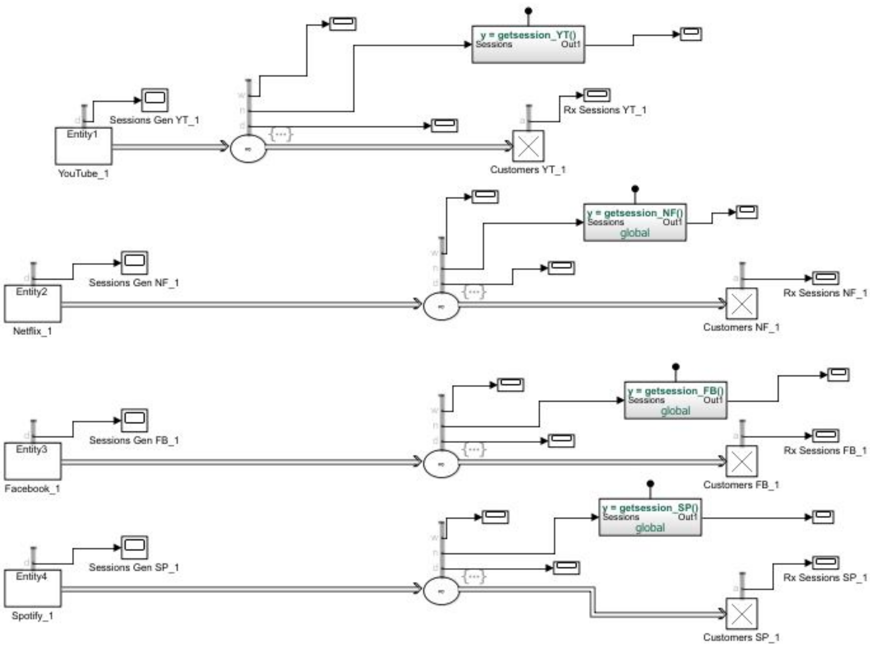

Figure 5.4: Session Generation level

In this setup (Figure 5.4), we model sessions within a time frame and then use the number of active sessions as an input for the packet generation level. The model gives the number of active sessions for each application on the cruise ship at any particular time. Entity generators block in simulink generates sessions at a rate based on exponential distribution. The average time between the sessions ($T_{\text{avg, session}}$) can be calculated by:

$$T_{\text{avg, session}} = L_{\text{avg, session}}/(D_{\text{avg, thr}}/V_{\text{avg, speed}}) \tag{5.2}$$

where:
$T_{\text{avg, session}}$ = Average time between the sessions
$L_{\text{avg, session}}$ = Average session length
$V_{\text{avg, speed}}$ = Average speed per user
$D_{\text{avg, thr}}$ = Average application throughput

Following which exponential distribution is used to generate random numbers:

$$dt = -T_{\text{avg, session}} * log(1 - rand()) \tag{5.3}$$

Substituting the value of $T_{\text{avg, session}}$ from equation 5.2 in equation 5.3 we get:

$$dt = -(L_{\text{avg, session}}/(D_{\text{avg, thr}}/V_{\text{avg, speed}})) * log(1 - rand()) \tag{5.4}$$

where:
dt = intergeneration time between the sessions.
rand() = returns a single uniformly distributed random number in the interval (0,1).

The generated sessions are then directly passed on to a server which holds the number of active sessions at a particular time instant. The server has a $T_{\text{avg, session}} = L_{\text{avg, session}}$ which is then substituted in the Equation 5.3. It gives the number of entities in the server which is the input (mu) for the packet generation model which is discussed in the next section.

5.3.2 Packet Generation level

In the current section, Packet Generation level is introduced through which analysis of packets is performed and QoE of users will be determined. Each active session generates data packets according to the specific parameters of the application. The combined data traffic is offered to the SD-WAN and satellite links. The model (Figure 5.5) has the following components:

1. Packet Generators
2. SDWAN (Application) Server
3. SDWAN (LEO Queue) & SDWAN (MEO Queue)
4. LEO & MEO servers
5. LEO & MEO Satellite Link
6. SDWAN (Customer) Server
7. End Customer of each application

- **Packet Generators**- Data packets are generated via the packet generators according to the specific parameters of the application. The packet generator generates packets with an inter generation time between the packets which can be represented as follows:

$$N(Pkts/sec) = mu * (V_{\text{avg, speed}}/Len_{\text{pkt}}) \tag{5.5}$$

$$mean = Len_{\text{pkt}}/(mu * V_{\text{avg, speed}}) \tag{5.6}$$

Using equation 5.3 for the calculation of service time(dt) and substituting the value of mean from equation 5.6 in equation 5.3 we get

$$dt = -(Len_{\text{pkt}}/(mu * V_{\text{avg, speed}})) * log(1 - rand()) \tag{5.7}$$

Where:
N = Number of packets/sec
mu = Number of active sessions of an application
Len_{pkt} = Packet length
$\text{V}_{\text{avg, speed}}$ = Average speed per user
dt = Mean time between the packets
Calculation specific to each application should be performed by considering values from Table 5.2.

- **SD-WAN & Satellite Link Modelling**- As mentioned earlier focus is on overlay modelling in SD-WAN hence model of SD-WAN at the application side and customer side is with a service time = 0 since the switching delay in the SD-WAN box is considered to be negligible due to the fast processing speed. After SD-WAN classifies the traffic and decides which link it wants to steer the traffic, on it enters the queue which is First In First Out (FIFO) type. A server which transfers the packets from the queue to the Satellite links with a service time (T) in secs, Packet length (Len_{pkt}) in bits and Capacity (C_{link}) in Mbps:

$$T = Len_{\text{pkt}}/C_{\text{link}} \tag{5.8}$$

The satellite link is modelled by a server with a service time (T) equal to the delay of the respective satellite links which is 140 ms & 28 ms for MEO & LEO respectively.

- **Model Description & Functioning** - In Figure 5.5 model of packet level simulation in Simulink is depicted. A packet generator (entity generator) which generates packets with a certain time between successive packets represented by equation 5.6. After which there is an SD-WAN box which can be considered as the brain of the model which steers the traffic over the desired link. Since the switching delay is negligible the service time of SD-WAN server (application) is zero. The packets then enter the queue from here each packet one by one with a service time equivalent to that mentioned in equation 5.8 is transferred to the satellite link. Satellite link has service time corresponding to the latency of the satellite link. After which the packet enters the SD-WAN box at the customer side which also has a service time equivalent to zero which then distributes the respective application packets to the group of users using the application.

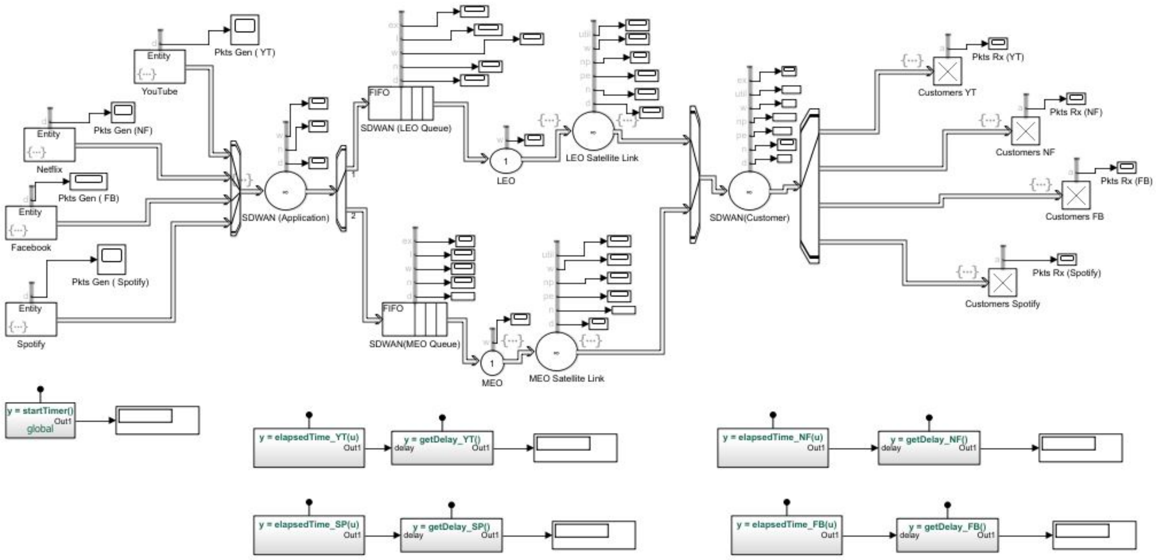

Figure 5.5: Packet Generation Model

5.3.3 Parameter for QoE Measurement

In the packet generation model Delay Function is defined for each application which computes the delay experienced by the group of customers using the application. In the following simulation delay is used as a metric to optimize the QoE of multiple users. It has three types of delay (ΔT) = Δt_1 + Δt_2+ Δt_3 :

1. Queuing Delay: Δt_1 = N*Latency of each satellite link
   where in N= number of packets in the queue.

2. $\Delta t_2 = Len_{pkt}/C_{link}$ from Equation 5.8

3. Δt_3 = Latency of the Satellite Link.

