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Performance Assessment of Networked Immersive Media in Mobile Health Applications with Emphasis on Latency

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The authors declare that they are the sole authors of this thesis and that they have not used any sources other than those listed in the bibliography and identified as references. They further declare that they have not submitted this thesis at any other institution to obtain a degree.

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ABSTRACT

Cloud VR/AR/MR (Virtual Reality, Augmented Reality, and Mixed Reality) services represent a high-level architecture that combines large scale computer resources in a data-center structure style set up to render VR/AR/MR services using a combination of very high bandwidth, ultra-low latency, high throughput, latest 5G (5th Generation) mobile networks to the end users.

VR refers to a three-dimensional computer-generated virtual environment made up of computers, which can be explored by people for real time interaction. AR amplifies human perception of the real world through overlapping of computer-generated graphics or interactive data on a real-world image for enhanced experience.

According to the Virtual Reality Society's account of the history of VR, it started from the 360-degree murals from the nineteenth century [18]. Historically, live application of AR was displayed when Myron Kruger used a combination of video cameras and projector in an interactive environment in 1974. In 1998, AR was put into live display with the casting of a virtual yellow line marker during an NFL game. However, personal, and commercial use of VR/AR was made possible starting with release of a DIY (Do it Yourself) headset called Google Cardboard in 2014 by Google, which made use of a smartphone for the VR experience. In 2014, Samsung also introduced Gear VR which officially started the competition for VR devices. Subsequently In 2014, Facebook acquired Oculus VR with the major aim of dominating the high-end spectrum of VR headset [18]. Furthermore, wider adoption of AR became enhanced with the introduction of Apple's ARKit (Augmented Reality Kit) which serves as a development framework for AR applications for iPhones and iPads [18].

The first application of VR devices in the health industry was made possible due to health workers' need to visualize complex medical data during surgery and planning of surgery in 1994. Since then, commercial production of VR devices and availability of advanced network and faster broadband have increased the adoption of VR services in the healthcare industry especially in planning of surgery and during surgery itself [16]. Overall, the wide availability of VR/AR terminals, displays, controllers, development kits, advanced network, and robust bandwidth have contributed to making VR and AR services to be of valuable and important technologies in the area of digital entertainment, information, games, health, military and so on. However, the solutions or services needed for the technology required an advanced processing platform which in most cases is not cost efficient in single-use scenarios.

The kind of devices, hardware, software required for the processing and presentation of immersive experiences is often expensive and dedicated to the current application itself. Technological improvement in realism and immersion means increase in cost of ownership which often affected cost-benefit consideration, leading to slower adoption of the VR services [14] [15]. This is what has led to development of cloud VR services, a form of data-center based system, which serves as a means of providing VR services to end users from the cloud anywhere in the world, using its fast and stable transport networks. The content of the VR is stored in the cloud, after which the output in form of audio-visuals is coded and compressed using suitable encoding technology, and thereafter transmitted to the terminals. The industry-wide acceptance of the cloud VR services, and technology has made available access to pay-per-use-basis and hence access to high processing capability offered, which is used in presenting a more immersive, imaginative, and interactive experience to end users [11] [12]. However, cloud VR services has a major challenge in form of network latency introduced from cloud rendering down to the display terminal itself. This is most often caused by other performance indicators such as network bandwidth, coding technology, RTT (Return Trip Time) and so on [19]. This is the major problem which this thesis is set to find out.

The research methodology used was a combination of empirical and experimental method, using quantitative approach as it entails the generation of data in quantitative form available for quantitative analysis. The research questions are:

Research Question 1 (RQ1): What are the latency related performance indicators of networked immersive media in mobile health applications?

Research Question 2 (RQ2): What are the suitable network structures to achieve an efficient low latency VR health application?

The answers gotten from the result analysis at the end of the simulation, show that bandwidth, frame rate, and resolution are very crucial performance indicator to achieve the optimal latency required for hitch-free cloud VR user experience, while the importance of other indicators such as resolution and coding standard cannot be overemphasized. Combination of edge and cloud architecture also proved to more efficient and effective for the achievement of a low-latency cloud VR application functionality.

Conclusively, the answer to research question one was that, the latency related performance indicators of networked immersive media in mobile health applications are bandwidth, frame rate, resolution, coding technology. For research question two, suitable network structures includes edge network, cloud network and combination of cloud and edge network, but in order to achieve an optimally low-latency network for cloud VR mobile health application in education, combination of edge and cloud network architecture is recommended.

Keywords:
Performance Assessment, Networked Immersive Media, Cloud Virtual Reality, Cloud Network, Edge Network.

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My acknowledgement would be incomplete without appreciating the man who long ago prepared the pathway for me and laid the foundation for all my achievements to this point, my late father, Johnson Ola Adebayo, I missed you Dad, continue to rest in peace Dad.

To cap it all, to God be the glory, who has been my strong and everlasting pillar and a place of refuge for me, and who has helped and given me the strength to complete this work. Thank you, Jesus.

DEDICATION

To my Dad and Mum, Late Presiding Elder Johnson Ola Adebayo (of blessed memory), and Deaconess Florence Olufunmilayo Adebayo, without whom I would not be where I am today.

To Jesus Christ, my strong pillar, and a place of refuge throughout the years.

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Abbreviations

AR	Augmented Reality
VR	Virtual Reality
MR	Mixed Reality
ATW	Asynchronous Time Warp
CDN	Content Delivery Network
CPU	Central Procession Unit
DASH	Dynamic Adaptive Streaming Over http
FOV	Field of View
GPU	Graphic Processing Unit
HMD	Head Mounted Display
IaaS	Infrastructure as a Service
IoT	Internet of Things
MTP	Motion to Photon
STB	Set Top Box
DIY	Do it Yourself
DoF	Degree of Freedom
ARKit	Augmented Reality Kit
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
5G	5^{th} Generation
RTT	Round Trip Time
NS	Network Simulator Tools
TCP	Transport Control Protocol
UDP	User Datagram Protocol
MDN	Media Delivery Network
SDN	Software Defined Networking

CDB	Cloud Database
GCC	GNU Compiler Collection
FPS	Frame Per Second
OSI	Open System Interconnection

1 INTRODUCTION

1.1 Introduction to Virtual Reality Services

Cloud VR/AR/MR (Virtual Reality, Augmented Reality, and Mixed Reality) services, referred to as networked immersive media, represent a high-level architecture that combines large scale computer resources in a data-center structure style set up to render VR/AR/MR services using a combination of very high bandwidth, ultra-low latency, high throughput, latest 5G (5th Generation) mobile network to the end users.

Historically, the first idea about VR was mentioned by Ivan Sutherland in 1965 through his paper titled “The Ultimate Display”. In 1962, Morton Heilig developed Sensorama which he described as the cinema of the future [26]. A live application of AR was displayed when Myron Kruger used a combination of video cameras and projector in an interactive environment in 1974. In 1998, AR was put into live display with the casting of a virtual yellow line marker during an NFL game. However, personal, and commercial use of VR/AR was made possible starting with release of a DIY (Do it Yourself) headset called Google Cardboard in 2014 by Google, which made use of a smartphone for the VR experience. In 2014, Samsung also introduced Gear VR which officially started the competition for VR devices. Subsequently, in 2014, Facebook acquired Oculus VR with the major aim of dominating the high-end spectrum of VR headset [18]. Furthermore, wider adoption of AR became enhanced with the introduction of Apple’s ARKit (Augmented Reality Kit) which serves as a development framework for AR applications for iPhones and iPads [18].

The first application of VR devices in the health industry was made possible due to health workers’ need to visualize complex medical data during surgery and planning of surgery in 1994. Since then, commercial production of VR devices and availability of advanced network and faster broadband have increased the adoption of VR services in the healthcare industry, especially, in planning of surgery and during surgery itself [16].

Overall, the wide availability of VR/AR terminals, displays, controllers, development kits, advanced network, and robust bandwidth have contributed to making VR and AR services to be of valuable and important technologies in digital entertainment, information, games, health, military and so on. However, the solutions or services needed for the technology required an advanced processing platform which in most cases is not cost efficient in single-use scenarios. The kind of devices, hardware, software required for the processing and presentation of immersive experiences is often expensive and dedicated to the current application itself. Technological improvement in realism and immersion means increase in cost of ownership which often affected cost-benefit consideration, leading to slower adoption of the VR services [14] [15]. This is what has led to development of cloud VR services, a form of datacenter-based system, which serves as a means of providing VR services to end users from the cloud anywhere in the world, using its fast and stable transport networks. The content of the VR is stored in the cloud, after which the output in form of audio-visuals is coded and compressed using suitable encoding technology, and thereafter transmitted to the terminals. The industry-wide acceptance of the cloud VR services, and technology has made available access to pay-per-use-basis and hence access to high processing capability offered, which is used in presenting a more immersive, imaginative, and interactive experience to end users [11] [12].

However, cloud VR services have a major challenge which is network latency introduced from cloud rendering down to the display terminal itself. This is most often caused by other performance indicators such as network bandwidth, coding technology, RTT (Return Trip Time) and so on [19].

1.2 Background Facts

In recent years, technological innovation, and advancement in quality of content has led to creation of new solutions offering more immersive experiences to both consumer and businesses. Increase in demand for VR services and applications in healthcare services and other industries has come to a point where there is limitation to scaling of the existing solution and hence the need for new approaches for VR service delivery.

There are two general forms of VRs, the omnidirectional which uses a phenomenon whereby special camera with microphone rig is used to capture natural scene, comparable to a traditional TV system having an unrestricted viewing arc, and computer generated/synthetic video that uses computer modelling and algorithm to create an artificial view using the current user gestures and other input stimuli [13]. "Cloud" refers to an on-demand availability of computer system resources which allow access to a combination of general and specific computing services, on a pay-as-you-go-basis. It gives access to any form of storage or compute request made by user of such services. Earlier cloud deployment of VR services in healthcare related industries built all the storage, network, and compute resources into a centralized data center, but cloud VR demands for very high-capacity network services with low latency and high bandwidth has given rise to combination of both cloud and edge computing by moving resources closer to the edge of the network. This works together with other core network resources to implement and complete a given task. By so doing, the latency challenges associated with cloud VR services are reduced [19]. other core network resources to implement and complete a given task. By so doing, the latency challenges associated with cloud VR services are reduced [19].

In healthcare and other industries, the applied cloud VR/AR/MR terminal devices such as display screen, speakers, vision positioning, and hand controller sensors use "thin client" architecture (building minimal functions into the client terminal). Whereas earlier traditional VR/AR/MR terminal devices use "thick client" which builds all the processing functions into the client terminal, with content retrieval from local storage or retrieval of streams of data from network services for processing by the terminal [15]. The emergence of thin client architecture has led to increasing application of VR in the healthcare, such as surgical simulation of actual real live surgery in the training of new surgeons, leading to reduction of error incidence in real life scenario. Other uses are in human anatomy, patient rehabilitation, and medical education [20].

Nevertheless, despite its plethora of usefulness in healthcare, cloud VR is not devoid of its challenges such as motion sickness, expensive computing devices, and most importantly dizziness associated with latency related performance indicators of cloud VR [21].

Since its historical usage in private and specialized flight simulators, military head-up displays [22], VR have evolved into usage in both the consumer and enterprise systems. This has resulted in essential needs to implement new approaches for servicing the VR applications, which would lead to increase in efficiency and effectiveness, as well as higher quality of experience in terms of user immersion, interaction, and imagination [1] [2] [3].

1.2.1 Key challenges of today's AR/VR services

Market research into the ecosystem of VR/AR services by Goldman Sachs Group shows that they have made progressive in-road into the consumer and enterprise domains over the last few years based on the investment, adoption and popularity of VR application services are in videogames, live events, live ticket sales, video entertainment in online streaming, retail in e-commerce, education in k-12 (Kindergarten to 12th grade) and higher-education software, healthcare in patient monitoring, healing and surgery, engineering in CAD/CAM (Computer aided Design, Computer-aided Manufacturing) software, real estate and military in defense training and simulation [11] [12]. However, VR technology adoption is hindered due to the following:

1. Expensive equipment such as terminal client (VR HMD, Head Mounted Display) and data source computing cost. This has limited the total number of people with access to required hardware to use VR services.
2. Display resolution and visual quality implies low visual experience which reduces the level of immersion and realism.
3. Reduced mobility means less usability, since the VR HMD are physically wired to the computing device which restricts freedom of movement. Need to constantly recharge VR devices with local wireless solution also implies reduction of operational usage apart from the complexity introduced.

1.2.2 Deployment of Cloud AR/VR and Requirements

To solve the problems associated with full VR adoption, this has led to the emergence of Cloud VR/AR services by transferring processing capability from the local terminal into the cloud with low latency, high bandwidth and state-of-the-art compute, network, and storage.

VR experience can be categorized into 3DoF (3 Degree of Freedom) and 6DoF (3 Degree of Freedom) VR services. The 3DoF allows user rotational movement in the x, y and z plane which allows the user to look around from the same fixed viewing point. While 6DoF allows combination of rotational and translational movement in a space, which makes the user to freely explore the VR scene [13].

Cloud VR, therefore, implies dependency on the capability of the network and access to computational services for data rendering. Based on this, the cloud VR services are divided based on the form of business interaction, into weak interactive services and strong interactive services.

1. Weak-interaction VR services allow users to select the view and location without interacting with the virtual environment entities. These are composed of applications such as, VR video services, IMAX Theatre, 360° panoramic video, and VR live broadcast [11] [12].
2. Strong-interaction VR services allow users to interact with the virtual environment entities via interactive devices. These are composed of applications such as: VR games, VR home fitness, and VR social networking [11] [12].

1.2.3 Network Bandwidth and Latency Requirements

Using currently available data, a typical 4k video uses around 20 to 40 Mbps and approximately latency of 50ms. The advent of 5G has led to considerable improvement in the available bandwidth, which has led to reduction of latency to approximately 10ms [11] [12] [13] [15]. This gives a better user experience. More details of currently implemented cloud VR bandwidth and latency requirements are given in Table 1.1.

Table 1.1: Bandwidth and latency requirements for current cloud VR applications [11] [12] [13] [15].

Resolution	**Frame rate (fps)**	**Coding Technology**	**View**	**Bandwidth (Mbps)**	**Latency (ms)**
12k	120	H.266	Sphere	200-300	<= 10
12k	120	H.266	FOV	200-300	<= 10
8k	90	H.265	Sphere	90-130	<= 20
8k	90	H.265	FOV	30-50	<= 20
4k	60	H.264	Sphere	20-40	<= 50

1.2.4 Service Architecture

A typical cloud VR is composed of 2 layers. The central node and the edge node. The central node takes care of the control plane and management plane function of the 5G network. While the edge node takes care of the user plane function as well as the edge computing platform function [11] [12] [15].

1.2.5 Technical Requirements

Cloud VR services consumes a lot of bandwidth and require a very low latency. High latency would hinder user experience, immersion, and interaction which would often lead to dizziness. Hence, it is very important to ensure that the MTP (Motion-To-Photon) latency is less than 20ms to maintain a high-quality image rendering. Some of the steps taken to ensure low latency are terminal-cloud asynchronous rendering, low-latency encoding and decoding optimization, and service assurance with network slicing [11] [12] [15].

Due to bandwidth requirements, only the latency requirements in weak and moderately strong-interaction scenarios have been met in actual applications, while only the weak interaction services are commercially available [11] [12].

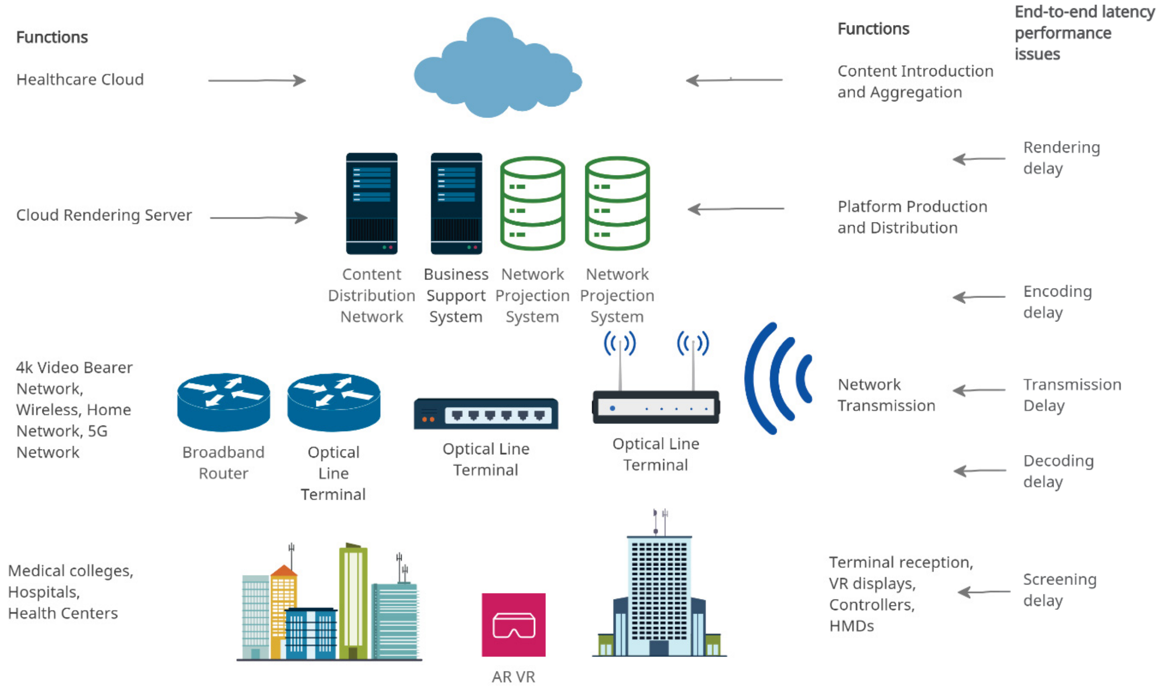


Figure 1.1: Cloud VR healthcare application network architecture use case diagram [11][12].

Cloud VR in its generality suffers from latency related performance issues. As shown in Figure 1.1, end-to-end latency is a major challenge which affects the experience and performance of cloud VR services including healthcare applications. The latency issue often arises from delay associated with rendering servers, encoding, transmission, decoding and display. These delays are categorized into:

1. MTP (Motion to Photon) delay (Attitude capture, secondary rendering and asynchronous timewarp).
2. Cloud rendering and streaming latency (Uplink transmission, logical calculation, real time rendering, encoding, downlink transmission, decoding).

The sum of all the delays constitutes operational or end-to-end latency.

1.3 Description of Problem to address and Research Focus

As stated in the identification of gap in existing work, it has been proven that latency is one of the key determinants of the three important factors affecting cloud VR experience which are immersion, interaction, and imagination. However, there have been very few existing studies on latency related performances, in relation to cloud VR health applications. This could have contributed to low adoption, acceptability, and investment in cloud VR services especially in health applications [12].

The existence of the development of modern VR surgical applications could be traced back to the 1980s, where robots were developed to perform human tasks in hostile and harmful environment such as nuclear plant, war front and seabed, where the use of helmet fixed with specialized tracking devices, 3D displays, and fiber optic glove, made it possible to teleport the wearer into an immersive environment and control the robots to perform given tasks in a safe and efficient manner. The concept of future surgeons was developed by University of North Carolina and the US Department of Defense in the 1990s. The robotic surgeons were equipped with VR headsets and programmed with robotic algorithms using advanced computer-generated images [17].

Some of the major application areas where virtual, augmented, and mixed reality services have been in operation in the general health industry are virtual surgery, planning of operation, diagnosis, physical therapy, education and training, treatment of mental illness to mention but a few [3] [4] [5] [6] [7].

Despite being one of the popular and acceptable VR services in demand by users, yet health related VR services are not as renowned as its counterparts like video and game VR services [11] [12]. Given that good health is number one priority of an average human being, and the fact that the importance and value of VR implementation in health application, in terms of making available innovative ways towards providing solutions to health issues, along with potential to achieve almost 100% efficiency in health-related treatment cannot be overemphasized, we have decided to streamline my research into the health VR application.

Hence, by this work, we intend to research the latency related performance of immersive media applications and the most suited network deployment strategy to achieve the optimum experience for users.

1.3.1 Aims and objectives

The aims and objective of this research work are:

By the above objectives, I intend to explore the performance of VR health applications with emphasis on the latency related indicators that affects cloud VR health applications efficient user experience in combination with the identified latency related indicators.

1.3.2 Research questions and hypotheses

Based on the goal of assessing the performance of networked immersive media in mobile health applications with focus on latency related performance, we have created and tailored two complimentary research questions (RQ) as specified below:

Research Question 1 (RQ1): What are the latency related performance indicators of networked immersive media in mobile health applications?

Research Question 2 (RQ2): What are suitable network structures to achieve an efficient low latency VR health application?

2 RELATED WORK

2.1 Discussion of Existing Work in Relation to Research Work

There has been multiple work done in relation to VR in area of healthcare education and with respect to its performance evaluation. The following related work were sourced using the data collection process section, of the research methodology employed for this work.

This includes Sebastian et al. [27] developed an AR application tool for transfer of knowledge between physician and the patient based on the difficulties associated with transfer of information about pathology and treatment to patience from their physicians, where they aim to determine the usability for purpose of the application.

In their work, Panteleimon et al. [28] detailed the history of VR in medicine along with driving principles of their functionality, where they presented the implementation of the found methods in medical trainings.

In the work of Viglialoro et al. [29] the hybrid application of AR and MR in healthcare simulation were reviewed. The study found that most of the existing studies did not make use of enough sample size and that only feasibility assessment and preliminary validation were done, hence the need for further research for validation and verification of the performance of the existing simulators.

In their work on AVR in education and the field of medicine by Mayowa et al. [30], the study established that application of AVR has great potential to make learning much easier, practical, and interesting due to its real time interaction between the users and the application. It also shows that AR in medicine has increased innovations towards improvement in diagnoses, learning, and treatment in healthcare. The study summarized that AR has the potentials that can be adopted in education and medicinal practices.

Another study on virtual technology and surgical training, conducted by Sarah et al. [31] gives an overview of effectiveness of surgical training in VR, where they developed a new training method to reduce cost of training and improve speed and efficiency of learning using VR, with its attendant wide application field. It established that the efficiency of the old training methods is questionable and very expensive, other training models were also found to be controversial and non-realistic.

Herpich et al. [32] work on how mobile AR is applied in education presented areas in which it has been applied. It was noted that there was very high interest in the application of AR in education from 2013 to 2017. It further showed that there was no standard agreed upon as regards platform, rather such requirement is defined based on the development team's expertise.

An et al. [33] compared the performance of an immersive VR and traditional desktop game, which was a system design to teach US Army on how to communicate well with Chinese army in a future joint humanitarian mission. The study concluded that there was no difference in performance between immersive VR and traditional desktop game, and that there was a strong positive interaction between gender and participants of the game.

In his systematic review, Prasanna [34] worked on the effectiveness of VR based immersive training for education of health professionals. It was established that VR simulators are a useful tool to improve clinical performance. It also leads to additional experience which is useful in real life treatment scenarios.

In his work, to investigate interaction metaphors for AR and VR on multiplatform for medical applications, Manisha [35] concluded that these applications can be of use in biomedical trainings for students in a college or healthcare institutions to serve as complement for the usual theoretical studies.

Orraryd [36] research work to explore the potential use of AR in medical education, it was concluded that VR would, on the long run replace the traditional desktop, though some improvements are still required to achieve this.

Also, Dorota et al. [37] research on VR and its application in education presented an overview of the trend, opportunity, and concerns of VR in different education areas including healthcare. Methods for VR scenarios, testing and validation were presented.

Visha [38] also worked on the application of innovative virtual world technologies to enhance healthcare education. He was able to demonstrate that the virtual world environment provides an alternate and very efficient educational platform for healthcare industries.

Maura and Nina [39] in their work on perspectives of XR in nursing found that previous work on XR in nursing was either not researched enough or conducted using systematic review. They also noted that available research work does not represent evidence-based approach or do not cover XR totally.

In his work on the effectiveness of an AR training paradigm, Brian [40] established that AR is a viable medium for transfer of knowledge in an effective and efficient manner.

Likewise, Kaplan et al. [41] in their meta-analysis, were able to collect evidence which confirmed the usefulness of virtual, augmented, and mixed reality as training enhancement methods.

Nesenbergs et al. [42] systematic review of the use of AR and VR in remote higher education concluded that both have a very high positive impact on earning outcomes, performance, and student engagements right from course preparation up to evaluation and grading.

Sankalp [43] developed two training modules for patient rehabilitation using VR technology. This was done as a solution to challenges faced in coaching patients in following rehabilitation program correctly and timely after surgery. It was shown that patient assessment, coaching and tacking of progress can be done efficiently using the VR module.

Mohd and Abid [44] in their article, VR applications towards medical field established that health professionals apply the technology for training, diagnosis, and treatment in emergency situations.

Anderson et al. [45] also depict the usefulness of VR in healthcare, specifically in interventional radiology. They developed a personal computer-based system *"for simulation of image-guided cardiovascular interventional procedures for physician and technician training, education, patient- specific pretreatment planning, and therapeutic device design and evaluation"* [45].

De Boer [46] worked on validation of a VR environment, as innovation in dental education, where they address the *"uncertainty between evidence-based and non-evidence-based conditions"*. This was in relation to simultaneous development, implementation, and evidence collection during the development of an innovation such as VR for dental education. It was established that using *"on-the-fly approach for development, implementation and collection of* *evidence for VR innovation in an academic environment appears feasible in serving both the professional, users and developers and system designers"*.

Peng [47] also concluded that virtual reality technology is efficient tool to enhance quality of treatment for emergency healthcare.

The implication of this related works is that, while there have been many works done in the areas of cloud VR application in healthcare, many of them serving as a necessary guide for this work. However, no specific work has been done as it pertains to latency measurements and its key performance indicators.

3 RESEARCH METHOD

3.1 Research Questions and Motivation

Based on the goal of assessing the performance of networked immersive media in mobile health applications with focus on latency related performance, We have created and tailored two complimentary research questions (RQ) as specified under the introductory section in chapter one of this work.

With the first research question, we seek to have a deep insight and find out how latency related performance indicators affect user experience in terms of their interaction, immersion, imagination, and fulfilment while using cloud VR healthcare applications. This is because one of the identified biggest challenges associated with large scale adoption of cloud VR in health care and generally is delay introduced at each processing point, from the home network, access network and cloud rendering servers. This is known to constitute dizziness and nausea and other associated cloud VR sickness, leading to very low user experience and little acceptance.

Following closely the above, the second research question will seek to identify the most efficient network architecture, in terms of edge, cloud or combination of both required to reduce delays associated with latency related performance issues to the minimum.

To answer the research question, the hypothesis below has been formulated:

H0: Null Hypothesis

Delays caused by bandwidth, RTT, bit rate, resolution, coding standard and view angle are the most important latency related performance indicators of networked immersive media in mobile health applications.

H1: Alternative Hypothesis

Delays caused by bandwidth, RTT, bit rate, resolution, coding standard and view angle are not the most important latency related performance indicators of networked immersive media in mobile health applications.

3.2 Method

The research methodology employed is a combination of empirical and experimental method, where we will seek to document activities as regards the research goals, identification of key factors behind the research topic by direct and indirect observation, and by finding out current activities, seeking for new insights and idea generation for new research.

We have chosen a quantitative approach as a research method of choice because it entails the generation of data in quantitative form available for quantitative analysis. For example, experimental method which is an example of quantitative research method gives much control of the research environment whereby, we will have control of some set of variables to observe what their effect is on other variables. Qualitative approach, on the other hand, deals more with phenomena which has to do with subjective assessment of opinions, attitudes, and behavior. This has more to do with eventual research insight and overall impressions. This type of research results is in a form which has not been subjected to quantitative analysis. This type of approach is not considered as the best option for my current project which deals with collection of data in a quantitative form. Table 3.1 contains a summary of comparison between empirical research methods.

Table 3.1: Comparison between empirical research methods.

Method	Primary Purpose	Primary Data	Design Type
Survey	Descriptive	Quantitative	Fixed
Experiment	Explanatory	Qualitative	Fixed
Case Study	Explanatory	Qualitative/Quantitative	Flexible

Another quantitative research method would have been to use survey or case study method. The survey method could not be applied due to its primary purpose of being a descriptive type of research methodology, survey typically deals with retrospective study of a situation in order to record relationship and outcomes. Although it has the attributes of being used to seek patterns in data and generalize to a wider population, yet it differs from the objective of this research work in the first instance not being a retrospective study, and in the second instance being a controlled investigation of an activity meant to identify, manipulate, and document important factors of the activities.

While the case study method, being an empirical investigation of a specific subject, and which could either be a qualitative or quantitative method, it does not fit for this research because it has a low level of control and replication, and the high difficulty of control and cost of replication. It also suffers from being able to generalize. Whereas an ideal research method for my research requires one with it a high level of control and replication, along with a low difficulty of control and cost of replication, which are essential characteristics of experimental method. This is depicted in Table 3.2.

Table 3.2: Comparison between empirical research methods.

Factor	Experiment	Case Study
Level of control	High	Low
Difficulty of control	Low	High
Level of replication	High	Low
Cost of replication	Low	High
Generalization	Yes	No

3.3 Data Collection Process

The process of data collection and research design was carried out as depicted in Figure 3.1.

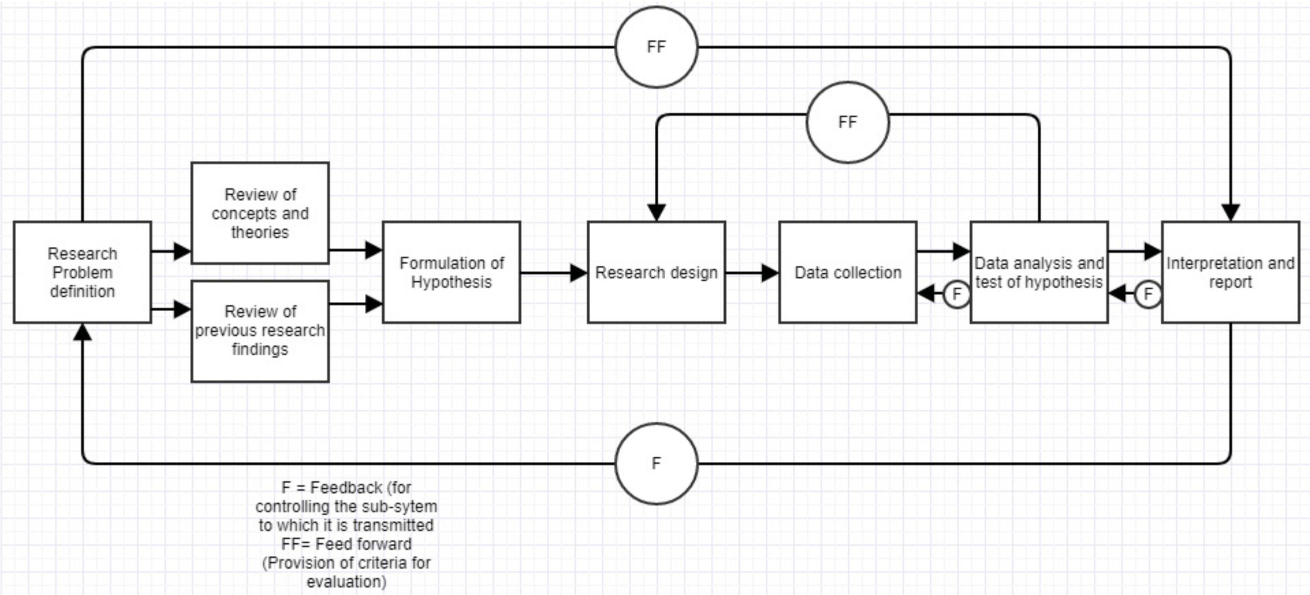


Figure 3.1: Flowchart of research phases [26].

Due to time constraint, a literature mapping study was conducted where focus was placed on the characteristics pertaining to place of research, source of fund, publishing journal or other medium. The mapping was premised on the concept that published papers represent both the findings and the activities relating to the findings. This was followed by qualitative analysis of the existing work.

The qualitative analysis entailed data compilation and segmentation of the important aspects of the current applications. The data compilation comprised use case identification, adoption benefit and challenges, current capabilities, and research.

Data segmentation was done to separate the compiled data into limitations, benefits, and areas in need of further development. After this, a quantitative analysis based on the segmented data was done. This involved simulation of different scenarios using different simulation setup based on the identified latency related performance indicators and network types. This was followed by results collection, presentation, and analysis. After this, final conclusions were made as regards answers to the research questions

3.3.1 Literature Review Method

Data Sources and Search Strategy

The literature review was conducted using three main phases, following guidelines provided by Kitchenham and Charters' [23]. This is shown in Figure 3.2.

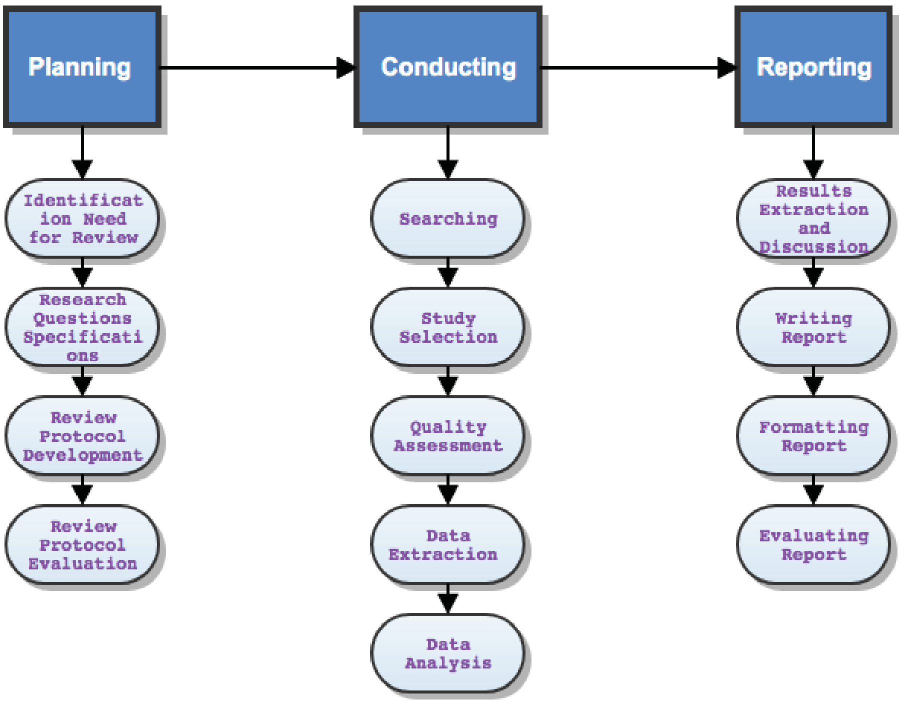


Figure 3.2: Phases of literature review [23].

We chose certain keywords along with search strings creation, then we make specification for search space and process to reduce the total number of papers. In the first process, we pull out some keywords from our study selection and then match with our stated research objectives. In the second process, we obtained likely and alternate words for the keywords, and we also optimize the keywords in an iterative manner. By this way, we were able to define a set of search keyword, searched for them in the chosen databases, then we made a final refinement. The search strings are:

"Performance assessment", "networked immersive media", "cloud virtual reality", "mobile health applications", "Latency", "key performance indicators ", "edge network", "cloud network", "network architecture".