5.4 Methodology of Experiment

There are three simulations performed in this analysis:

- **Simulation 1**- In Table 5.3 input parameters (Latency, Bandwidth and Applications) for Simulation 1 are presented

MEO	LEO
Latency- 140 ms (two way)	Latency- 28 ms (two way)
Bandwidth- 225 Mbps	Bandwidth- 150 Mbps
Applications: Netflix, Spotify	Applications: YouTube, Facebook

Table 5.3: Input Parameters & Application Mix for Simulation 1

The total available bandwidth is 375 Mbps (150 + 225 = 375). YouTube and Facebook stream on LEO link which has a capacity of 150 Mbps. The average application throughput on the LEO link (Table 5.2) is 155.8 Mbps. Netflix and Spotify stream on MEO link which has a capacity of 225 Mbps. The average application throughput on MEO link (Table 5.2) is 150.69 Mbps. LEO is an expensive link hence it has a lower capacity than MEO. The average throughput on LEO link is greater than the capacity so severe congestion is expected which might lead to higher delay.

- **Simulation 2-** In Table 5.4 input parameters (Latency, Bandwidth and Applications) for simulation 2 are presented.

MEO	**LEO**
Latency- 140 ms (two way)	Latency- 28 ms (two way)
Bandwidth- 200 Mbps	Bandwidth- 175 Mbps
Applications: Netflix, Spotify	Applications: YouTube, Facebook

Table 5.4: Input Parameters & Application Mix for Simulation 2

The total available bandwidth is the same (200 + 175 = 375 Mbps) as in simulation 1 but using more of expensive LEO bandwidth. Since the average application throughput on LEO link (155.8 Mbps) is smaller than the bandwidth (175 Mbps) the delay of applications on LEO link in the simulation is expected to be limited.

- **Simulation 3-** In Table 5.5 input parameters (Latency, Bandwidth and Applications) for simulation 3 are presented. Input parameters are the same as in Simulation 1. In

MEO	**LEO**
Latency- 140 ms (two way)	Latency- 28 ms (two way)
Bandwidth- 225 Mbps	Bandwidth- 150 Mbps
Applications: Netflix, Spotify	Applications: YouTube, Facebook

Table 5.5: Input Parameters & Application Mix for Simulation 3

this simulation load balancing mechanism is used to protect the QoE of YouTube on expensive LEO link.

5.5 Results & Analysis

Results of each simulation is presented in this section.

5.5.1 Results of Simulation 1

The input parameters for this simulation are mentioned in Table 5.3 and the simulation time is T = 120 mins.

5.5.1.1 Analysis of Applications on LEO link- Simulation 1

As discussed earlier the average application throughput on LEO link (155.8 Mbps) is higher than the bandwidth (150 Mbps) of the link. In Figure 5.6 and Figure 5.7 active sessions of YouTube and Facebook are presented. Load on the LEO link is defined by

$$Load_{\text{LEO}} = (V_{\text{avg, speedYT}} * mu_{\text{YT}} + V_{\text{avg, speedFB}} * mu_{\text{FB}})/C_{\text{LEO}} \quad (5.9)$$

where:
$\text{V}_{\text{avg, speedYT}}$, $\text{V}_{\text{avg, speedFB}}$ = Average speed assigned to each YouTube and Facebook users.
mu_{YT}, mu_{FB} = Number of active sessions of YouTube and Facebook.
C_{LEO} = Bandwidth of LEO link.
If $\text{Load}_{\text{LEO}} < 1$ then the total traffic on the link is less than the capacity of the link whereas if $\text{Load}_{\text{LEO}} > 1$ then the total traffic exceeds the capacity of the link which leads to increment in delay.

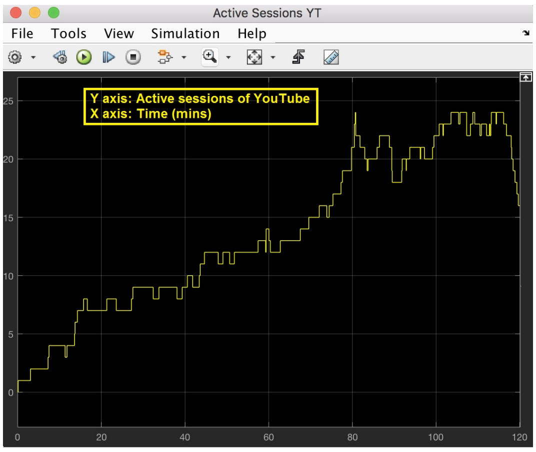

Figure 5.6: Active Sessions in YouTube Simulation 1

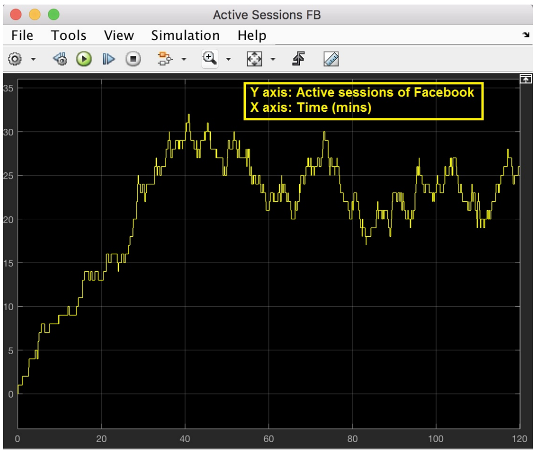

Figure 5.7: Active Sessions in Facebook Simulation 1

- Till T = 73 mins $\text{Load}_{\text{LEO}} < 1$ as the total traffic is less than the capacity of the link the delay of YouTube and Facebook (Figure 5.8, Figure 5.9) is constant at 28 ms which is the latency of LEO link.

- Around T = 70 - 73 mins the number of packets in the queue starts to increase (Figure 5.10) hence queuing delay also starts to increase (Figure 5.11). At T = 74 mins $\text{Load}_{\text{LEO}} > 1$ hence delay of Facebook and YouTube increases.