Thereafter, these keywords were concatenated using Boolean *or* operator. The final design of our search string is of the form below. After this, a search strategy following the methodology provided in the Figure 3.3 was followed.

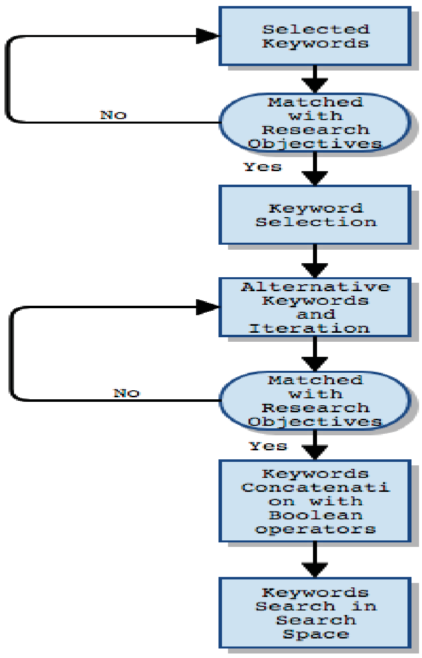


Figure 3.3: Search strategy [26].

The following strategy was followed to reduce search results:

1. Usage of full search string
2. Application of search strategy
3. Application of selection criteria
4. Manual title search
5. Manual abstract search
6. Manual content search
7. Snowballing (Repeat of 1-6 n number of times) using both forward snowballing (search the paper that cited the paper) and backward snowballing (search the paper reference list). This is shown in Figure 3.4.

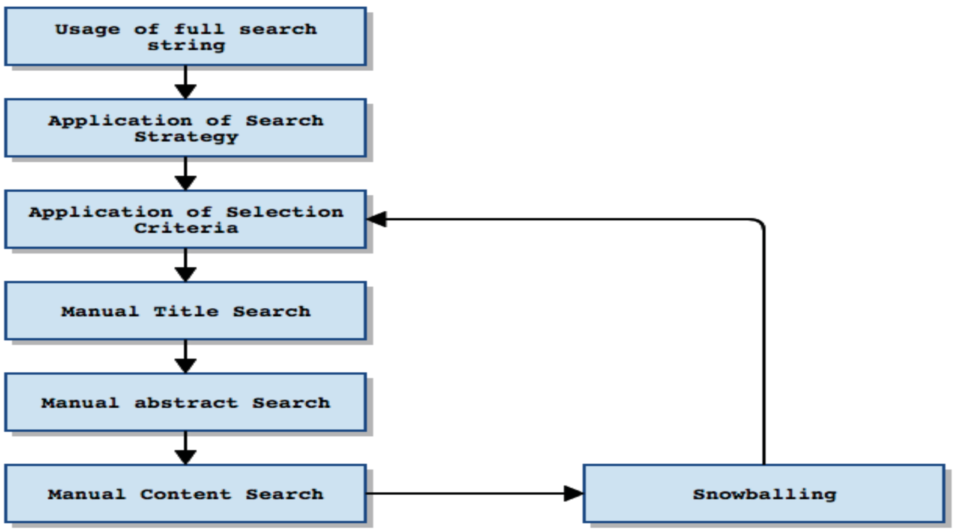


Figure 3.4: Search reduction strategy [26].

3.3.2 Study Selection

3.3.2.1 Inclusion Criteria

The inclusion was based on papers that were written in English, publication dates from 1995until date, papers about VR, AR, MR, cloud VR, networked immersive media, papers related to "Networked Immersive Media in Mobile Health Applications with Emphasis on Latency Related Performance", and papers associated with "Performance Assessment of Networked Immersive Media".

3.3.2.2 Exclusion Criteria

These are papers and studies with incomplete text, studies not related or focused on VR, AR, or MR, papers that only present ideas and recommendation, papers which deliberate on applications without in-depth analysis of the underlying methods and tools.

3.3.3 Data Extraction

3.3.3.1 Theory triangulation

By using alternative theories (study of work artifacts) or viewpoints documents.

1. **Data Extraction:** A form for data extraction was set up based on the guidelines provided by Kitchenham and Charters' [23], using excel sheet.
2. **Basic Information:** Title, authors, publication date, digital object identifier (DOI) and universal resource locator (URL).
3. **Publication data:** Such as Journal, Conference and dates, publisher, volume, pages, keywords, and abstracts.

3.3.4 Process for Data Analysis

3.3.4.1 Existing Theory Data Analysis

This was done using qualitative analysis that is thematic analysis [25], whose steps are familiarizing with data: by reading and examination of the research items to form the initial ideas for analysis.

1. Generating initial codes
2. Searching for themes
3. Reviewing and refining themes
4. Defining and naming themes

3.3.5 Data Synthesis

A data extraction form was separated into both demographic and contextual attributes, followed by employment of descriptive statistics for analysis of

1. The Research method: for example. experiment, quasi-experiment, lessons learnt
2. Case study, opinion survey or tertiary study
3. Research approach: deductive, inductive or hybrid
4. Short summary
5. Results and contributions
6. Personal assessment
7. Number of included references
8. Number of papers that cited the study

This was followed by classification into six research types which are validation research, evaluation research, solution proposal, philosophical paper, opinion paper, and experience report [24].

By following the method for data collection and research design as detailed, we have a high confidence of being able to achieve the aim of this research work based on getting quality data for processing and analysis.

4 RESULTS AND ANALYSIS

4.1 Result Background

4.1.1 The Network Simulation Tool

A network simulation tool models the behavior of a real time network through the computation of different interaction that takes place between each of the network devices. To simulate the Cloud VR network, there was need to select a network simulation tool which fulfils the criteria for our simulation. This functionality includes the ability to process data with a good degree of accuracy, reliability and speedily. We also require that the simulation tool can model especially the data link and transport layer of the Open System Interconnection (OS1) model.

The three different simulators which closely suit the criteria for a simulation tool are MATLAB, Omnet++ and the Network Simulator Tools (NS-3). Although MATLAB was our first choice due to its popularity and versatility, however, it was difficult to implement the Cloud VR functionality using the Simulink provided by it. NS-1 to 3 simulation tools, on the other hand, provides almost the same functionality as the Omnet++ tool, but a further research into how suitable they are for our research scenarios made Omnet++ a much more convenient simulation tool of choice. This is because of the availability of more Omnet++ documentation as compared to NS-1 to 3. This includes a very rich graphical user interface and the possibility for step-by-step debugging, measurement possibilities in form of graphs and implementation of easy drag and drop automated coding to minimize the coding complexity, and provision of a good network model for use.

4.1.2 Network Model

This refers to an abstraction of the major functions of a real time device or interconnected entities. To make the simulation implementation task easier, we made use of a set of models called frameworks made available within the Omnet++. The frameworks emulate each node almost as it is in real life using event driven engine and models which depicts the processes when an event is triggered. This has the capability to schedule one or multiple follow up events after the triggering of the first event.

Omnet++ provides a framework called INET with functions and capabilities for our intended criteria and scenarios [48]. This includes the basic application models such as Transport Control Protocol (TCP) and User Datagram Protocol (UDP), other Internet stack and mobility which are essential for the project’s simulation.

4.1.3 Description of Simulated Network Architecture

The network architecture use-case diagram in Figure 1.1 is used for the implementation of the simulated network. This is as described as follows:

1 **Content Layer:** This includes the content provider and aggregator who serves as funnel for provision of VR contents to the platform layer. It consists of the management system which provides operation personnel and media resources, and production system which performs slicing and transcoding functions of the video content to the outputting of the streams to the Media Delivery Network (MDN) system [11] [12].

2 **Platform Layer:** It consists of cloud rendering server for platform production and distribution of the content provided by the content layer [11] [12].

3 **Network Layer:** This consists of the 4k video bearer network, Wi-Fi home network and the 4G/5G network. This is responsible for providing a highly scaled network transmission with sufficiently low latency. For the simulation model as shown in Figure 1.1, the network has been flattened in order to minimise the risk associated with convergence [11] [12], this is what have also motivated the placement of devices on the network.

4 **Terminal Layer:** Its major function is the presentation of the VR content from the content provider, authentication of user and access to home network [11] [12].

4.1.3.1 Login Sequence

The login scenario is as follows:

The user initialize login from the terminal, upon authorization from the cloud VR service platform, the list of educational VR contents is presented to the terminal, while the terminal user selects a content of choice and begins to stream selected content. This is shown in Figure 4.2.

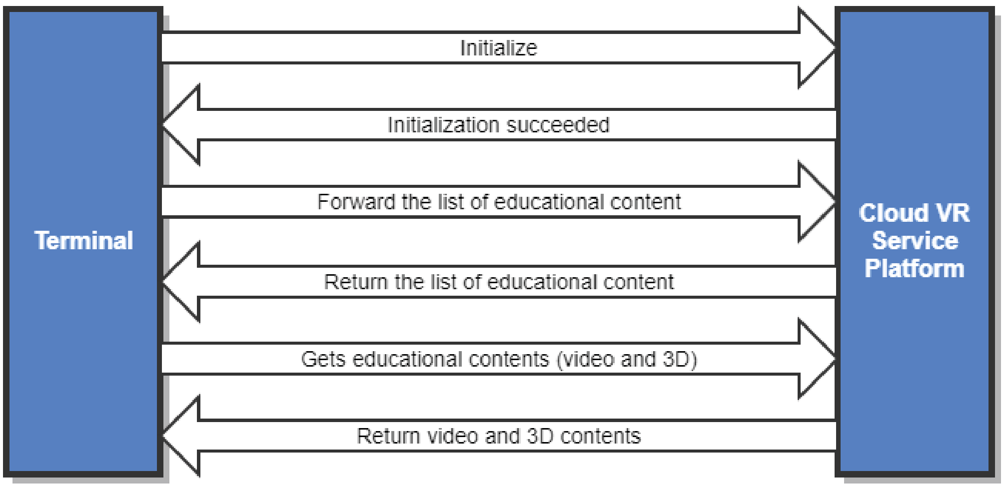


Figure 4.2: Interaction process between user interaction with terminal and login to the service platform [11] [12].

4.2 The Simulated Cloud VR Service Solution

The simulated Cloud VR service solution for transcoding, slicing and stream output consists of three major parts, which are the terminal, network layer and the platform layer that combinesthe core network and the content or distributing provider. This is shown in Figure 4.3.

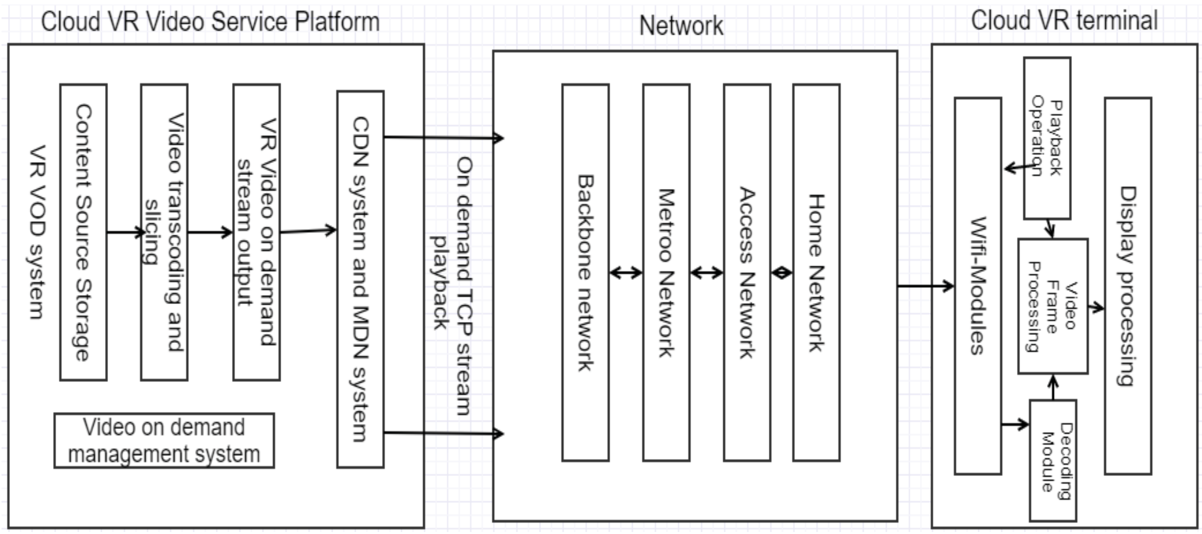


Figure 4.3: Simulated Cloud VR service solution processing [11].

4.3 Setup

4.3.1 Machine Specification

The experiment was performed on an Intel core i7 2.4Ghz system with 16GB RAM size, running Windows 10 Pro. We use Omnet++ Version 4.2.2 and compatible INET framework Version 2.2.0. The main simulation was conducted via the graphical user interface provided by the Omnet++ software.

4.3.2 Experimental layout

Figure 4.4 shows the diagramatic representation of the simulated network diagram as earlier described in previous sections. These were set up exactly as shown in the network architectural diagram in Figure 1.1.

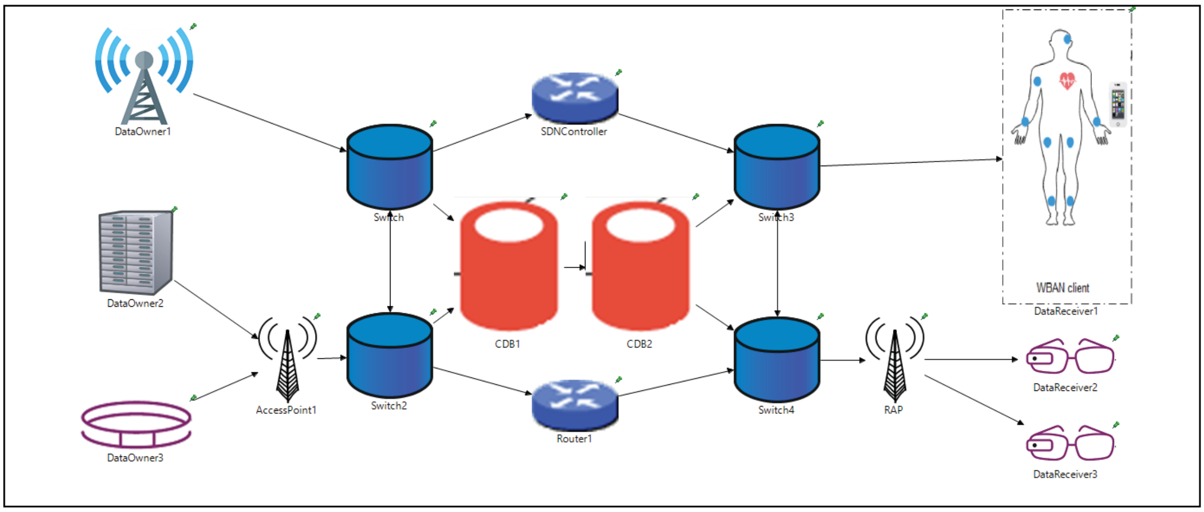


Figure 4.4: Diagramatic representation of the simulated cloud VR network diagram.

4.3.3 Description of Network Components and Functions in Relation to the Simulated Network Diagram

The data owners (1 , 2 and 3) were used to implement the content provider and distributor for the service platform, while the combination of switch, switch2, router1, SDN Controler, CDB (Cloud Database) and CDB2 implements the cloud and edge network functionality. The switch3, switch4, Remote Access Point (RAP) device implements the network layer and data receivers (1, 2 and 3) implements the Cloud VR terminals. We have specifically deployed data receiver1 to implement 3D visual of an anatomy teaching scenario in an educational setting.

4.3.4 Network Entities Simulation

The simulation was done through the combination of drag and drop featute provided by Omnet++ tool and additional coding using mostly C++ programming language. INET framework was used as a model to implement the 5G and broadband fucntionality of the network entities. The code setup, snippets and schematic for each segment of the simulation are explained further.

Generally, all the code implementations were executed in two separate C++ files and an header file, the main C++ file contains the main code implementation while the header file which are user defined and are used for input and output streams in the main code implementations.

In addition, the main C++ code were segmented into five different classes and methods which are referenced in such a way to achieve desired results. These are

1. **Initialize :** Used to assign an initial value for a data object or variable.
2. **Handle Message:** Used to implement how a message request is handled.
3. **Cipher:** Used to implement secrets.
4. **Encipher:** This converts messages into coded forms.
5. **Decipher:** This converts coded messages into its originally sent form.

These were combined with other private and public classes amd methods to complete the code implementation for each of the network devices, and their interaction.

4.3.5 Code Structure

The code snippets representation for each group of the network entities are presented in the Appendix.

4.3.6 Running the Simulated Codes and Measurements

The project was built in release mode with the aid of GCC (GNU Compiler Collection) compiler. We used a simulation time limit of 600 seconds for each build and running of the experiment. This was conducted for a total number of 20 times using a combination of different keys and timeouts. The keys and timeouts were hardcoded to impact the generated results measurements in form of the cloud performance indicators.

The simulation is run by running the generated .ini (initialization) file at the start of the code execution. A sample screenshot of the of the simulation is given in Figure 4.5 and 4.6.

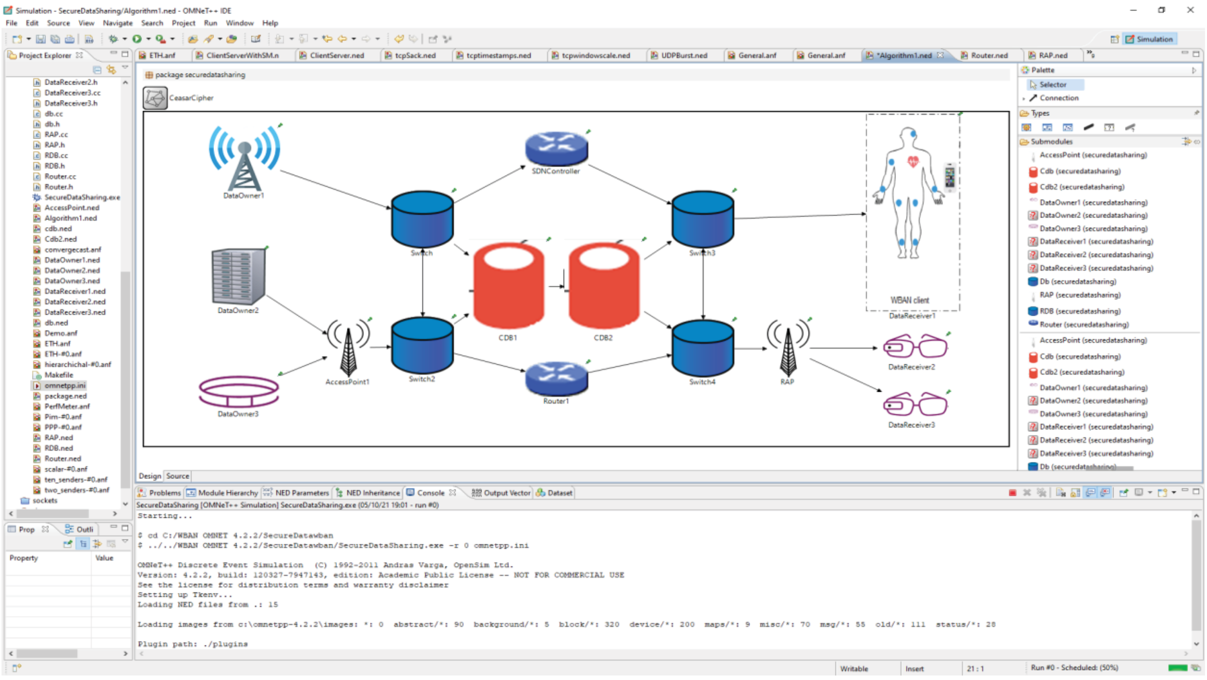


Figure 4.5: Sample simulation run A.

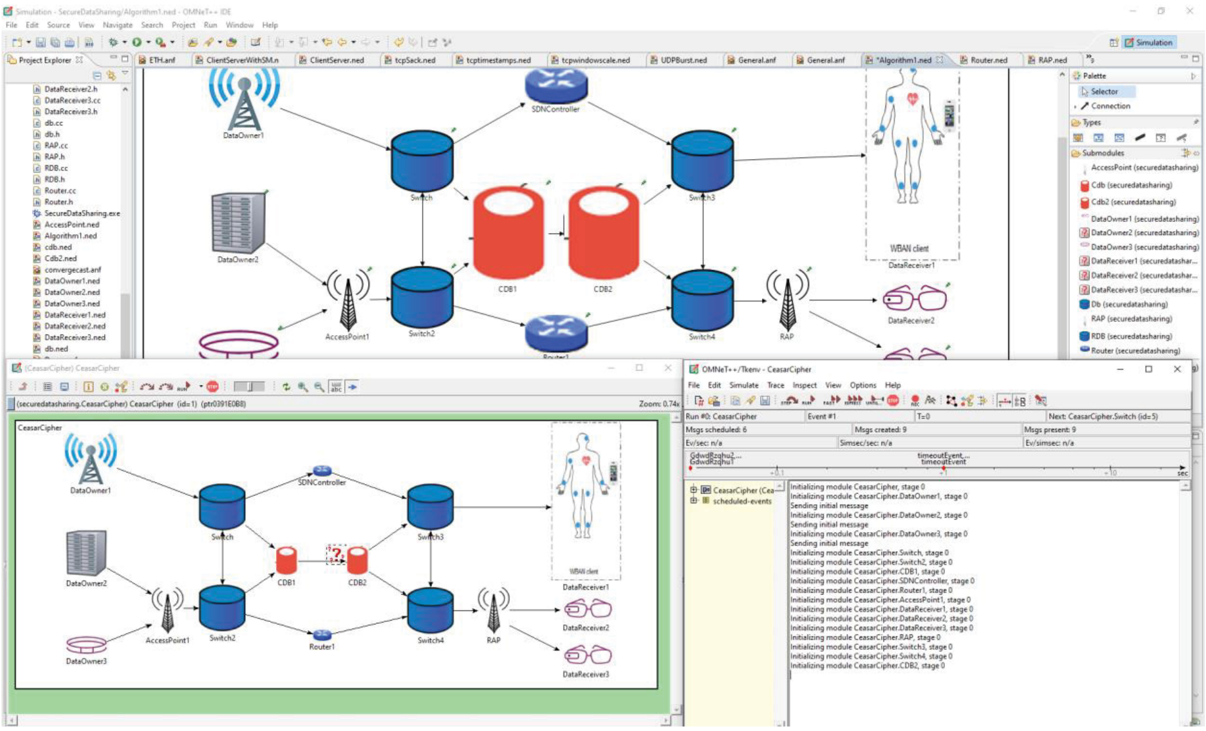


Figure 4.6: Sample simulation run B.

Examples of the generated event log files are shown in Figure 4.7, Figure 4.8 and Figure 4.9, while the collected result after each of the simulation are as shown in Figure 4.10, Figure 4.11 and Figure 4.12.

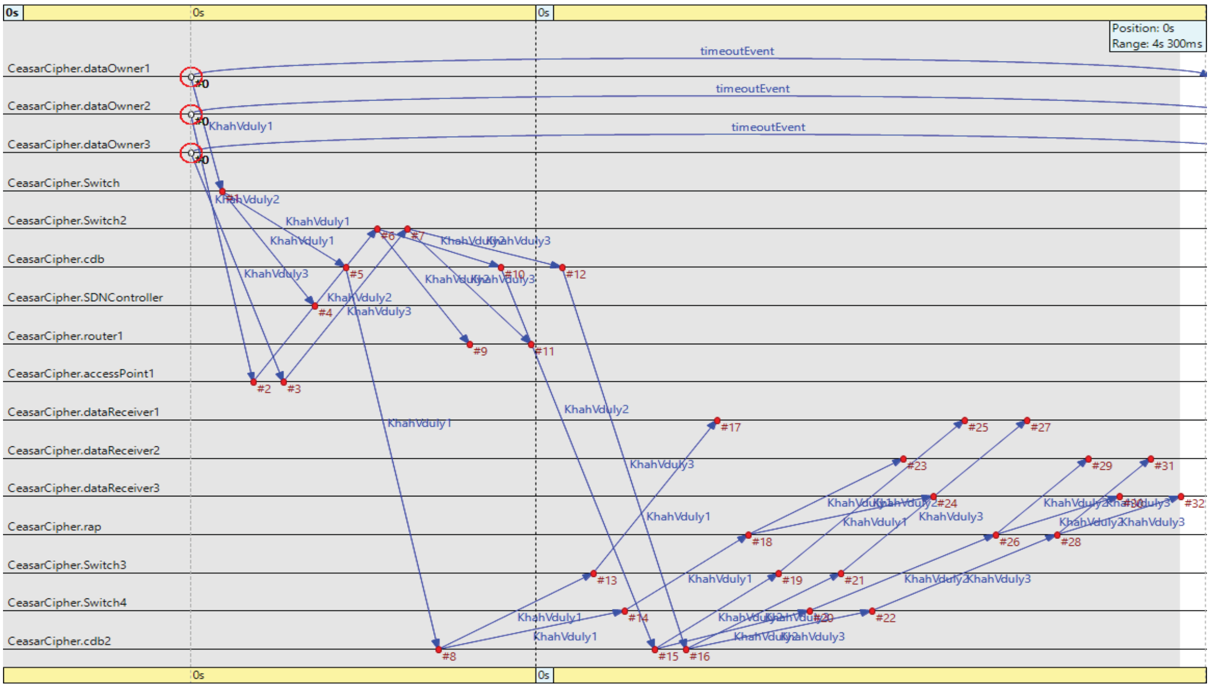


Figure 4.7: Event Log.

4.4 Analysis of Result

4.4.1 Event log file

The event log file in Figure 4.8 shows a detailed sequence of events and timing. It records simulation events such as creating and deleting messages, scheduling, and cancelling events, packet transmission changes in topology and display strings [48].

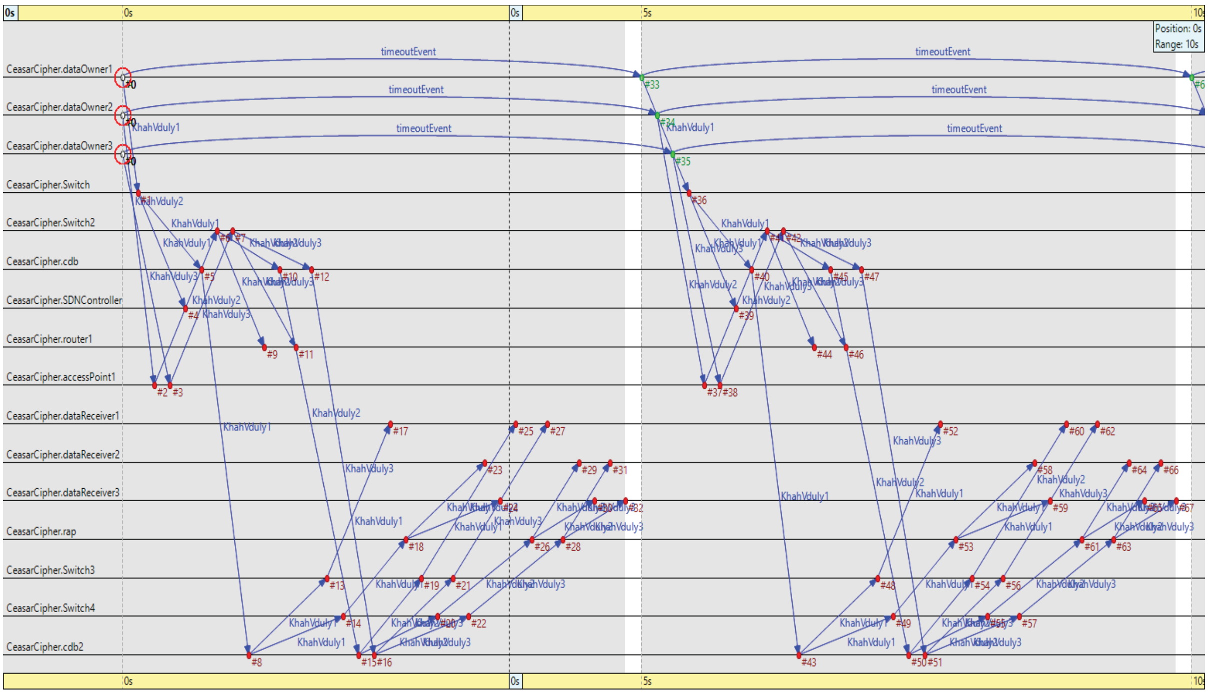


Figure 4.8: Event log file with increase in delay A.

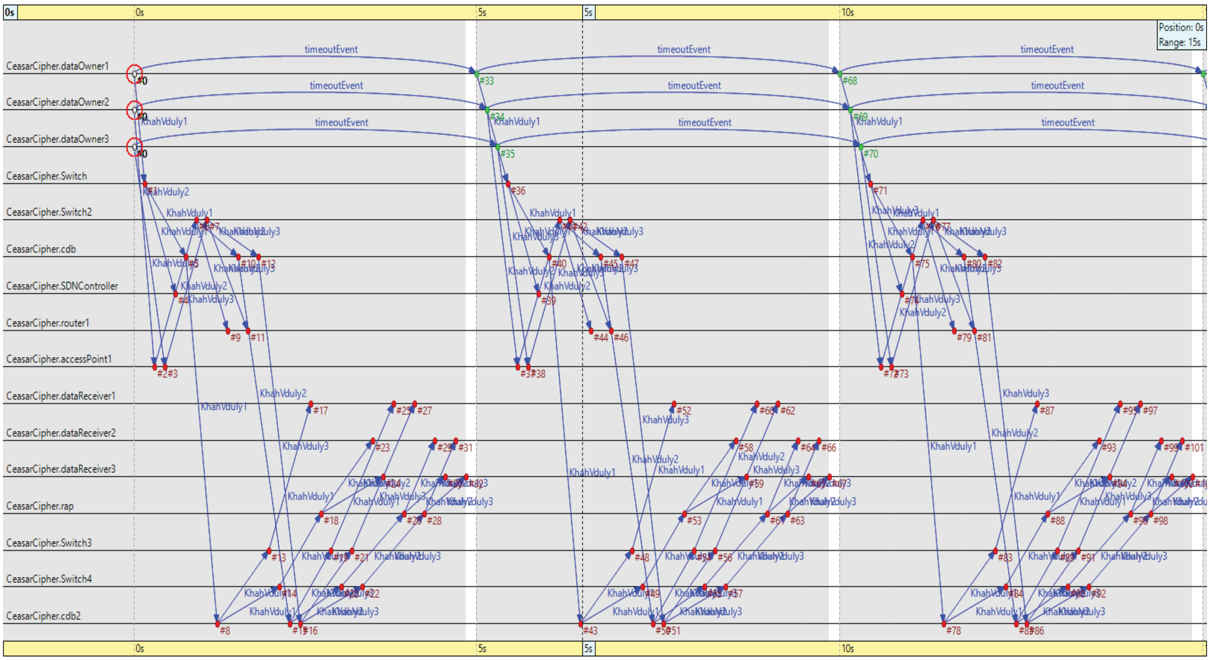


Figure 4.9: Event log file with increase in delay B.

Analysis of the recorded event log file during different stage of the events simulation by changing cloud VR user interaction with the content providers based on changes in bandwidth and resolution shows a seamless transition without much delay in message processing. Also, all the event messages are processed in record time by the content provider and sent back in timely manner to the terminal users.

For all the simulated scenarios, resolution, encoding, and content view are kept constant as shown in Table 4.1. Furthermore, due to constraints in taking and editing measurement from the simulation tools, it was difficult to properly label the graphs as shown in Figure 4.10 to 4.18. For ease of reading, the “blue” bars represent node inlet on the network, while the “red” bars represent node outlet. Node on the graphs refers to the network devices connection point for receiving, creating, storing, and sending data across the network routes.

4.4.2 First Simulation Scenario

For the first simulation, a bandwidth of approximately 160 Mbps was used, this results in frame rate measurement of 60 fps (frame per second) and the latency measurement of 29 ms (millisecond). These are shown in Figure 4.10, Figure 4.11 and Figure 4.12. This result although gives a latency very close to a recommended latency of 20 ms, which could be still work for cloud VR application. Yet, it did not generate the recommended latency of at least 20 ms required for a cloud VR application devoid of any form of dizziness, lagging and frame freezing.

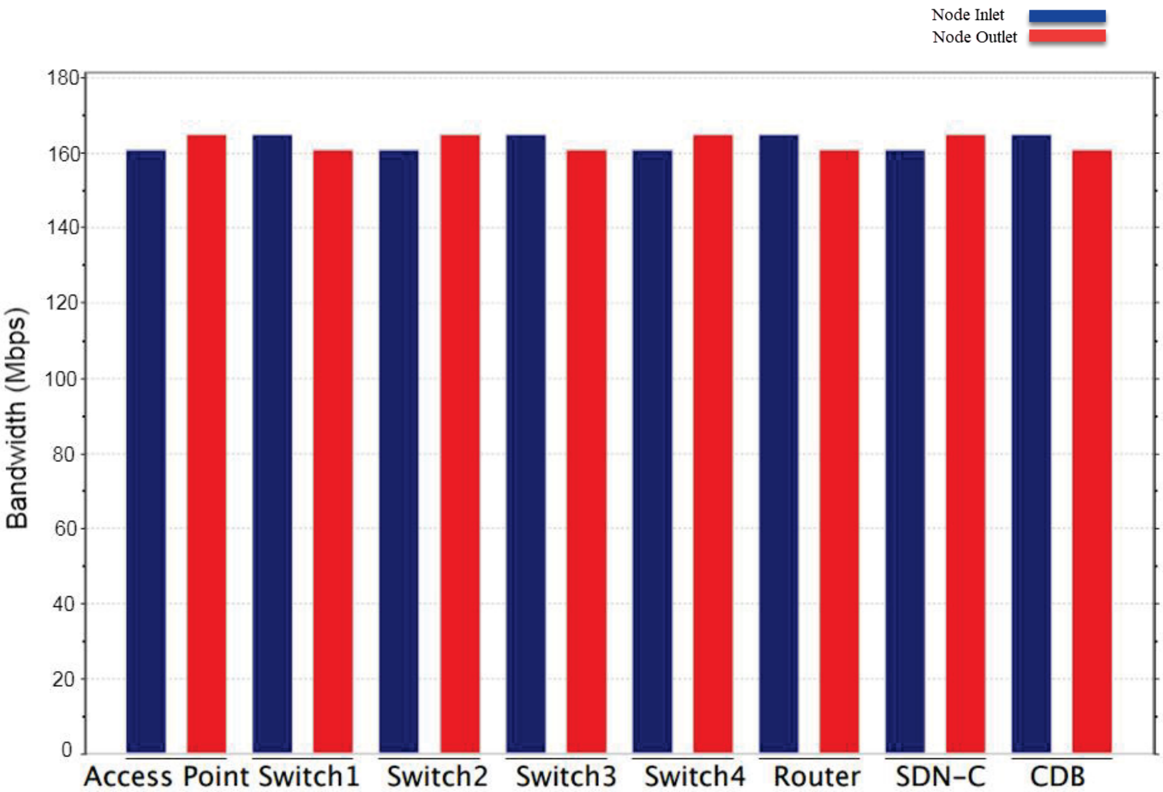


Figure 4.10: Simulated bandwidth for the first scenario.