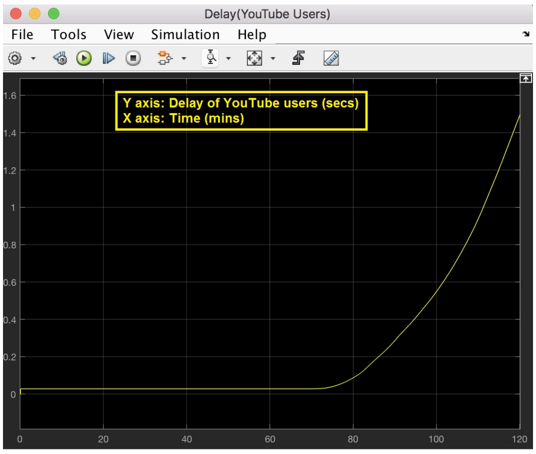

Figure 5.8: Delay (YouTube Users) Simulation 1

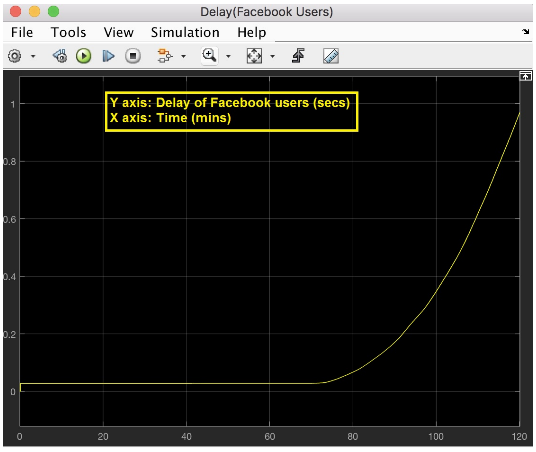

Figure 5.9: Delay (Facebook Users) Simulation 1

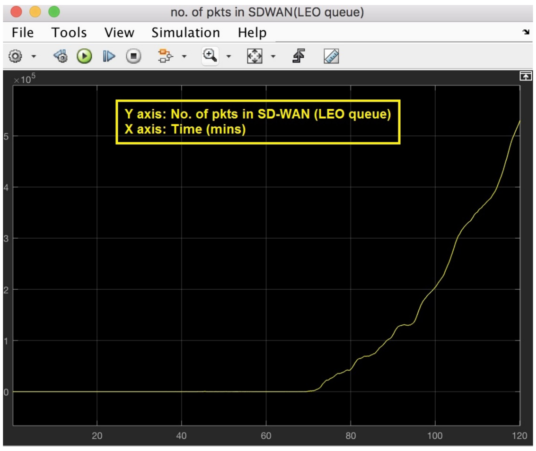

Figure 5.10: No.of pkts. in SDWAN (LEO Queue)- Simulation 1

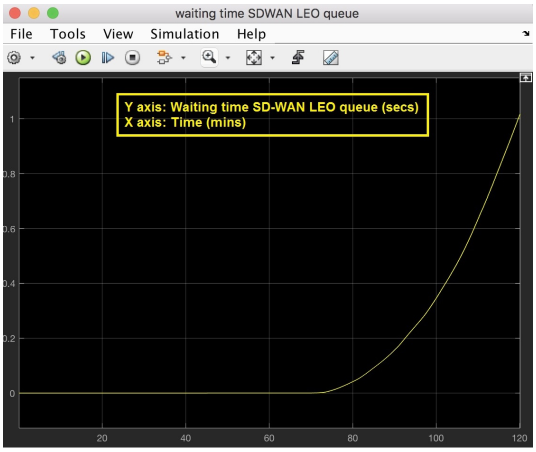

Figure 5.11: Waiting time SDWAN (LEO Queue) (Δt_1)- Simulation 1

- Delay in YouTube is higher than delay in Facebook as the average throughput of YouTube is greater than the average traffic in Facebook.
- In a real life network TCP with its inbuilt flow control would throttle back the traffic but in the simulation as there is no TCP implemented the queue of the LEO link would fill the queue and the delay would keep increasing.

5.5.1.2 Analysis of Applications on MEO link- Simulation 1

As discussed earlier the average throughput on MEO link (150.69 Mbps) is lower than the bandwidth (225 Mbps) of the link. In Figure 5.12 and Figure 5.13 active sessions of Netflix and Spotify are presented. Load on the MEO link is defined by

$$Load_{\text{MEO}} = (V_{\text{avg, speedNF}} * mu_{\text{NF}} + V_{\text{avg, speedSP}} * mu_{\text{SP}})/C_{\text{MEO}} \quad (5.10)$$

where: C_{MEO} = Bandwidth of MEO link.
$\text{V}_{\text{avg, speedNF}}$, $\text{V}_{\text{avg, speedSP}}$ = Average speed assigned to each Netflix and Spotify users.

mu_{NF}, mu_{SP} = Number of active sessions of Netflix and Spotify.

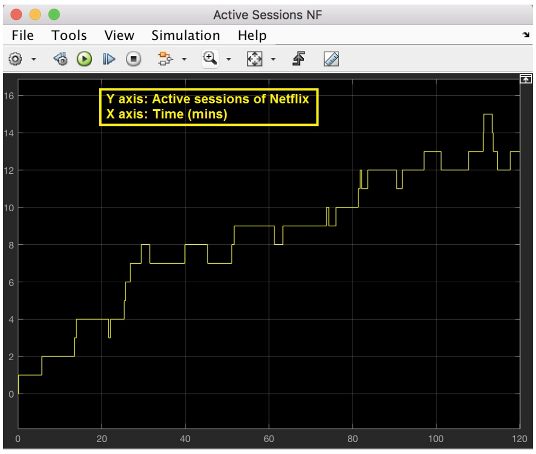

Figure 5.12: Active Sessions in Netflix Simulation 1

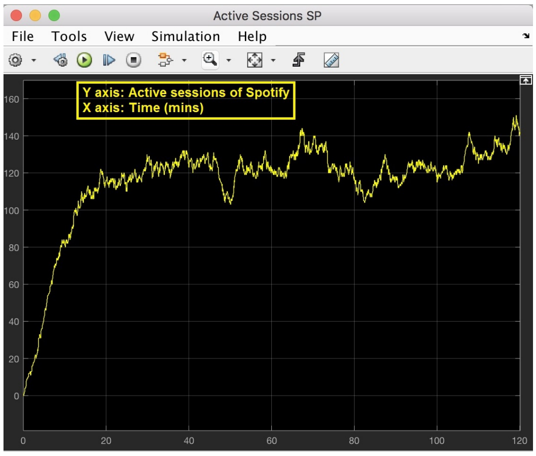

Figure 5.13: Active Sessions in Spotify Simulation 1

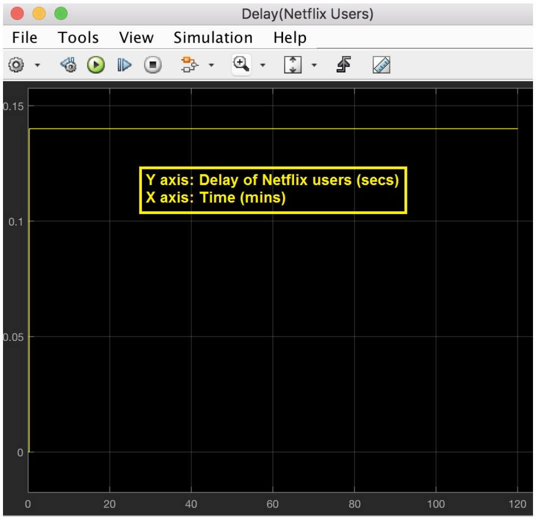

Figure 5.14: Delay (Netflix Users) Simulation 1

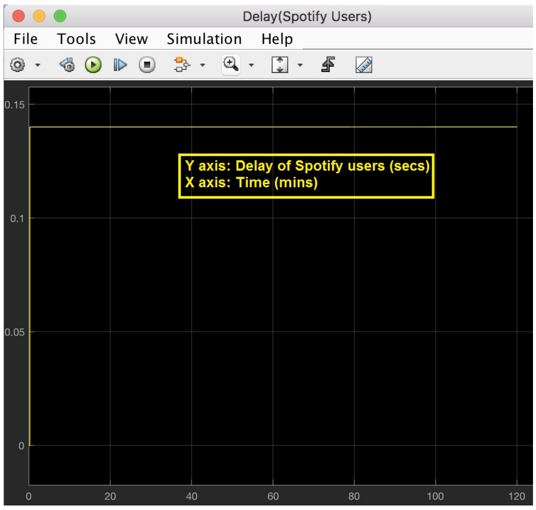

Figure 5.15: Delay (Spotify Users) Simulation 1

- Since, the total traffic on the link is less than the capacity the analysis is pretty straightforward. $Load_{MEO} << 1$ and hence the waiting time (Figure 5.17) in the queue is small which clearly reflects in the delay of Netflix and Facebook which is almost constant at 140 ms (Figure 5.14, Figure 5.15).

5.5.2 Results of Simulation 2

The input parameters for this simulation are specified in Table 5.4 and the simulation time is T = 200 mins. Total bandwidth is the same as in simulation 1 but in this simulation more

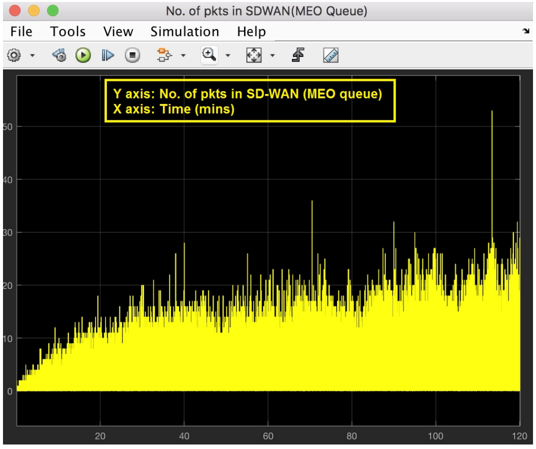

Figure 5.16: No.of pkts. in SDWAN (MEO Queue)- Simulation 1

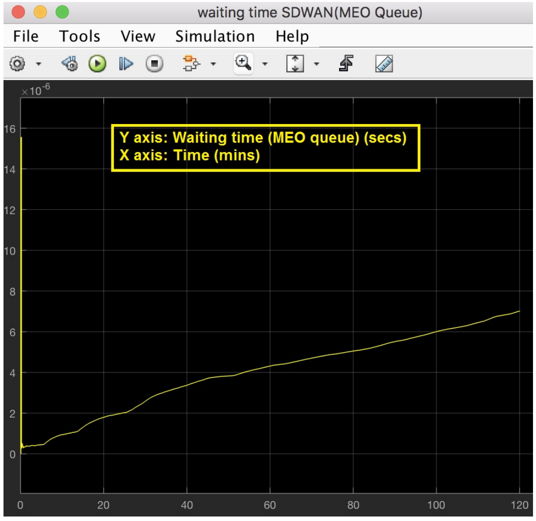

Figure 5.17: Waiting time SDWAN (MEO Queue) (Δt_1)- Simulation 1

bandwidth of expensive LEO link is used. The average application throughput on LEO link (155.8 Mbps) is not higher than the capacity of the link (175 Mbps) in this simulation. Hence the delay is expected to be rather limited.

Figure 5.18: Active Sessions in YouTube Simulation 2

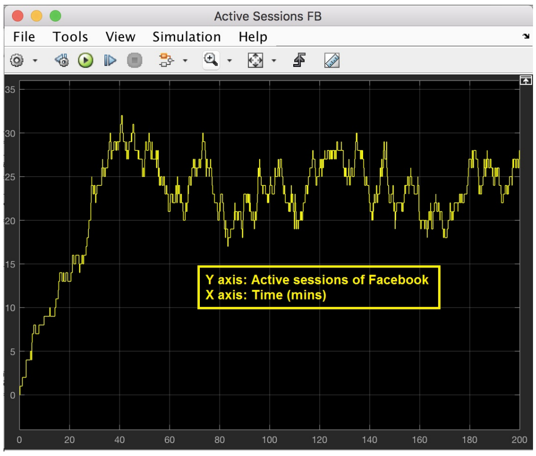

Figure 5.19: Active Sessions in Facebook Simulation 2

5.5.2.1 Analysis of Applications on LEO link- Simulation 2

In Figure 5.18 and Figure 5.19 active sessions of YouTube and Facebook are presented.

- As expected the delay in YouTube (Figure 5.20) and Facebook (Figure 5.21) is rather limited if compared to the first simulation as the available capacity of LEO link for this simulation is higher.
- From T = 105 mins the delay in both Facebook and YouTube starts to increase as the

Figure 5.20: Delay (YouTube Users) Simulation 2

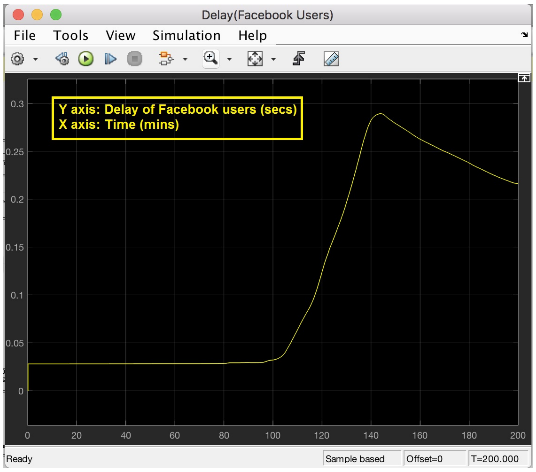

Figure 5.21: Delay (Facebook Users) Simulation 2

Figure 5.22: No.of pkts. in SDWAN (LEO Queue)- Simulation 2

Figure 5.23: Waiting time SDWAN (LEO Queue) (Δt_1)- Simulation 2

traffic offered (Figure 5.18, Figure 5.19) to the link exceeds its capacity. The delay starts to decrease around T =143 mins as the total traffic on the link starts to decrease. As expected there was a period of significant delay on LEO link.

- For this simulation the capacity of expensive LEO bandwidth (175 Mbps) was increased in comparison to simulation 1 (150 Mbps). Hence, the delay of YouTube and Facebook decreased.

- The increased delay in simulation 1 (Figure 5.8, Figure 5.9) was compensated by buying more capacity of expensive LEO link for current simulation. The delay on LEO link was optimized in simulation 2 but is an expensive method of achieving QoE optimization.

5.5.2.2 Analysis of applications on MEO link- Simulation 2

The capacity of MEO link is less if compared to simulation 1 but it still exceeds the average application throughput (150.69 Mbps). So delay on Netflix and Spotify is expected to be constant. In Figure 5.24, Figure 5.25 active sessions of Netflix and Spotify are presented.

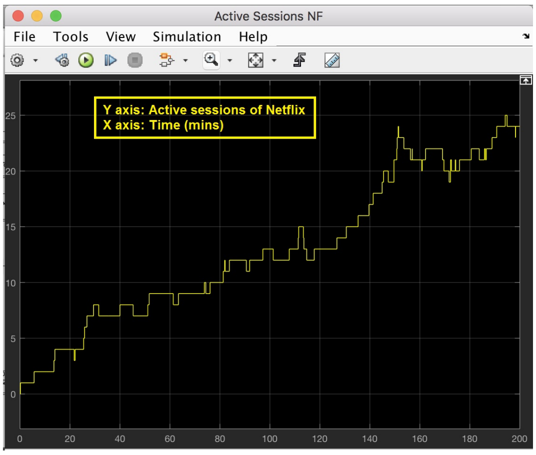

Figure 5.24: Active Sessions in Netflix Simulation 2

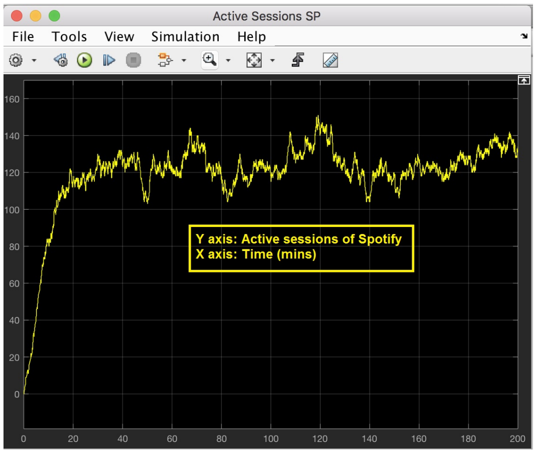

Figure 5.25: Active Sessions in Spotify Simulation 2

Figure 5.26: Delay (Netflix Users) Simulation 2

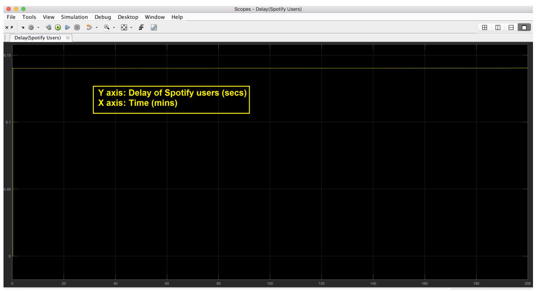

Figure 5.27: Delay (Spotify Users) Simulation 2

- Analysis of applications on MEO link is straightforward. The delay of Netflix (Figure 5.26) and Spotify (Figure 5.27) are stable at 140 ms as the average application throughput (Figure 5.24, Figure 5.25) is lower than the available capacity (200 Mbps). The load increases towards the end of simulation the amount of packets in the queue (Figure 5.28) also increase but it is not enough hence the delay of Netflix and Spotify are constant.

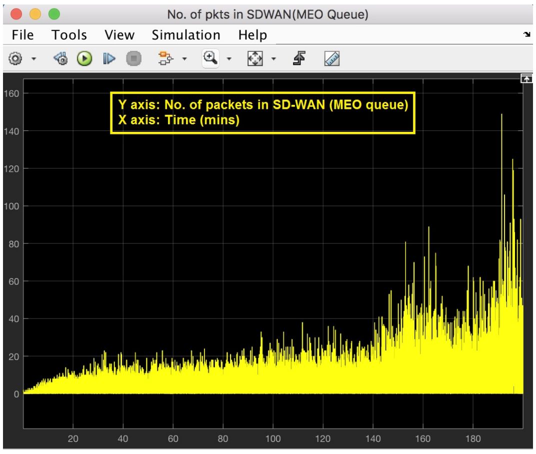

Figure 5.28: No.of pkts. in SDWAN (MEO Queue)- Simulation 2

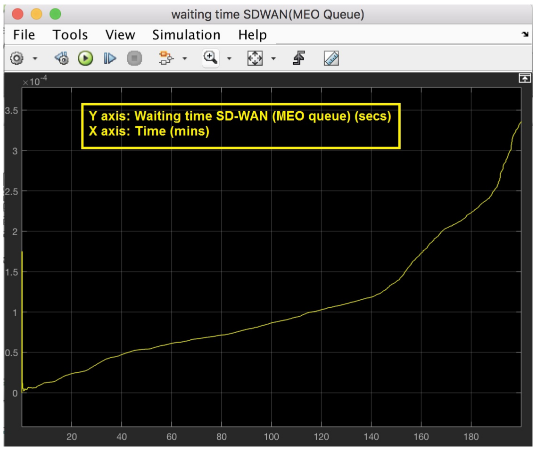

Figure 5.29: Waiting time SDWAN (MEO Queue) (Δt_1)- Simulation 2

5.5.3 Results of Simulation 3

The input parameters for this simulation are specified in Table 5.5 and simulation time is T = 200 mins. The capacity of the links is the same as in simulation 1. The main idea behind this simulation is to devise a load balancing algorithm to protect the QoE of video applications on both LEO and MEO link at a lower bandwidth cost. Comparison of delays in Simulation 2 and Simulation 3 will be performed. A load balancing mechanism (algorithm 3- Intelligent steering) is defined for the current simulation.