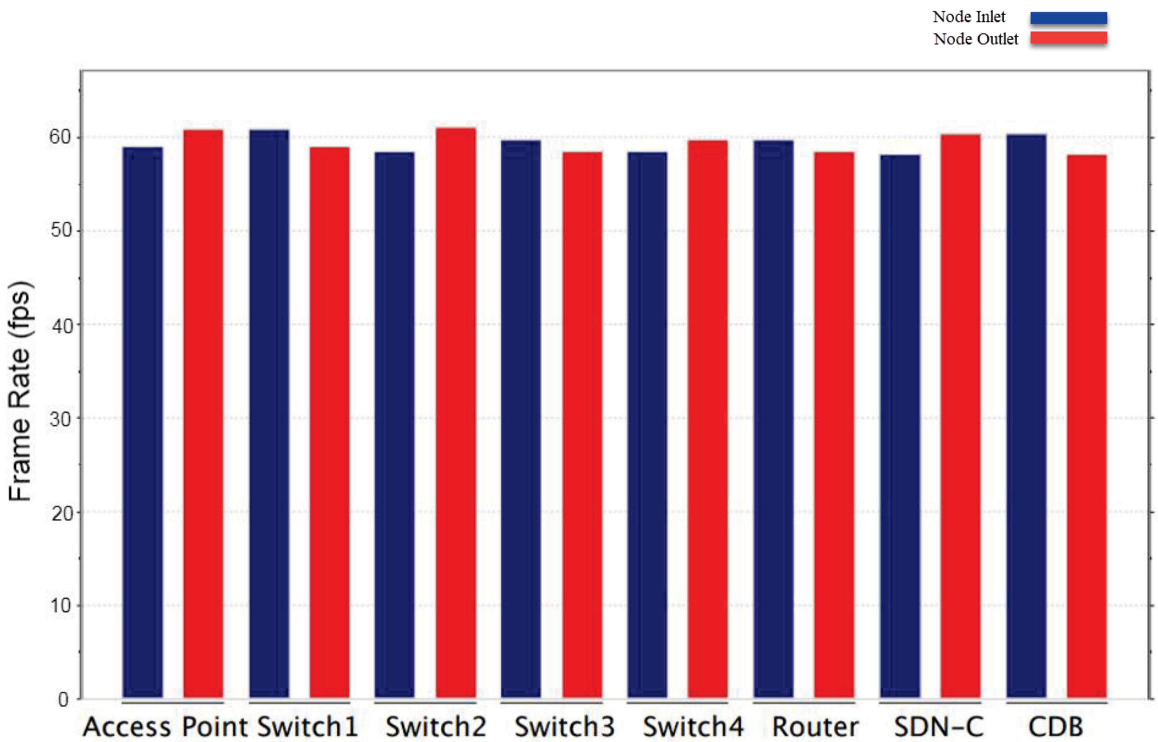


Figure 4.11: Measured change in frame rate for the first scenario.

Figure 4.12: Measured end-to-end delay or latency for the first scenario.

4.4.3 Second Simulation Scenario

After the first simulation, changes were made in the code to reduce the bandwidth to an average of approximately 105 Mbps as shown in Figure 4.13. This led to a reduction of the frame rate from initial average of 60 fps to 50 fps (see Figure 4.14). However, there was an increase of latency from initial 29 ms to 39 ms in Figure 4.15. The use of a reduced bandwidth shows a clear decrease in performance indicator. This would further reduce the kind of immersion, interaction and imagination of the terminal user.

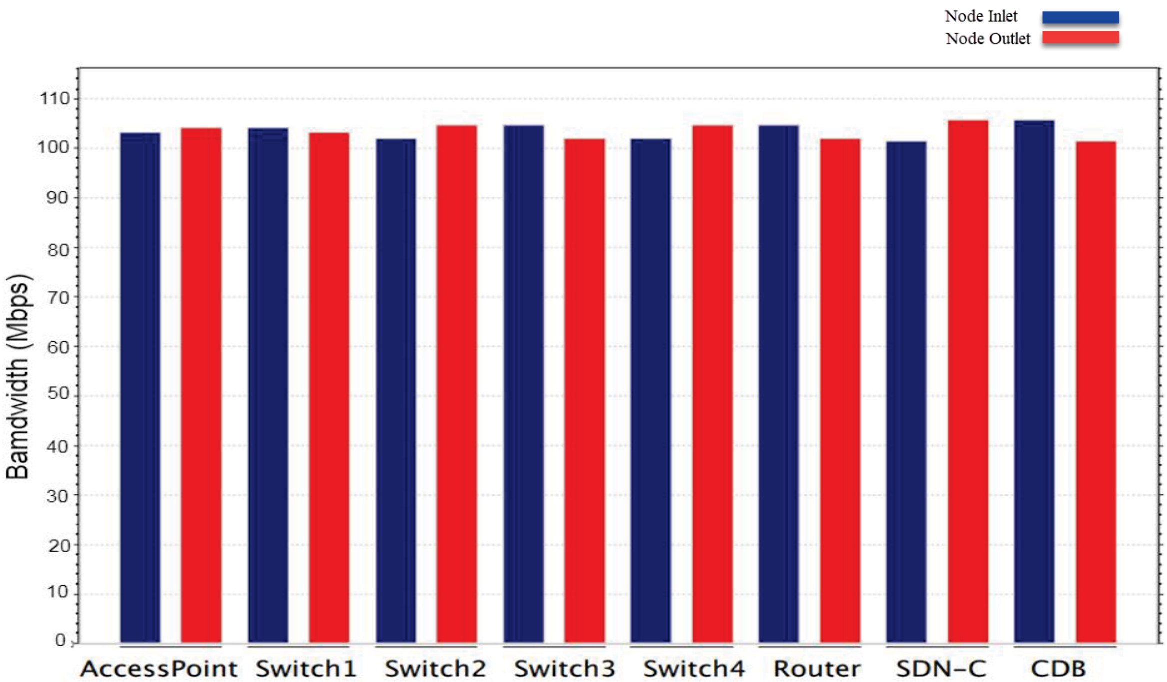


Figure 4.13: Simulated bandwidth for the second scenario.

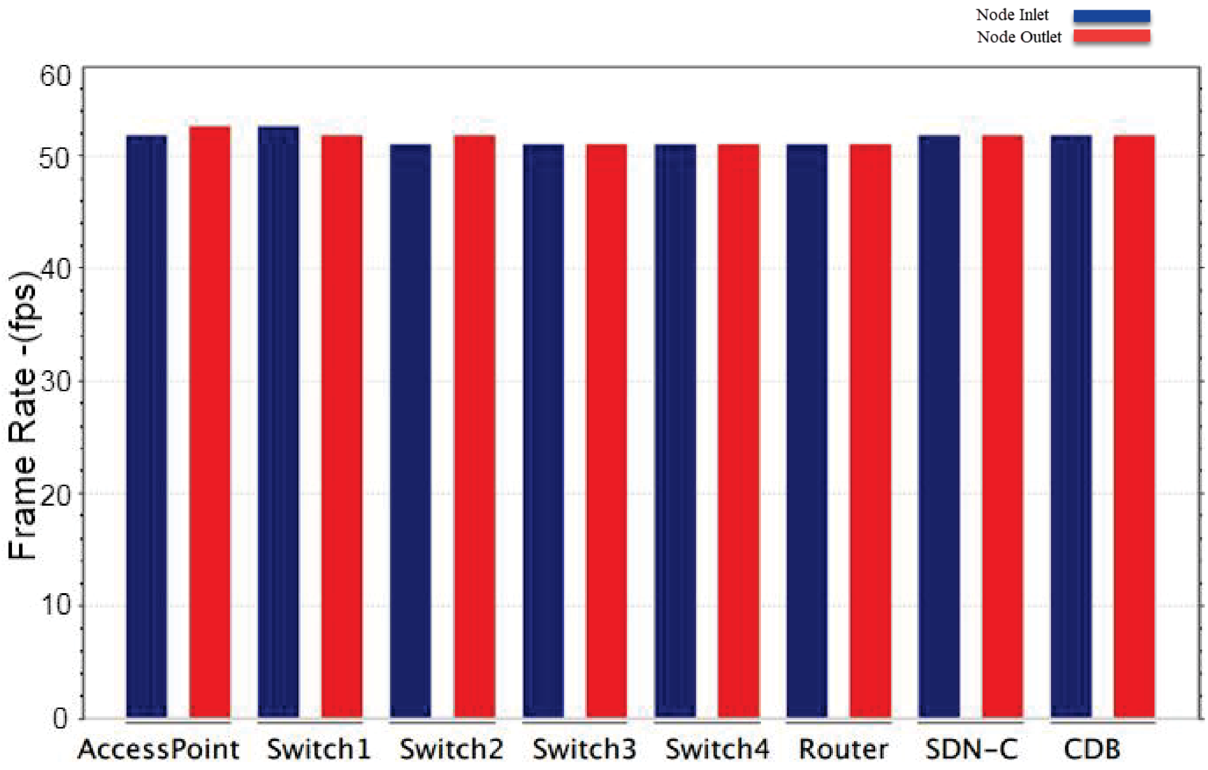


Figure 4.14: Measured change in frame rate for the second scenario.

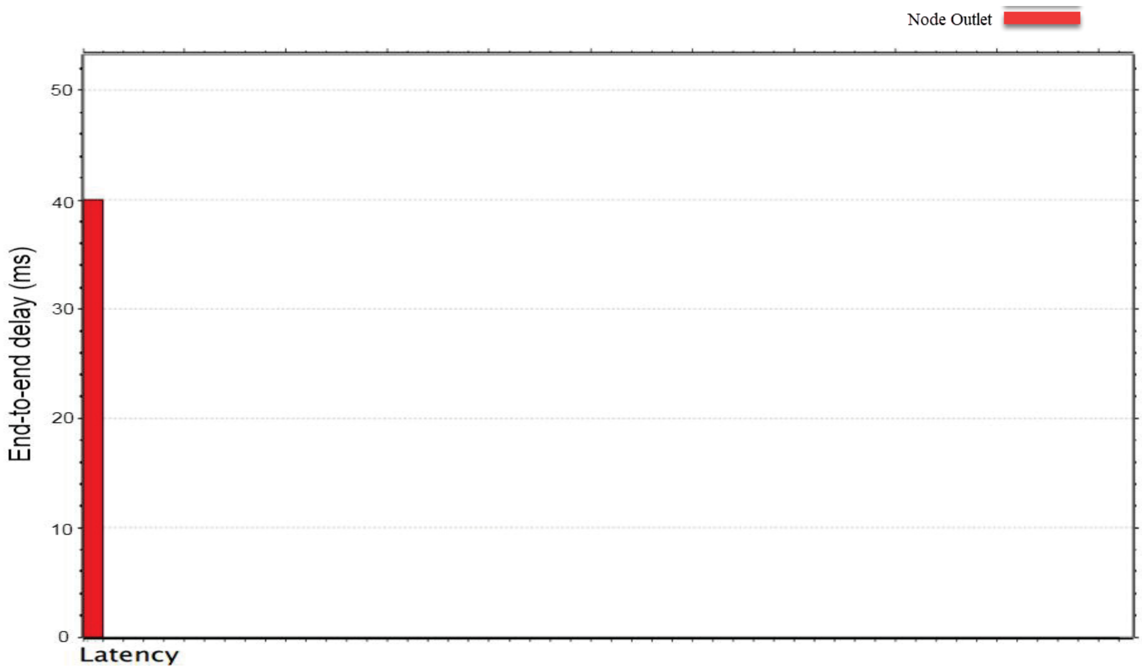


Figure 4.15: Measured end-to-end delay or latency for the second scenario.

4.4.4 Third Simulation Scenario

After the second simulation, the bandwidth was further reduced from 105 Mbps to an average of approximately 80 Mbps as shown in Figure 4.16. This led to an decrease of frame rate from an average of 50 fps to 45 fps in Figure 4.17, with a further delay introduced in form of latency which increased from 40 ms to 65 ms in Figure 4.18. Although, the difference in latency is not very large, but some form of additional discomfort introduced by increase in buffering, and additional lag, leading to extra dizziness resulting from increase in latency would be experienced at the terminal end.

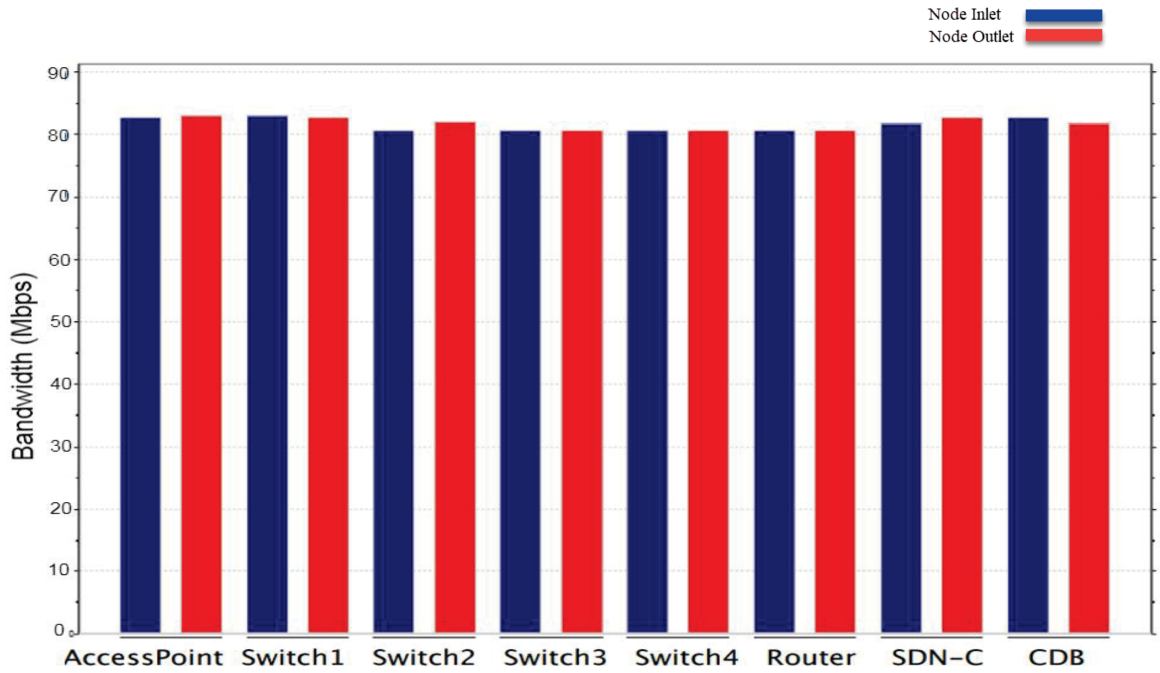


Figure 4.16: Simulated bandwidth for the third scenario.

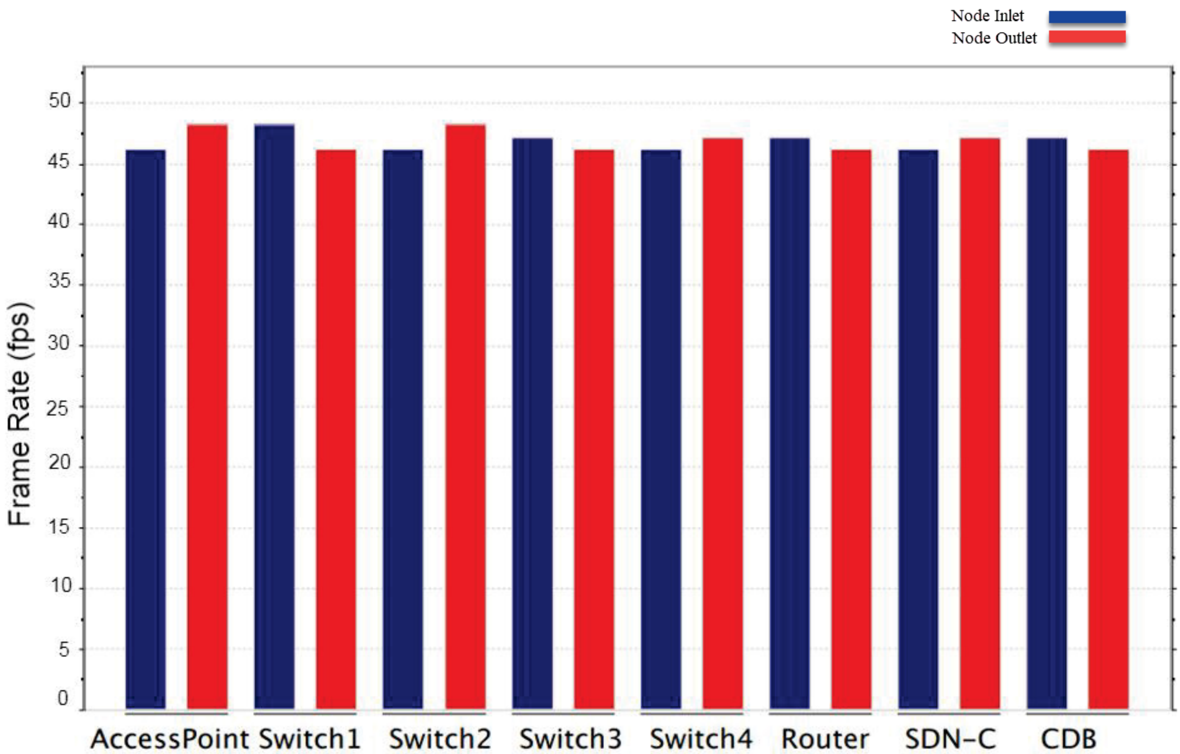


Figure 4.17: Measured change in frame rate for the third scenario.

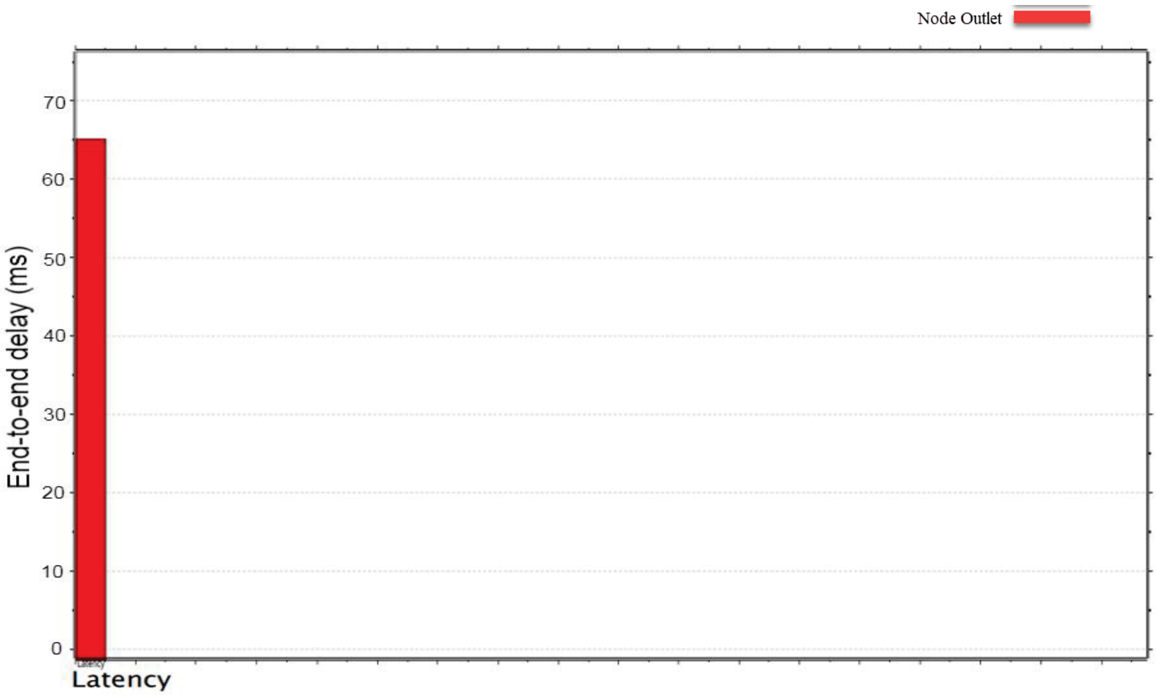


Figure 4.18: Measured end-to-end delay or latency for the third scenario.

4.4.5 Low Bandwidth Simulation

Based on cloud VR high dependency on high bandwidth, we decided to go further and simulate lower bandwidth to determine the associated latency and other performance indicators. This was done basically to have an idea of what the expected user experience would be, if lower bandwidth is used, based on the performance indicators. Therefore, two additional fourth and fifth scenario were further simulated as shown in Table 4.1. However the graph for this was not taken, because its obvious that the result is far away from the performance criteria being expected, and as this would have affected other important measurement needed to be taken considering the time.

Table 4.1: Summary of initially simulated scenarios

	Latency Performance Indicators Measurements				
	Scenario 1 ((Bandwidth = 160 Mbps)	**Scenario 2** ((Bandwidth = 105 Mbps)	**Scenario 3** ((Bandwidth = 80 Mbps)	**Scenario 4** ((Bandwidth = 40 Mbps)	**Scenario 5** ((Bandwidth = 20 Mbps)
Resolution (full view)	4k	4k	4k	4k	4k
Bandwidth (Mbps)	160	105	80	40	20
Frame Rate per Second (fps)	60	50	45	29	13
Latency, millisecond (ms)	29	40	65	90	120
Encoding	H.264	H.264	H.264	H.264	H.264
Content View, full view (degrees)	360	360	360	360	360

4.4.6 Simulated Higher Bandwidth to Generate Minimum Required Latency

At this point, it was found out that all the simulated bandwidth from the first to the fifth the scenario so far (see Table 4.1), would not be sufficient based on the latency requirement for current cloud VR applications. Hence, to determine the minimum bandwidth required for a latency of at least 20 ms, required in real life cloud VR for mobile health application, especially as it relates to health education, further experiments were performed. These are explained further below, with summary of measurement in Table 4.2.

4.4.6.1 Sixth Simulation Scenario

After some further research into the simulation tool and framework being used, to get additional knowledge on how to overcome the problem associated with using higher bandwidth for the simulation, we made some changes to the simulation tools and the written code, we were able to simulate higher bandwidth. After multiple simulated trials, we finally observed that a bandwidth of between 350 Mbps and 400 Mbps would be required to get a latency of at least 20 ms. The result of the simulation, using a bandwidth of 400 Mbps is shown in Figure 4.19 . The result generated a latency of 15 ms in Figure 4.21, and average frame rate of 110 fps in Figure 4.20.

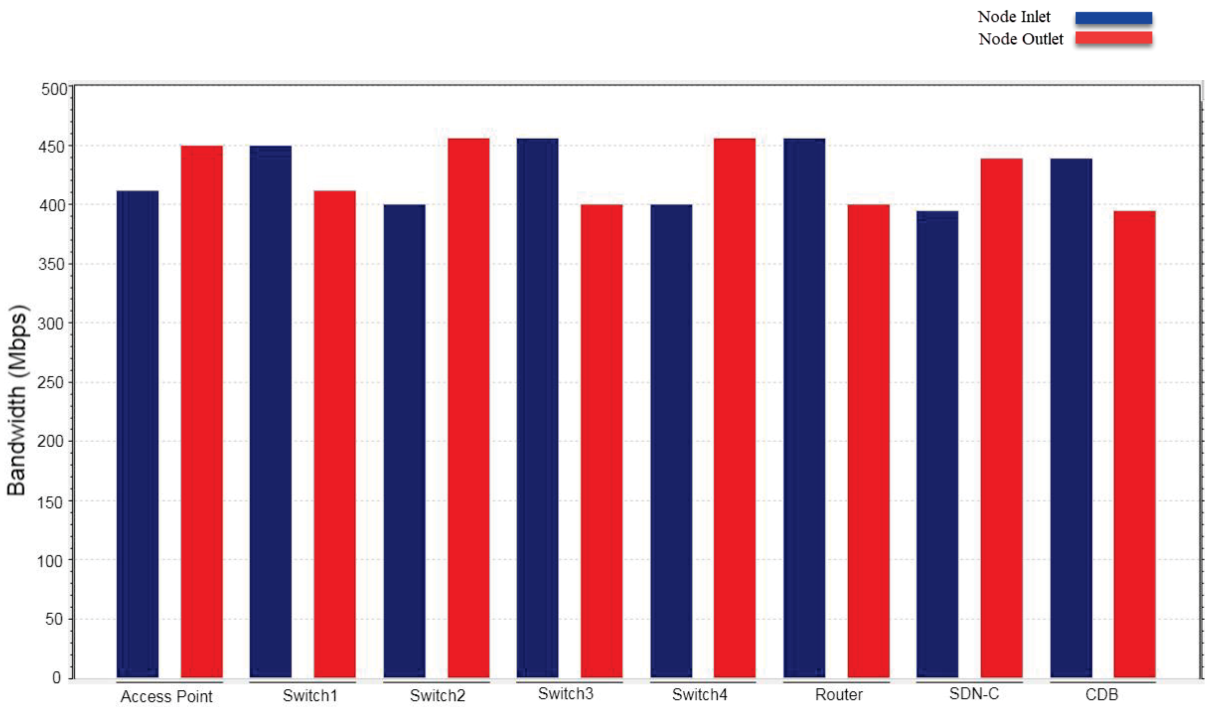


Figure 4.19: Simulated bandwidth for the sixth scenario.

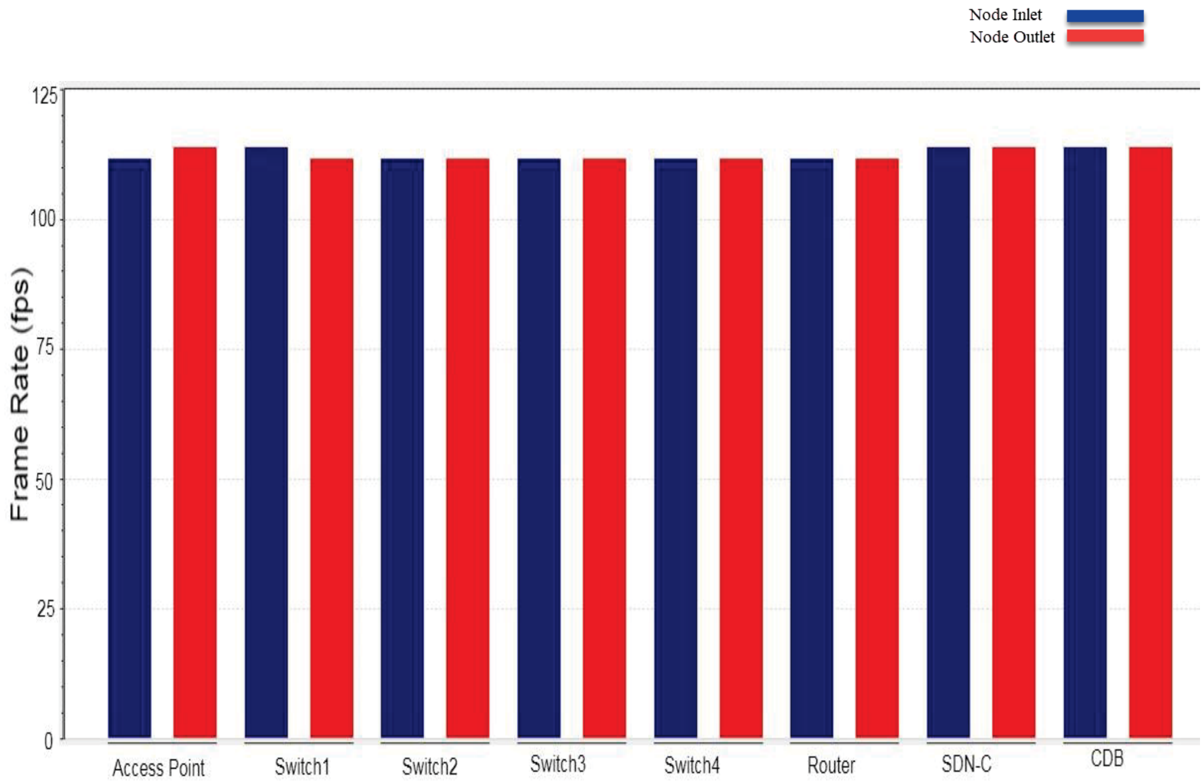


Figure 4.20: Measured change in frame rate for the sixth scenario.

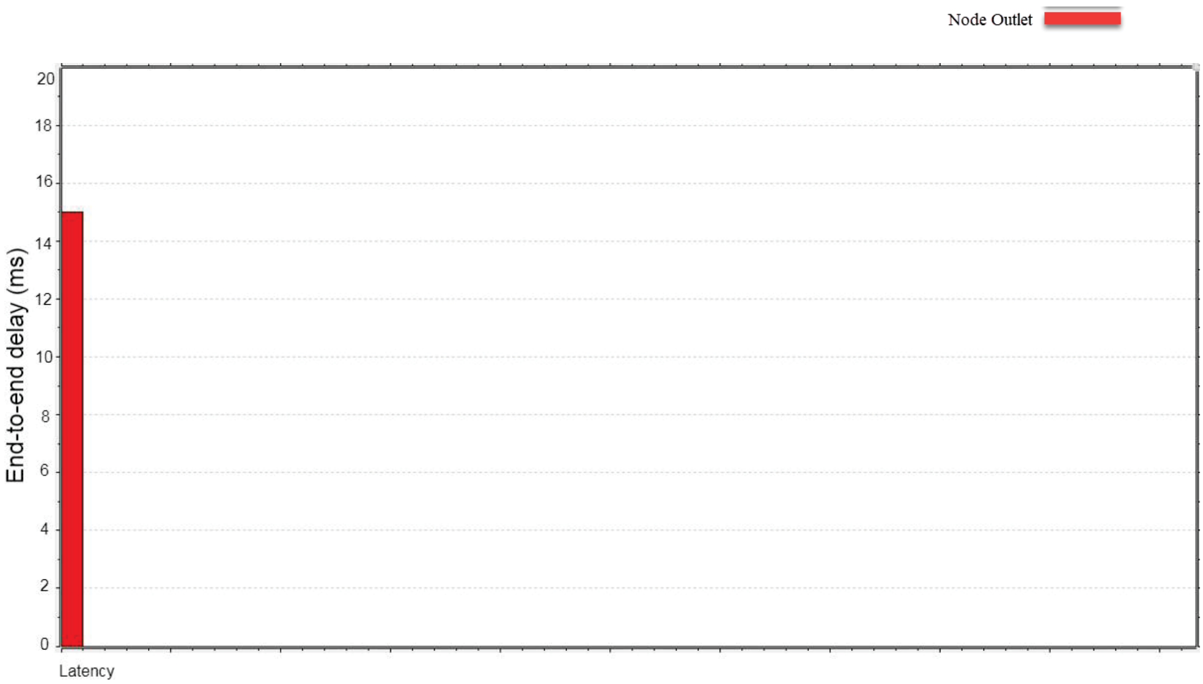


Figure 4.21: Measured end-to-end delay or latency for the sixth scenario.

4.4.5.1 Seventh Simulation Scenario

Following the result generated using a bandwidth of 400 Mbps, we ran another simulation, and increased bandwidth to 500 Mbps in Figure 4.22. This time, although not as big as being expected, but there was a reduction of latency from 15 ms to 11 ms in Figure 4.24 , and an increase in frame rate from 110 fps to 170 fps in Figure 4.23.

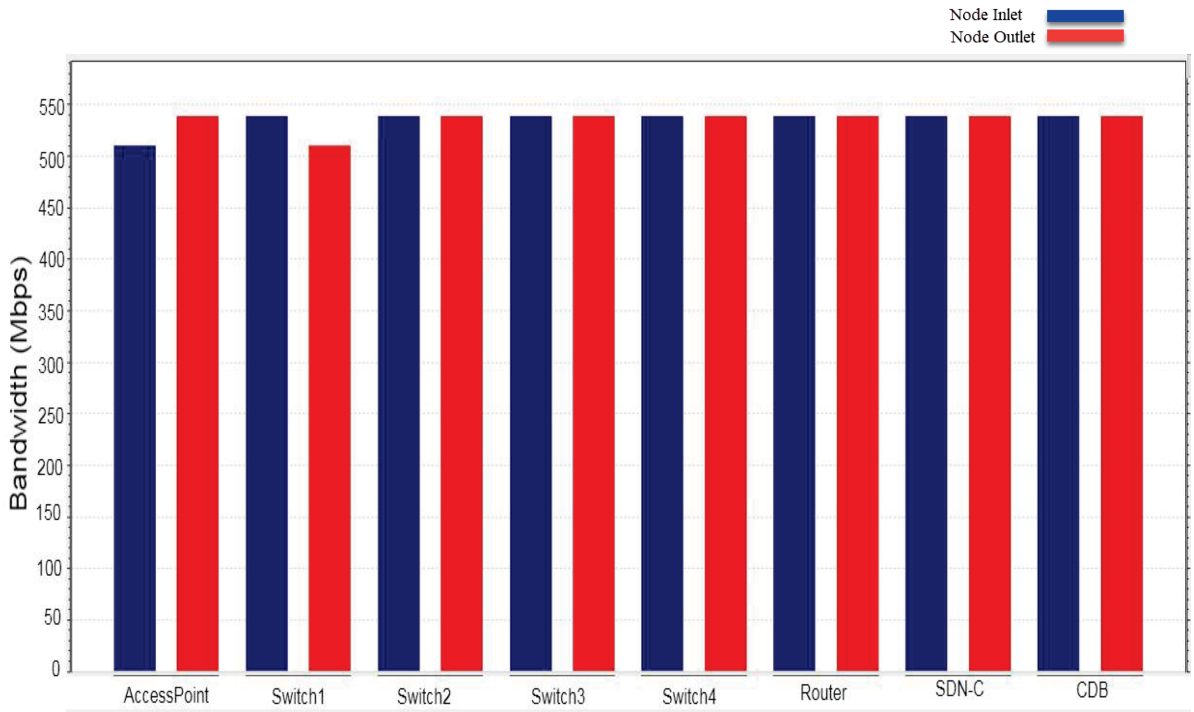


Figure 4.22: Simulated bandwidth for the seventh scenario.