- Traffic steering in the algorithm is based on delay experienced by the application.
- First steering mechanism proposed in the algorithm is if the delay of YouTube exceeds 200 ms then Facebook traffic is shifted to MEO link. This is done to optimize QoE of YouTube at lower bandwidth cost (since less LEO capacity is used as compared to simulation 2)
- Secondly Netflix is given priority-1 in its own queue (SD-WAN MEO Queue) in order to protect its QoE.
- Delay value in the algorithm (algorithm 3) are chosen to achieve better QoE (lower delay) than in Simulation 2.

After applying the load balancing algorithm delay charts are obtained which are explained as follows

5.5.3.1 Analysis of Applications on LEO link- Simulation 3

- Till T = 73 mins $\text{Load}_{\text{LEO}} < 1$ as the total average throughput is less than capacity of the link. Delay of YouTube and Facebook (Figure 5.30, Figure 5.31) is constant at 28 ms.
- At T = 70 mins the number of packets in the LEO queue starts to increase (Figure 5.34) which then leads to queuing delay.

Figure 5.30: Delay (YouTube Users) Simulation 3

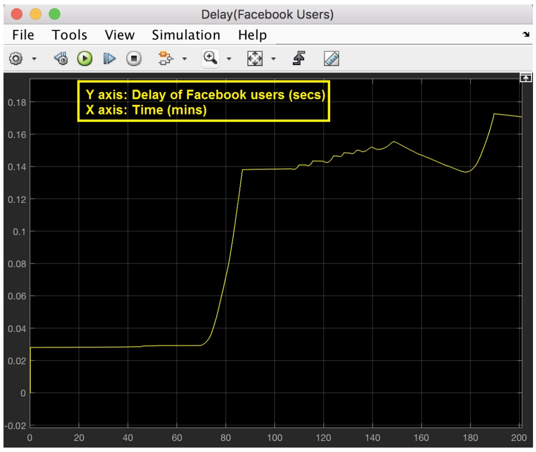

Figure 5.31: Delay (Facebook Users) Simulation 3

Figure 5.32: Active Sessions in YouTube Simulation 3

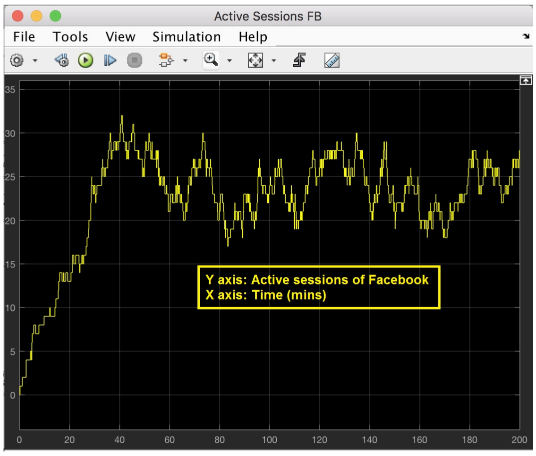

Figure 5.33: Active Sessions in Facebook Simulation 3

- Around T = 82 mins as soon as delay in YouTube reaches 200 ms (Figure 5.30) Facebook traffic is steered to MEO link, the number of packets in LEO queue starts to decrease (Figure 5.34).
- The delay chart of Facebook (Figure 5.31) from 83-110 mins shows a constant delay of 140 ms which is the latency of MEO link.
- Delay in YouTube starts to decrease as the load on LEO link decreases due to steering of Facebook traffic on MEO link.
- Delay in YouTube and Facebook from T=110 mins to T=150 mins keeps fluctuating around 200 ms due to back and forth steering of Facebook traffic between LEO and MEO links.
- From T=150 mins to T= 178 mins $Load_{LEO}<1$ so a dip in delay is observed for both YouTube and Facebook which then continue to stream on LEO link.

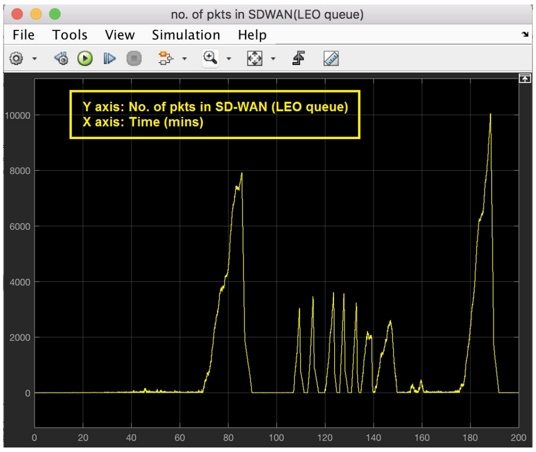

Figure 5.34: No.of pkts. in SDWAN (LEO Queue)- Simulation 3

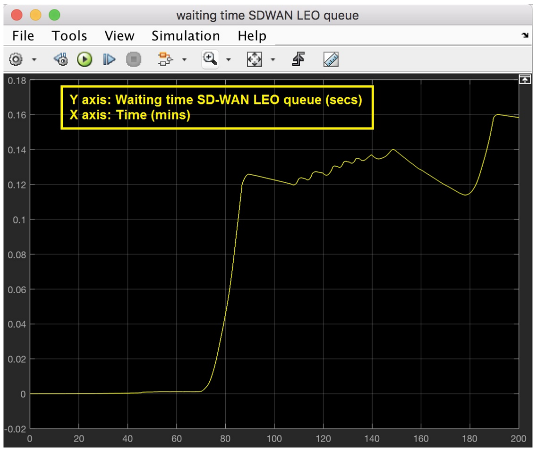

Figure 5.35: Waiting time SDWAN (LEO Queue) (Δt_1)- Simulation 3

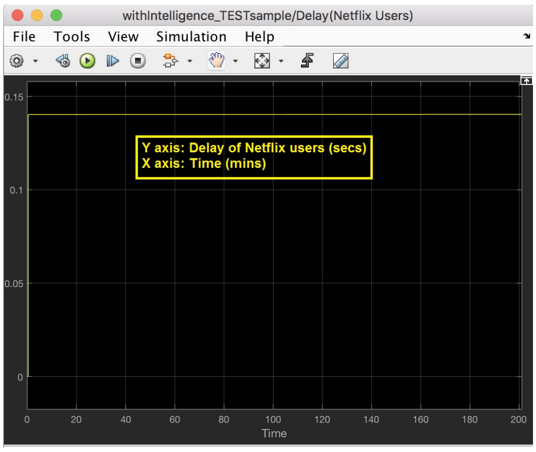

Figure 5.36: Delay (Netflix Users) Simulation 3

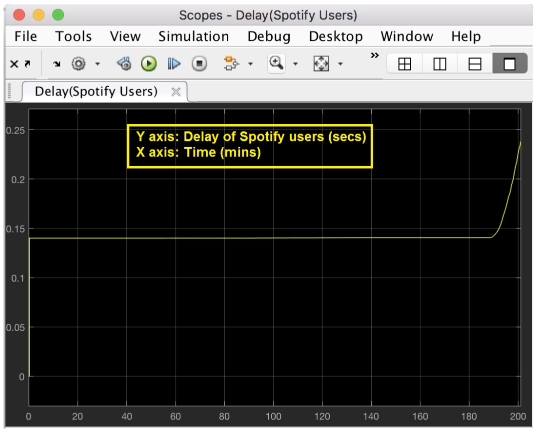

Figure 5.37: Delay (Spotify Users) Simulation 3

- At T=180 mins Load_{LEO}>1 so delay increases and Facebook is steered back to MEO link