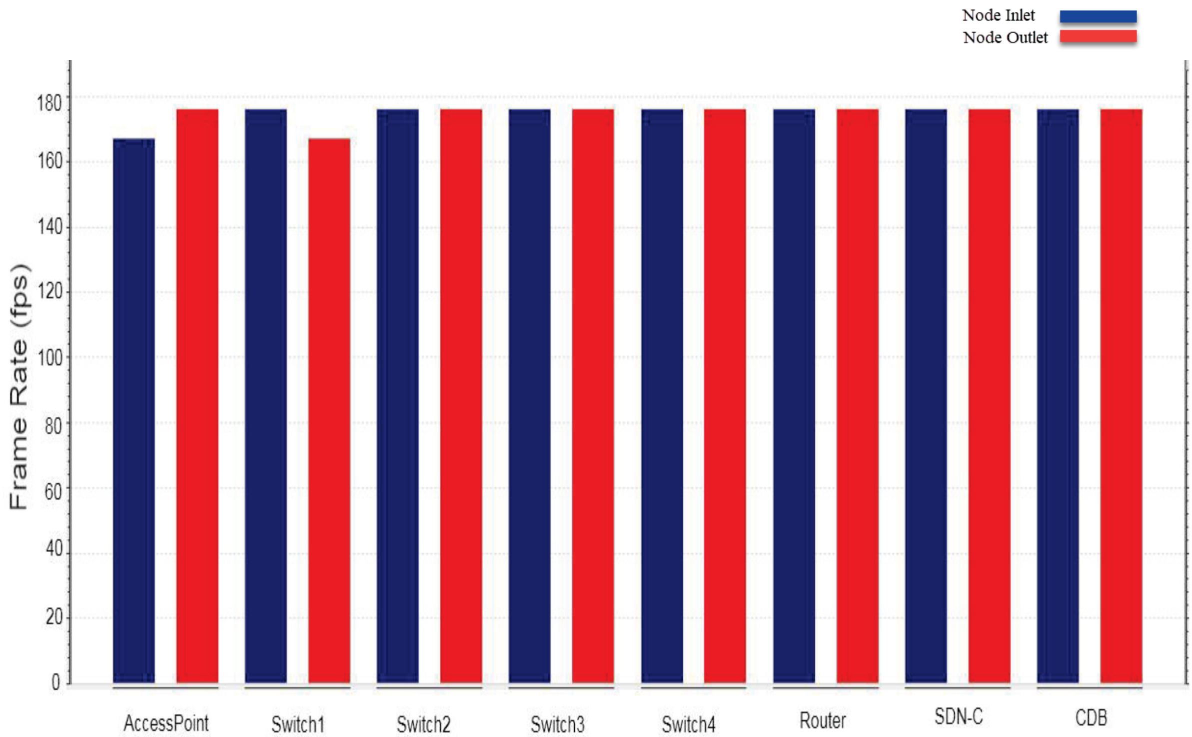


Figure 4.23: Measured change in frame rate for the seventh scenario.

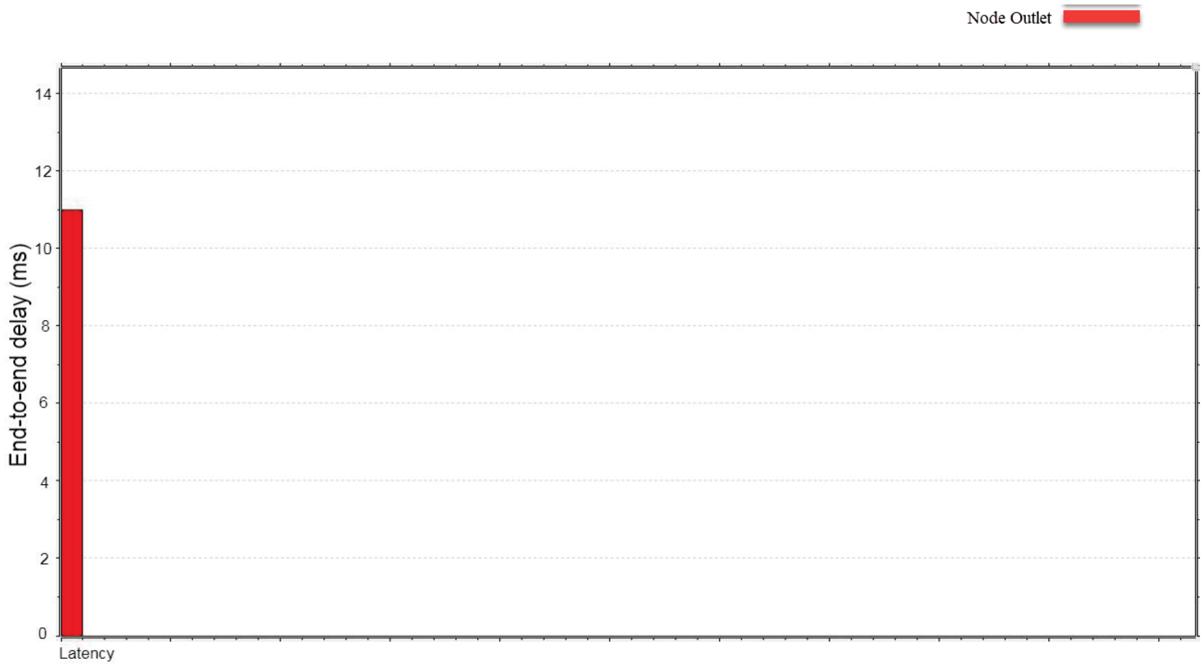


Figure 4.24: Measured end-to-end delay or latency for the seventh scenario.

Table 4.2: Summary of improved simulated scenarios.

Latency Performance Indicators Measurements		
	Scenario 6	**Scenario 7**
Resolution (full view)	4k	4k
Bandwidth (Mbps)	400	500
Frame Rate (fps)	110	170
Latency (ms)	15	11
Encoding	H.264	H.264
Content View, full view (degrees)	360	360

4.4.7 Contribution of Each Network Layer or Node to Latency Measurement

As part of the improvement made to simulate higher bandwidth, we also made further improvements to determine which of the network layer or component contribute mostly to the overall end-to-end delay, as shown in the sixth and seventh scenarios in Table 4.2. By this, we wanted to measure the latency generated at each layer of the simulated network architecture in Figure 1.1. This is expected to give a clearer picture and understanding of which of the network component contributes the lowest and highest to the overall network latency. After the simulation, Table 4.3 and Figure 4.25 shows how each of the latency measurements in the sixth and seventh scenario were distributed among each of the network layers.

Table 4.3: Summary of latency measurements on each network layer.

Latency Measurements							
	Processing in the cloud (ms)		Network transmission delay (ms)	Home (ms)	Terminal screening delay (ms)	Total (ms)	Bandwidth (Mbps)
	Rendering delay	Encoding delay		Decoding delay			
Scenario 6	2.5	1.5	2	3	6	15	400
Scenario 7	2	1.5	1	2.5	4	11	500

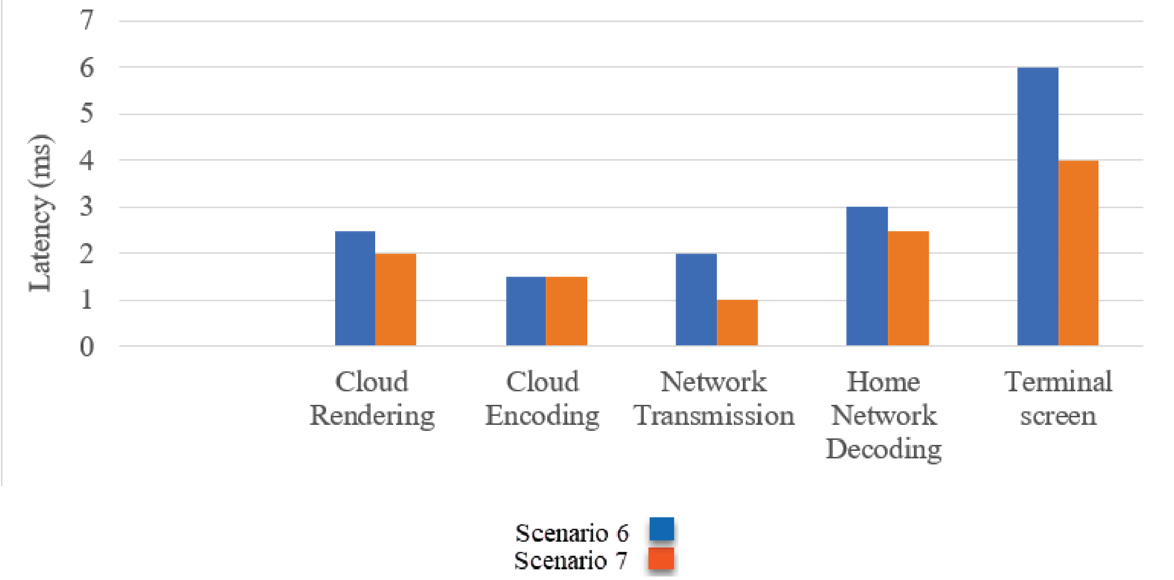


Figure 4.25: End-to-end delay or latency distribution for both sixth and seventh scenarios.

5 DISCUSSION

5.1 Performance assessment

This chapter discussed the performance assessment of networked immersive media in health application with a particular emphasis on health education aspect as simulated and presented in the results and analysis section.

The simulation was initially performed using a purely cloud based network architecture without any processing capabilities on the edge of the network. However, this led to a significantly slow network and a very low latency measurements which is not sufficient for the cloud VR network simulation. But after introducing some processing capabilities on the edge of the network in conjunction with the core network processing capabilities, this led to a better and faster network enough for our cloud VR network simulation. This implies a combination of edge and cloud network architecture is required to achieve a more efficient and a low latency VR health services especially in health education. This is a confirmation of the recommended type of network architecture based on the existing work [11]. This aspect of the simulation was, however, not recorded due to short span of the project.

5.1.1 Simulated Network and Scenarios

5.1.1.1 Network

The network architecture shown in Figure 1.1 was used for the simulation, below are the discussion based on the simulation results.

1. Terminal:

Based on the simulated network in Figure 1.1, a simple terminal with capability to receive cloud VR services, content display, user authorization, as well as capability for asynchronous rendering is sufficient for the cloud VR. This would ensure a very smooth service experience for end user. This is in accordance with existing work done in terminal requirement for a cloud VR service platform in both the weak and strong interactive VR services [11].

2. Operator Network:

The simulated cloud VR services operator network is composed of 4k video bearer network, access and home network which serves to provide a highly stable bandwidth with corresponding low latency for the cloud VR services. This closely matches the type of network deployed in the currently operated cloud VR solutions in both weak and strong interactive VR services, especially, in gaming and video services. This is combined to provide very reliable bandwidth for a sufficiently low latency needed for cloud VR services in health education [12].

3. Platform:

For the simulated cloud VR services, which is mainly focused on the VR video service platform as it relates to usage in academic teaching environment, the VR content was provisioned through the reuse of video platform resources along with some dedicated systems for the purpose of cloud rendering and VR video production and distribution. This was used based on the currently existing most efficient platform setup for the weak cloud interactive service, which is the basis of this work, as well as the strong interactive services. This was for a faster and a well robust network with capability for scaling and highly efficient service needed for health education related cloud VR services [11][12][15].

4. Content:

The content provider was segregated and placed on top of the architecture to produce high quality content which satisfy different cloud VR scenario such as weak interactive services such as video and cinema, and strong interactive services such as games, to the service platform. This helps in the implementation of quick aggregation and VR content introduction to the main service platform [12].

The adopted architecture is well in conformity with the existing services in the area of VR and AR cloud services. This helps in ensuring that the major aim of determining the most efficient cloud VR architecture and the latency performance indicator is achieved.

5.1.1.2 Scenarios

As shown in Table 5.1, the first simulation scenario depicts a performance indicators which is close to the recommended minimum latency that is required for an efficient user expericne in terms of realism, immersion, and users imagination. In the second scenario, the reduction of the bandwidth by a third of the first bandwidth shows a clear decrease in performance indicators, which would lead to much interference in terms of initial buffering, lagging and freezing on the part of the terminal user experience. However, in the third scenario, although the latency diffirence was no so big, but some form of additional discomfort would still be introduced in form of increase in buffering, and added lag at the terminal end.

Following the same pattern, the fourth and the fifth scenarios, simulated to know how latency is affected by lower bandwidth and other related performance indicators, shows a further degrading latency and other indicators as the bandwidth is reduced. In the fifth scenario, with the bandwidth reduced to around 25% of that of the first scenario, the generated latency, and frame rate were much lower than any of the preceding scenarios. In the last instance of the first set of simulations, the bandwidth was reduced much further to around 11% of the first scenario, at this stage, the generated latency and frame rate were extremely low to give a fair support of any of the currently existing cloud VR service in health as it relates to education.

Due to the inability to get the minimum target latency measurement of 20 ms, which is the recommended value for a health education related cloud VR services from the first five set of the simulated scenarios. Additional sixth and seventh simulated scenarios done after improvements were made in the simulated tools, to provision for higher bandwidth, provided us with the minimum recommended latency requirement as shown in Table 5.1. An increase of the first simulated bandwidth by 150%, from 160 Mbps to 400 Mbps generated an average latency of 15 ms and an average frame rate of 110 fps, for the sixth scenario.

A further increase of the bandwidth to average of 500 Mbps for the seventh scenario, generated an average latency of 11 ms and average frame rate of 170 fps. However, the seventh scenario is a form of further contribution made by this work to know the required bandwidth to achieve a very low latency, with high frame rate required for highly interactive cloud VR applications such as gaming and may not be realistically obtained in real life applications due to needed network requirements, required to achieve such key performance indicators.

5.1.1.3 Latency Measurements on Each Network Layer

Table 4.3 and Figure 4.25 show the summary of measurements taken from the simulation done to determine the contribution of each of the components that made up the network layers, as shown in the network architecture in Figure 1.1, to the recommended end-to-end latency result generated in the sixth and seventh scenarios (see Table 4.51). Based on the end-to-end latency measurement of 15 ms for the sixth scenario, the latency of 6 ms introduced at the terminal screen contributed most to the end-to-end latency, this is followed by the total cloud rendering and encoding delay of 4 ms (2.5 ms and 1.5 ms respectively), home network decoding delay of 3 ms, and network transmission delay of 2 ms. This latency distribution and relationship is shown in Figure 5.1.

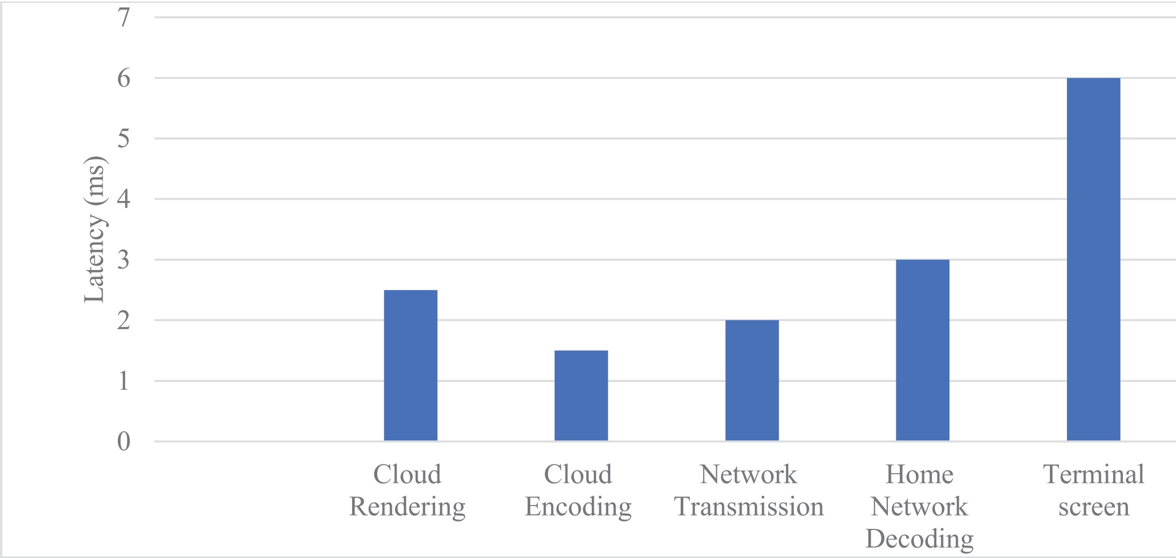


Figure 5.1: End-to-end delay or latency distribution for sixth scenario.

For the seventh scenario which generated a very low latency of 11 ms, and a very high frame rate, comparable to that usually required in strong interactive or comfortable experience phase of cloud VR services, the latency of 4 ms introduced at the terminal screen contributed most to the end-to-end latency, this is followed by the total cloud rendering and encoding delay of 3.5 ms (2 ms and 1.5 ms respectively), home network decoding delay of 2.5 ms, and network transmission delay of 1 ms. This latency distribution and relationship is shown in Figure 5.2.

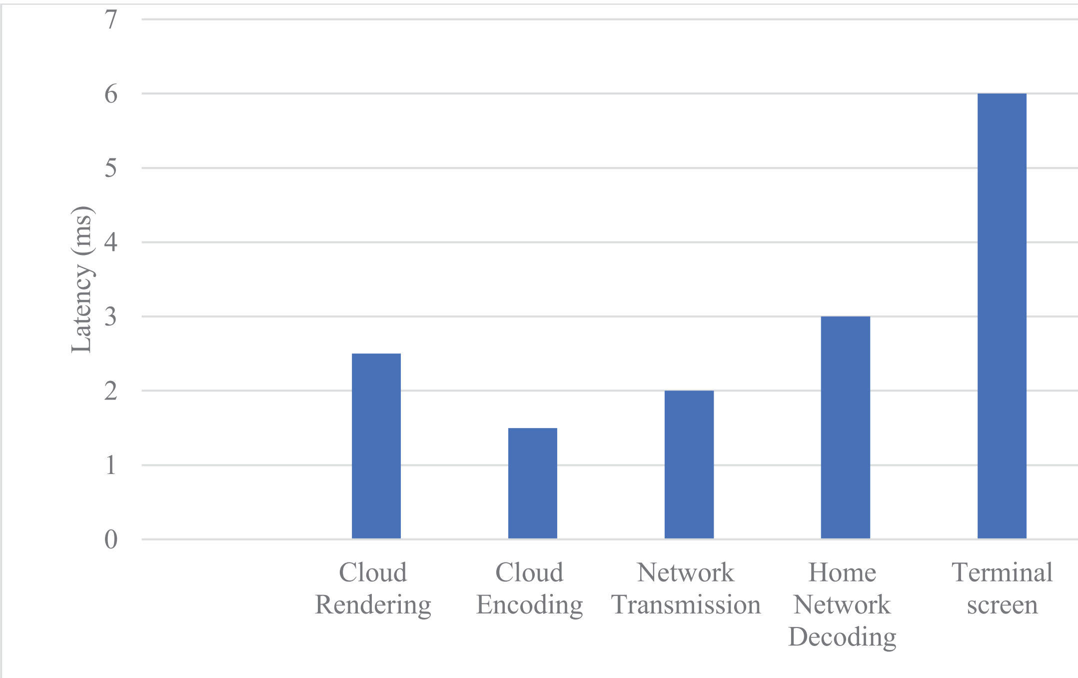


Figure 5.2: End-to-end delay or latency distribution for sixth scenario.