5.5.3.2 Analysis of applications on MEO link- Simulation 3

- Initially Load_{MEO}<<1 so delay of Netflix and Spotify are constant at 140 ms.
- Around T = 190 mins for the first time in all three simulations Load_{MEO}>1 (Figure 5.40) so delay of Facebook increases further (Figure 5.31).
- Towards the end of the simulation Load_{MEO} = 0.844 (Figure 5.38, Figure 5.39) which shows high link utilization and thus delay in Spotify starts to build up (Figure 5.37. Similarly, towards the end Load_{LEO}>1 (Figure 5.32, Figure 5.33).
- Due to load balancing Facebook traffic would be steered to MEO link as soon as delay of YouTube is more than 200 ms, this might lead to higher delay in Netflix and Spotify

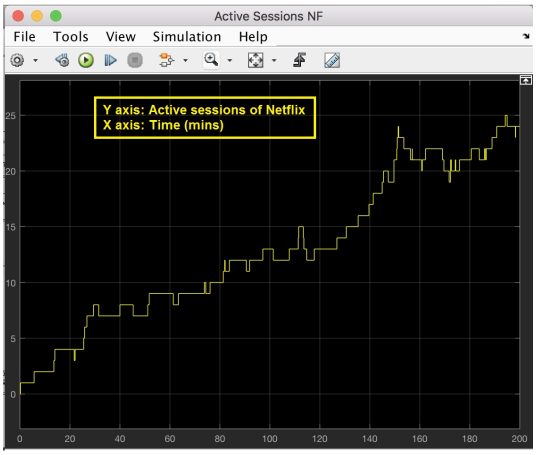

Figure 5.38: Active Sessions in Netflix Simulation 3

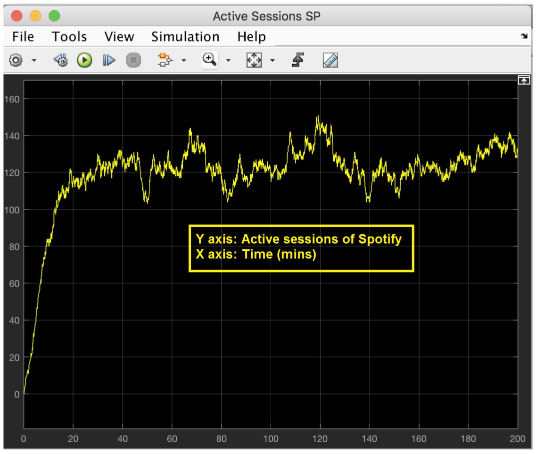

Figure 5.39: Active Sessions in Spotify Simulation 3

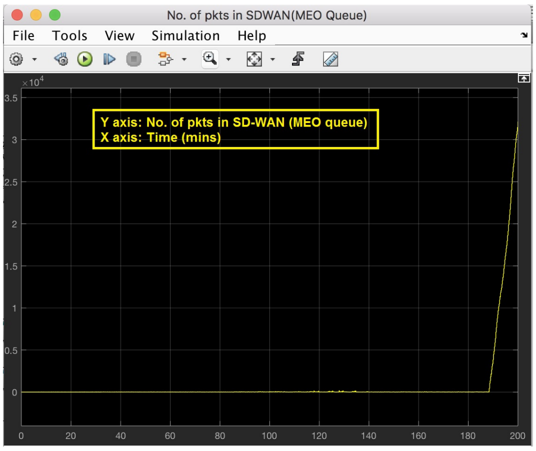

Figure 5.40: No.of pkts. in SDWAN (MEO Queue)- Simulation 3

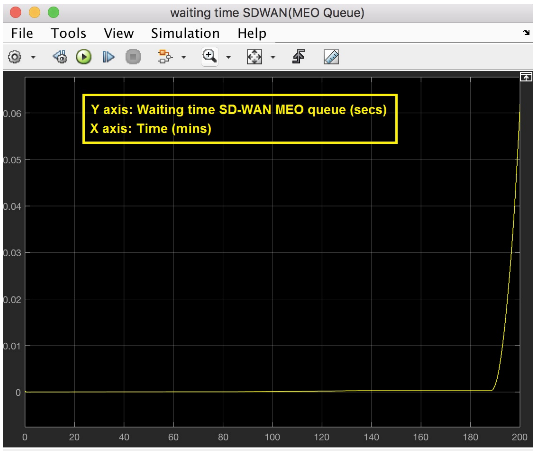

Figure 5.41: Waiting time SDWAN (MEO Queue) (Δt_1)- Simulation 3

as after steering of facebook traffic on MEO Load$_{\text{MEO}}$>> 1. But since Netflix is given priority in the queue it maintains a constant delay (Figure 5.36).

- Thus, even at higher load/congestion at both LEO and MEO the QoE of both Netflix and YouTube is protected via the load balancing algorithm.
- Even further in the simulation even if the load increases Netflix won't be affected instead spotify would have a higher delay as it has a lower priority in the queue.

If the delay graphs of Video applications in Simulation 2 (Figure 5.20, Figure 5.26) and Simulation 3 (Figure 5.30, Figure 5.36) are compared, then it is evident that performance of the algorithm (algorithm 3) is better. Through the load balancing algorithm QoE optimization of Video applications (Netflix and YouTube) has been achieved at a lower bandwidth cost (LEO capacity is less if compared with that of simulation 2). Hence, to conclude the objective of optimizing the QoE of multiple users of applications by load balancing mechanism as been achieved.

5.6 Summary

The main theme of the chapter is to investigate how QoE can be improved with load balancing through simulation in a future use case. In order to realize the objective two simulations of varying bandwidths followed by defining load balancing mechanism to optimize performance in the third simulation were performed.

1. QoE of simulation 1 (where LEO link was congested as the total traffic was higher than the capacity of the link) is poor due to an overloaded link which leads to severe congestion followed by high delay.

2. QoE in simulation 2 (where capacity of LEO link was higher if compared with simulation 2) is optimized but it is made possible by increasing more expensive LEO bandwidth. It does reduce delay on LEO link but it is not an cost effective alternative.

3. QoE in simulation 3 (bandwidth same as in simulation 1) is the best due to load balancing algorithm which protects the QoE of video applications. Delay is lower in simulation 3 if compared to simulation 2 without increasing any expensive LEO bandwidth. The load balancing algorithm not only optimizes QoE but it is also a cost effective alternative to manage QoE.

6 Conclusion & Future Work

Satellite networks suffer from congested circuits due to increased application traffic which in turn affects the QoE. With Satellites becoming a more mainstream part for the global cloud scale environment they not only need to have sufficient bandwidth but also intelligence to inspect and prioritize traffic at application layer to ensure QoE. SD-WAN is a relatively new concept in the satellite industry. This thesis project explores how QoE of users using satellite services can be optimized using SD-WAN. The conclusions, recommendations and future work are presented below.

6.1 Conclusion

The main goal of the thesis is to investigate how to optimize Quality of Experience (QoE) of users via application aware load balancing over satellite links using SD-WAN.
From the analysis performed in the thesis conclusions addressing how to improve QoE of users using applications over satellite links using SD-WAN are presented below:

1. How applications are classified, generalized and derived conclusions these days is incorrect. The most obvious practice is to classify applications into a single category (like Video, Music etc.), test a few applications of the category and then generalize the behaviour for all applications in that category. Each application has its own performance, variation and should be dealt accordingly. During the experiments (subsection 4.6.2) it was observed that two applications who fall in the same category have varied performances in different scenarios. E.g. in the video application category, YouTube can tolerate higher loss than Netflix.

2. In each use case, there are key applications that drive the behaviour of experience or are critical to the business. They should be identified and steered accordingly to the best possible link so that overall user experience could be improved. In this research video applications were considered as key applications and during load balancing (section 4.7, subsection 5.5.3) optimizations were derived keeping in mind QoE improvement of these video applications.

3. In the research it was revealed that identifying application thresholds and their performance on different satellite links and congestion scenarios is an important aspect. This gives us freedom to steer applications which are more tolerant towards delay and loss to a link with higher latency which improves the performance of delay and loss intolerant applications thus optimizing QoE.

4. In the case of higher load on both links used for load balancing the key application traffic can be prioritized on the same link in order to achieve QoE improvement as performed in subsection 5.5.3.

6.2 Recommendations

Following are the recommendations when using SD-WAN setup to shape QoS application based traffic flows to optimize QoE:

1. The application based analysis should be used to steer the traffic and define policies since that gives insight about the customer behaviour and usage of applications which in turn helps to prioritize critical application traffic.

2. Similarly, the application based analysis should be performed separately for Upstream Bandwidth and Downstream Bandwidth as the traffic profiles and application performance differ per profile. Following which different traffic steering schemes can be devised.

3. The expected outcome in terms of QoS and definition of good service for the customer is important to know to make any steering decisions. Customer perception of service is an important factor which would assist in making good policies.

4. Other than Network Congestion evidence of Behavioral congestion management (e.g. if customers stop doing things at certain times due to congestion) should also be investigated.

5. Since very small changes in application behavior lead to large changes in bandwidth consumption it is important to always steer the traffic. Measure it and then define Quality of Service.

6. With Networks changing rapidly the application mix also changes, so repeating the QoE analysis within a regular time interval of few months is essential to update the policies accordingly.

7. In a cruise or communications on move type of network the automatic updates should be kept in check because they might consume the bandwidth required and probably causing contention amongst the available resources without customers actually using satellite capacity. Pushing the uploads or automatic updates to the off peak hours could be good network monitoring strategy.

8. Policies can also be defined considering the time of the day. For e.g, during day time customers on cruise ships are busy clicking and uploading pictures so Upstream traffic (icloud, Facebook, Instagram) could be given priority whereas during night they use video applications (YouTube, Netflix) for streaming videos so during that time Downstream video traffic could be given priority so as to improve user experience.

9. A separate plan and go to market strategy for each target vertical (Maritime, Fixed Data, Aero and Global Government) should be defined. Gather idea from customers in different verticals about what they expect in terms of QoS improvements. This could be a better way to start planning for future tests and then defining policies accordingly.

10. SD-WAN gives the flexibility to prioritize the traffic on the same link, so defining a policy to prioritize business critical application traffic over the same link when traffic steering or load balancing is not possible due to overbooking of the satellite capacity. This would also improve the QoE of the satellite service users.

11. It is crucial to identify the performance of the satellite links before defining any load balancing mechanisms. This performance analysis becomes crucial when we consider the Radio Frequency (RF) characteristics of satellites. Although RF characteristics were not considered in the current project but real satellite links using different bands (C, Ka or Ku band) perform differently in different scenarios e.g. adverse whether conditions impact Ka band much more than other bands. So steering latency sensitive applications on Ka band satellite on a heavy rainy day would not a be a good idea.

6.3 Future Work

The possible directions for future research are as follows:

1. Due to commercial reasons the following tests (subsection 4.6.2) were not performed on the real satellite links so it could a good exercise to perform it on a real satellite link to get an idea about Radio Frequency loss behaviour.

2. Gaming and other latency sensitive applications could be included in testing to further widen the application set and to increase the possibilities for future business.

3. Possible deployment of the same setup (Experimental setup) in the cloud should be performed and similar analysis could be performed to validate the results which could also ease the future testing methodology.

4. Security is the area which should be inspected specifically with segmented security levels across the same link.

5. In the simulation model functionality enabling other parameters like throughput, jitter etc. could be the next possible approach in order to make the model more diverse.

6. The current exercise of writing policies could be obviated once we have the controlled loop capability with Machine Learning and Artificial Intelligence that can understand the intent of the policies and generates its optimisation.

7. A detailed analysis of link capacity in relation with traffic and cost of the link can be performed.

Appendix A

A.1 SD-WAN Proof of Concept Architecture

The following illustrates SD-WAN test plan to demonstrate real world traffic in a lab environment. Director (FlexVNF Manager and Orchestrator) and Analytics will be used in conjunction with FlexVNF to support Operation and Maintenance (OAM) functions associated with the various services under test providing the core SD-WAN architecture and services.It is made of three software components:

1. Flex Virtual Network Function (VNF)
2. Director
3. Analytics

The hub unit network components run over x86 based hardware either as bare-metal, hypervisor based VM using KVM hypervisor.

A.1.1 Flex VNF

The remote unit network component runs on a bare metal white-box server. At the heart of networks SD-WAN solution is FlexVNF which is a highly available distributed virtual network services appliance that is built from the ground up for multi-tenancy, dynamic elasticity (aka scale-out/in), high-availability and service chaining capabilities.
The FlexVNF is a purpose-built multi-tenant system delivering Software based network services. It has a distributed architecture with clean/clear separation of control plane and forwarding plane. It is configured and managed through Director which provides REST based API for integration with existing third-party management applications in the network. FlexVNF also exports a rich variety of Security, NAT, SD-WAN and audit logs for compliance and analytics derivation for the services running in the network to Analytics, in charge of generating appropriate dashboard reports and this on a per tenant basis. FlexVNF is a software instance that lets users seamlessly configure and manage layer 4 through layer 7 network services. FlexVNF can be installed as bare-metal (i.e. on 3rd party white box appliances that can be used as CPE, Hub Routers and SD-WAN Controllers) or as hypervisor based-VM on NFVI like vCloud Director or OpenStack infrastructure. FlexVNF provides the following network services:

1. Routing Services: L3 CPE (L3 customer-premises equipment), route reflector, provider edge, carrier grade NAT.
2. Security Services: L3/L4 Firewall, next generation firewall, intrusion detection and prevention (IDP/IPS), zero day attack prevention, network anti-virus and anti-malware, URL filtering, DDoS protection, application identification and control, WAF.

3. VPN Services: site to site IPSEC VPN.
4. Network Services: DHCP Server and relay, QoS, VRRP, BFD and ethernet OAM.
5. Software-Defined WAN (SD-WAN) with link SLA monitoring.

A.1.2 Director

Director is the virtualized network function (VNF) manager that controls a set of FlexVNF software instances running on general-purpose servers. Director is the brain behind how the services are instantiated, scaled-up and scaled-down and orchestrated to be multi-tenant.The key components in the Director are distributed in two primary layers:

1. Infrastructure management layer. Responsible for discovery of tenants and its associated compute/network information from either vCloud Director, OpenStack, or baremetal.
2. Service orchestration layer. Responsible to configure and manage various network services.

Director supports 3 different set of interfaces:

1. Southbound interface toward FlexVNF instances using Netconf over SSH which is used to push configuration/service template and FlexVNF performance management (allowing to trigger scale-out/in process for example).
2. Northbound interface exposing REST APIs and WebUI interface. REST APIs are used to interface with third party orchestration system or self-care portal, but its also used to interface with Analytics for authentication purpose as well as to access Analytics dashboards/reports using Director WebUI.
3. In case an NFVI would be used, Director also provides a Westbound set of APIs to interface with Openstack or vCloud Director environment.

When it comes to service provisioning/activation, Director heavily leverages the concept of service template. If multiple sites, branches or FlexVNF instances use a similar set of configurations, templates can be used to build a generic configuration that can be applied to one or more FlexVNF instances. Altering configurations across many software instances or nodes can be tedious and time-consuming, and templates save time by applying the necessary configurations and ensuring consistency across sites. Director also automates the discovery of a new branch deployment and configuration via pre-provisioned templates.

A.1.3 Analytics

The Analytics (VAN) is a multi-tenant carrier-class analytics that runs either on bare-metal or virtualized environment. Analytics allow administrators to perform network planning, traffic/application analysis, network security analytics and behavior anomaly detection. It shows high-level dashboard view in to what is happening on the network, and with just a few clicks the user gets a detailed view to learn more about the who, where and what about a user from an application point of view.
This provides a complete view in to what is happening in the network, what applications are running on, and what those applications are doing, combined with what threats are being

detected and thwarted. You can get a description of the application or threat, the applications key features and behavioral characteristics, details on the users using that application and the details on those who are affected by a threat. It also includes:

1. Real time network security Event Monitoring
2. Internal and external threat monitoring
3. Zero day anomaly detection
4. SD-WAN (NG-VPN) topology and SLA monitoring

The Analytics engine is a 360-degree view in to the activity on your network and help you analyze events from a current and historical perspective. Analytics engine is a single interface that forms a reliable decision support system to help keep your network secure and assess application performance.

A.2 Hardware Requirements

Below are, for each software component, the required resource specifications:

1. **FlexVNF (2 SD-WAN Controllers):**Runs over any generic Inter Based x86_64 bits with VT technology either as baremetal or as VM. For the current experiment, we assume that both controllers will be represented by a VM instance on an NFVI environment with the below minimum requirements.
   (a) CPU requirements: 4 vCPU
   (b) Memory requirements: 8 GB of RAM
   (c) HDD: 20 GB of HDD
   (d) 4 vNICs per FlexVNF instance of type virtio (Openstack) or vmxnet3 (VMWare).
2. **Director:**Runs over any generic Inter Based x86_64 bits with VT technology either as baremetal or asVM. For the current experiment, Director will be represented by a VM instance on an NFVI environment with the below minimum requirements.
   (a) CPU requirements: 4 vCPUs
   (b) Memory requirements: 8 GB RAM
   (c) HDD requirements: 80GB of HDD
   (d) 2 vNICs per Director instance of type virtio (Openstack) or vmxnet3 (VMWare).
3. **Analytics:**Runs over any generic Inter Based x86_64 bits with VT technology either as baremetal or as VM. For the current experiment, Analytics will be represented by a VM instance on an NFVI environment with the below minimum requirements.
   (a) CPU requirements: 4 vCPUs
   (b) Memory requirements: 8 GB RAM
   (c) HDD requirements: 100 GB of HDD
   (d) vNICs per Director instance of type virtio (Openstack) or vmxnet3 (VMWare)

There are total 5 appliances in the lab environment and the naming conventions are as follows:

1. CTRL-SINTRA
2. Controller 1
3. DRAGON-GWY (Gateway)
4. MEO-SDWAN Gateway
5. RMT4-DRAGON (Remote Site Gateway)

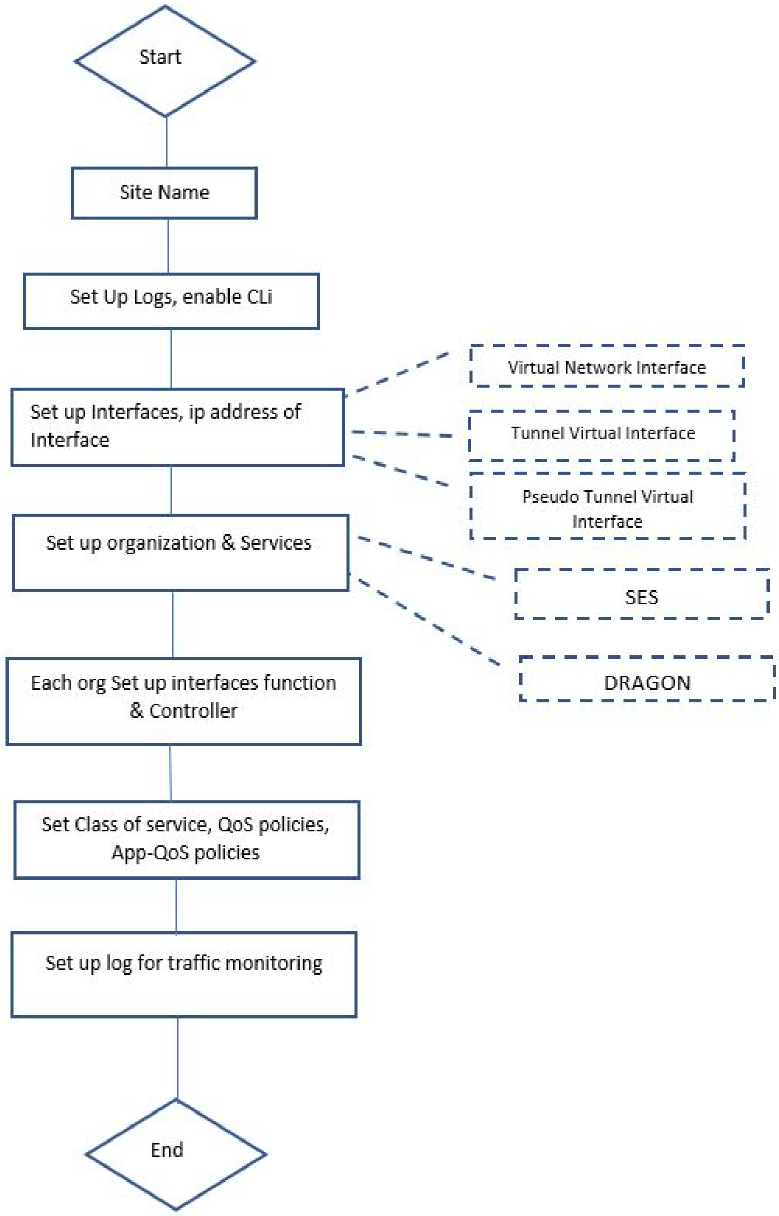

Figure A.1: Flow Chart on how to setup a template

A.3 Interfaces of Appliances

Other than setting up different interfaces defining the organization is the next step, the organization is the closed loop where in all the current interfaces and sdwan setup works. For this we have two separate organizations namely SES & DRAGON, but we use only DRAGON organization for the tests that we perform. In the organization we can setup the routing instances, traffic identification interfaces, sdwan setup and the controller setup that corresponds to the particular links (GEO, MEO & LEO).
Next step could be Quality of service & application Quality service policies, setting up of the Internet Protocol Security (IPSec) which takes care of the security services of the IP network traffic. Which then completes the template configuration of the RMT4-DRAGON template. Similarly seeing the process, the other templates can be configured accordingly.

```
org DRAGON {
                    services                          [ sdwan ];
                    available-routing-instances       [ DRAGON-Control-VR
                        DRAGON-LAN-VR MPLS-WAN-Transport-VR SES-Control-VR
                         ];
                    owned-routing-instances           [ DRAGON-Control-VR
                        DRAGON-LAN-VR ];
                    available-provider-orgs           [ SES ];
                    available-networks                [ DRAGON-INET DRAGON-
                        LAN MPLS-WAN ];
                    dhcp-profile                      dhcp-limits;
                    options {
                        session-limit 1000000;
                    }
                    traffic-identification {
                        using          [ ptvi8 ptvi9 tvi-0/8.0 tvi-0/9.0
                            ];
                        using-networks [ DRAGON-INET DRAGON-LAN ];
```

A.4 Algorithms

Algorithm 1 Application level Traffic steering on MEO & GEO link

```
Input: Forwarding Profile Name (FP): Prefer_GEO, Prefer_MEO; Application= SPOTIFY,
       YOUTUBE.
if FP =Prefer_GEO, then
|  Update circuit as = GWY-P2P
|   Update SLA Profile = SLA_1
else
|  Use FP =Prefer_MEO, Update circuit as = MPLS MEO,MPLS WAN
|   Update SLA Profile = SLA_2
end
while Application = SPOTIFY do
|  FP = Prefer_GEO
|
end
while Application = YOUTUBE do
|  FP = Prefer_MEO
|
end
```

Algorithm 2 Load balancing in SD-WAN

Input: Forwarding Profile Name (FP): Prefer_MEO, Prefer_LEO; Application= Netflix; SLA Profile= Maximum Delay (ms), Maximum Packet Loss (%).

```
if FP =Prefer_MEO, then
    Update circuit as Ckt 1 = MPLS MEO, MPLS WAN
    Update SLA Profile = SLA_1
    Load Balancing = Per Flow
else
    Use FP =Prefer_LEO, Update circuit as = GWY-P2P
    Update SLA Profile = SLA_2
    Load Balancing = Per Flow
end
while Application =Netflix do
    FP = Prefer_MEO
    if SLA_Violation 1 = Maximum Delay (ms)<2400 OR Maximum Packet Loss (%) <4
    then
        SLA_Violation 1= No
        SLA_Violation 1 Action = Stay
        Use FP=Prefer_MEO
    end
    if SLA_Violation 1 = Maximum Delay (ms)>2400 OR Maximum Packet Loss (%) >4
    then
        SLA_Violation 1 = Yes
        SLA_Violation 1 Action = Forward
        Use FP= Prefer_LEO
    end
    if SLA_Violation 2 = Circuit Utilization <90% then
        SLA_Violation 2 = No
        SLA_Violation 2 Action = Stay
        Use FP= Prefer_LEO
    end
    if SLA_Violation 2 = Circuit Utilization >90% then
        SLA_Violation 2 = Yes
        SLA_Violation 2 Action = Forward
        Use FP= Prefer_MEO
    end
end
```

Algorithm 3 Intelligent Steering

Input: Packet Length (Len_{pkt}) = a; Average speed per user ($V_{avg,\ speed}$) = b; No. of Active sessions in an application = mu, service time = dt, Load on LEO link = $Load_{LEO}$, entity.Type=3 (Facebook Traffic), entity.Type= 4 (Spotify Traffic), entity.Route= 1 (LEO link), entity.Route=2 (MEO link)

```
if mu==0 then
    dt=0.1
else
    m=(a)/(b*(mu))
    dt= -m*log(1-rand())
end
if entity.Type ==3 then
    entity.Route=1
end
if entity.Type ==4 then
    entity.Route =2
end
if getDelay_YT() >= 0.200 then
    if entity.Type ==3 then
        entity.Route =2
    end
end
while Application =Netflix do
    Priority MEO Queue = 1
end
```

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