This shows that, for cloud VR application as it relates to healthcare education, the delay contributed by the terminal or HMD is the highest, followed by the delay from the cloud core, while the layer contributing the least delay is the network transmission. This is shown

5.1.2 Latency Related Performance Indicators

On one hand, from the analysis of result whose summary is shown in Table 5.1, we established that bandwidth is a significant factor which determines the performance of a cloud VR application in an academic environment. This is because a sufficient amount of bandwidth is required for a very low latency and high frame rate during the simulation. This, in turn, would lead to a better user experience in terms of the resolution with attendant effects on realism, immersion, and interaction of the content being access from the cloud.

On the other hand, lack of sufficient bandwidth would result into corresponding lower frame rate and higher end-to-end delay, which most often leads to reduced user experience and other related lower realism, lack of immersion, almost impossible interaction, dizziness and much lag.

Table 5.1: Overall summary of the end-to-end latency performance indicators for all simulated scenarios.

End-to-End Latency Performance Indicators Measurements							
	Scenario 1 ((Bandwidth = 160 Mbps)	**Scenario 2** ((Bandwidth = 105 Mbps)	**Scenario 3** ((Bandwidth = 80 Mbps)	**Scenario 4** ((Bandwidth = 40 Mbps)	**Scenario 5** ((Bandwidth = 20 Mbps)	**Scenario 6** ((Bandwidth = 400 Mbps)	**Scenario 7** ((Bandwidth = 500 Mbps)
Resolution (full view)	4k	4k	4k	4k	4k	4k	4k
Bandwidth (Mbps)	160	105	80	40	20	400	500
Frame Rate (fps)	60	50	45	29	13	110	170
Latency (ms)	29	40	65	90	120	15	11
Encoding	H.264	H.264	H.264	H.264	H.264	H.264	H.264
Content View, full view (degrees)	360	360	360	360	360	360	360

From the measurements in Table 5.1, it could be observed that while an average bandwidth lower than the measured bandwidth 400 Mbps, would provide some form of user interaction, however, this would lead to some form of limited user experience and enjoyment. A bandwidth of approximately 400 Mbps is needed to provide a latency below the minimum recommended latency value of 20 ms to experience an efficient and realistic cloud VR services in mobile health applications such as in education. Furthermore, a bandwidth below 160 Mbps with its corresponding end-to-end latency of 29 ms is not recommended to achieve almost perfect cloud VR end user experience devoid of any kind of dizziness, lag, and with very high frame rates and very low latency.

5.1.3 Relationship Between Latency Related Performance Indicators

Figure 5.3, 5.4 and 5.5 depict the relationship between different latency related cloud VR performance indicators previously highlighted. There is a clear direct relationship between bandwidth and frame rates. A reduction in bit rate for each of the simulated scenarios resulted in lower frame rates and vice versa. On the other hand, reduction in bandwidth for each of the simulated scenario resulted in an increase in end-to-end delay in form of latency across the network. This means there is an inverse relationship between bandwidth and latency. Also, from the latency result generated by using different bandwidth, it is clear that adequate bandwidth is one of the very key performance indicators needed during the planning and implementation stage of cloud VR services.

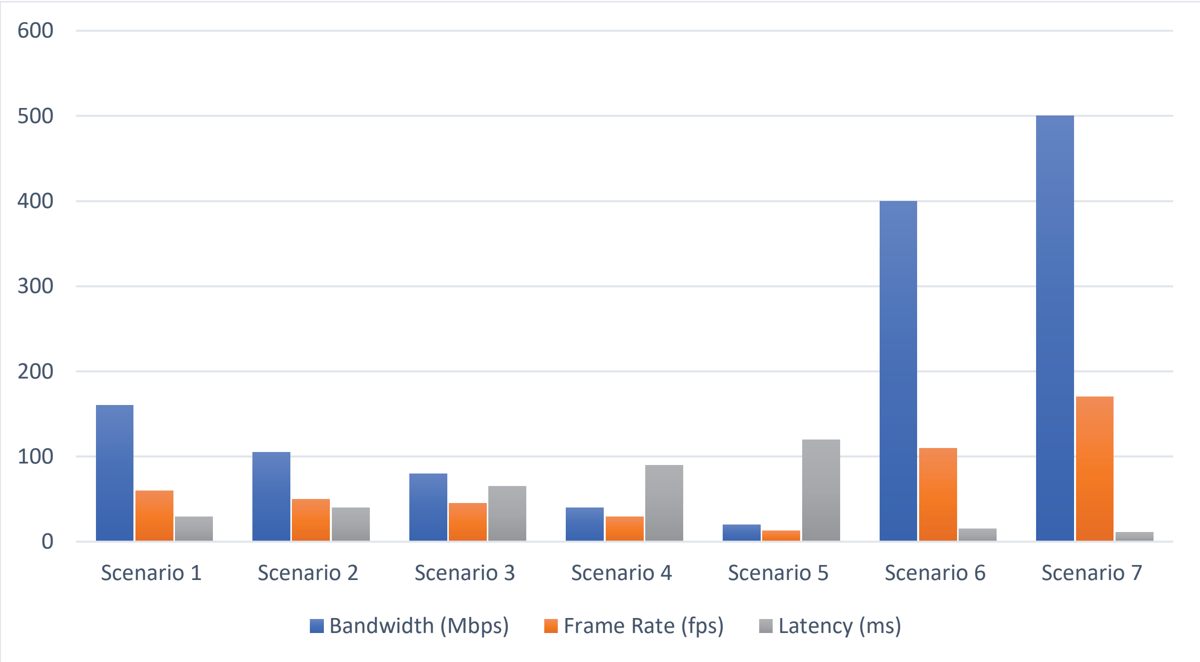


Figure 5.3: Relationship between bandwidth, frame rate and latency.

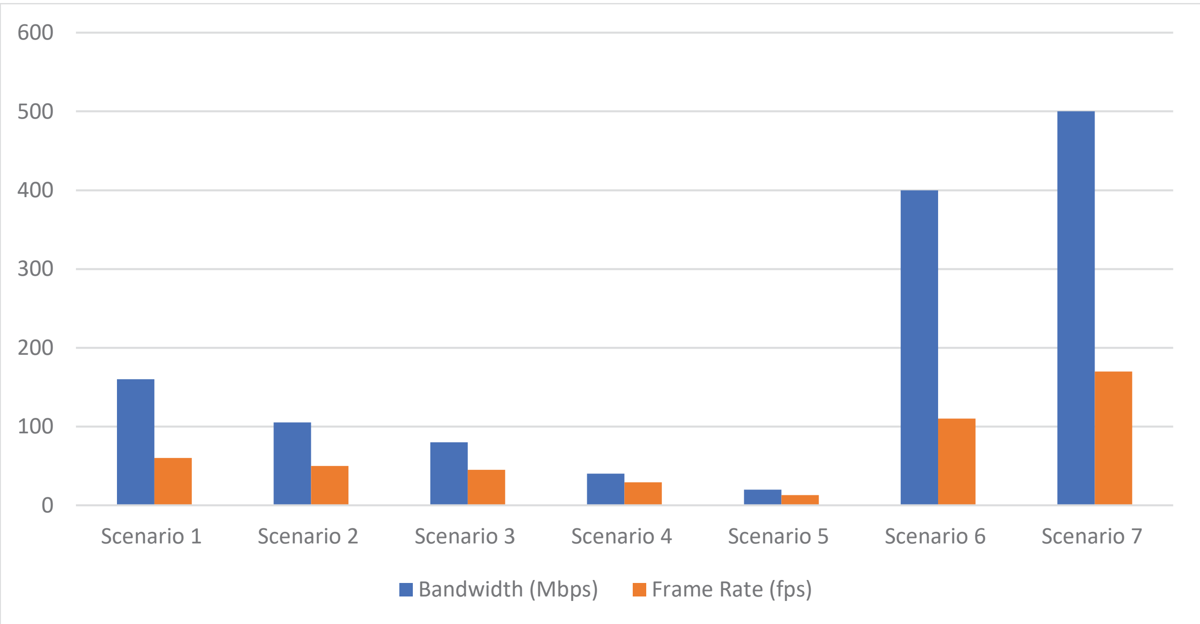


Figure 5.4: Relationship between bandwidth and frame rate.

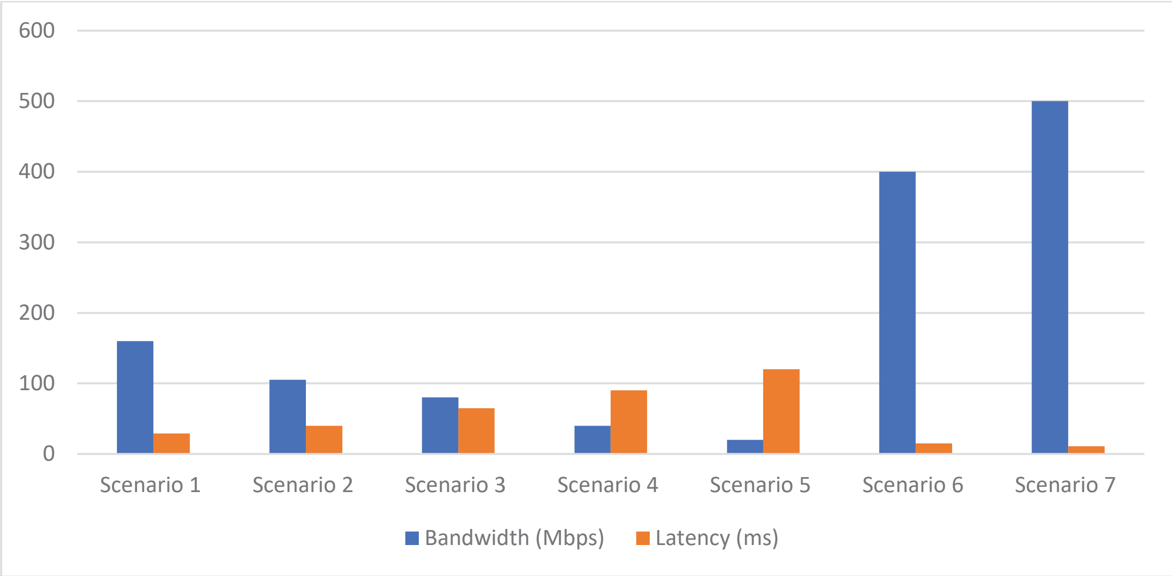


Figure 5.5: Relationship between bandwidth and latency.

5.1.3.1 Other Key Performance Indicators for Efficient Cloud VR Experience in Mobile Health Applications

1. Content View:

In reality, 360 degrees panoramic content is the most common type of VR video content which gives user the capability to view the received VR video content on the terminal in a full view as simulated. However, there is also FOV (Field of View) transmission solution which transmits contents based on the user's perspective. The 360 degrees solution is easier to implement both in reality and simulated scenario due to no special video requirement hence its popularity and the reason for its implementation.

2. Frame Rates:

In comparison with existing work, the minimum frame rate required for a smooth cloud VR video experience in general for an unaided end user vision is about 24 fps to 30 fps [11][12]. This means the minimum measured frame rates of 110 fps as simulated in the improved sixth scenario will lead to an highly efficient and effective smooth VR experience for an unaided end user eye.

3 Resolution:

Due to restrictions in the availability of 8k resolution from the video and game content providers, a 4k resolution with an image quality which is equivalent to a 240 pixel for a TV view is adopted, meeting the current minimum requirements for most users. This is the currently general image quality in existence for both video and gaming content provider in the area of cloud VR services.

3. Encoding:

Video compression is required by the encoder before transmission, to reduce the network resources requirement. For the currently existing work and solution, H.263, H.264, H.265 are the dominating coding standards, but due to the more common 4k video content production, a H.264 encoder is used for encoding. Although for a more richer and highly interactive 8k video content, a H.265 encoder would be required in order to improve generated video compression rate and minimize the amount of pressure placed on the network.

4. Bit rate:
Although the bit rate determines how good the image quality is, as the higher the bit rate, the higher the image quality. However, for simulated video resolution of 4k, it was observed that once a certain bit rate is attained, then further increase in the bit rate does not generate much improvement in terms of image and video quality. The minimum required bit rate for the 8k video resolution was however not observed, as it is out of the project's coverage and due to time constraints [11].
5. Initial Buffering:
The initial wait or buffer time between the time a terminal user interact with the cloud services and when the content is received and begins to play is found to be below 1 second. Although not very important at the initial stage, but at the same time important for better user experience while playing cloud VR videos with a 4k resolution.

Ensuring adequate bit rate, usage of correct video encoding type, sufficient frame rate all contributes to avoidance of frame freezing during playback, which occurs in the event that downloaded data by the terminal could not satisfy the video playback requirements. It is generally recommended to avoid frame freezing to enhance the users experience in terms of realism, immersion and interaction while using the VR services in both weak and strong experience integration phases [12].

5.1.4 Answers to Research Questions
Research Question 1 (RQ1): What are the latency related performance indicators of networked immersive media in mobile health applications?

From the discussion made so far in preceding sections, the identified latency related performance indicators of networked immersive media in mobile health applications, as it relates to education are bandwidth, frame rate, coding standard, and resolution, out of which bandwidth is the most significant indicator, contributing to latency related performance of cloud VR mobile health applications in education.
Research Question 2 (RQ2): What are suitable network structures to achieve an efficient low latency VR health application?

Based on the initial simulation setup during the commencement of the work, as earlier pointed out, combination of both computing capability at the edge of the network and the cloud was found to greatly enhance the speed and overall performance of the network during simulation. Although, either cloud or edge network could also be implemented, but for a more efficient network architecture required for robust and fast network with high performance and reliability, combination of cloud and edge network is recommended, to achieve an efficient and low latency cloud VR health application, as used for this work.

6 CONCLUSION AND FUTURE WORKS

6.1 Conclusion

In this thesis, we have been able to explore and simulate latency related performance indicators in immersive media mobile health application as it related to health education. By so doing, we have been able to identify bandwidth to be of the most significant indicator in terms of performance, this is followed by frame rate, and resolution. It was established that an average of 400 Mbps, and an average frame rate of 110 fps is required to generate a latency below the minimum recommended value of 20 ms, which is required for smooth cloud VR experience, in terms of immersion, imaginaging and interaction with the application, in the fair to moderate user experience phase, which is the basis of this work [11].

6.2 Contribution to Existing Body of Knowledge in the Area of Cloud VR Applications

By this work, we have been able to contribute to the existing body of knowledge in cloud VR video services as it relates to the mobile health education. Firstly, we have contributed to determining some of the required key performance indicators such as bandwidth of 400 Mbps, and frame rate of 110 ms in Table 5.1, needed for the achievement of the recommended minimum latency of 20 ms required for an effective and efficient cloud VR health application in the fair to moderate user experience phase. Secondly, we also went further in contributing to the determination of the average bandwidth of 500 Mbps and frame rate of 170 ms required for achievement of recommended minimum latency of less than 15 ms in Table 5.1, needed for the strong user experience phase of the cloud VR applications such as gaming [11][12]. Though this is subjected to further research work and validations as it was not the focus of this research work

Also, being a fast-developing research area, by our work on the performance assessment of networked immersive media in mobile health applications with emphasis on latency, we have contributed to some of the important key performance indicators, especially bandwidth, and frame rates, their relationship, and their effect on the amount of latency generated in cloud VR applications and services.

6.3 Limitation

The simulation was limited by being unable to take measurements for resolution. This was mainly due to the shortcoming on part of the available framework used for development of the simulation, that is Omnet++ and INET. Hence a fixed resolution of 4k was used for the simulation. In addition, we were time limited and hence unable to simulate separately cloud VR architectures such as edge and cloud. Furthermore, limitation was experienced in terms of taking different measurements for the cloud VR simulation itself, while the experimental set up issue was fixed, we were faced with other issues with respect to taking measurements, partly because there has been not much existing work in which latency performance indicators were measured. Hence, no existing and recorded documentations containing recommendations on which kind of specific tools is required to best execute the work. This led to a lot of work at the initial stage to find a tool which can be used for the simulation. In like manner, a fixed encoding of H.264 and colour depth of 8 bits was used throughout the simulation.

6.4 Research Opportunity

The work was carried out in a research area without much existing work as it relates to latency performance indicators, except some existing closely related cloud VR work in healthcare. This has limited our ability to research deeper than we would have loved to do. Further research opportunity is opened in terms of delving more into researching side-by-side different cloud VR architecture such as edge and cloud, to do a more comprehensive analysis of the best architecture for a low latency cloud VR mobile health application, in fair to moderate user experience phase. Another future research opportunity is measurement of latency contribution of each of the network component instead of the measurements taken at and in between each of the network layers in this work. Further research work is also opened in the areas of increasing resolution from 4k to 8k, the colour depth from 8 bit to a higher bit and a higher encoding version such as H.265.

As an extension, future research work could also be extended into the latency related performance indicators in the areas of strong interactive VR services such as cloud VR gaming services.

REFERENCES

1. Jessie Y. C. Chen, Gino Fragomeni (Eds.), "Virtual, Augmented and Mixed Reality Applications and Case Studies Part II," HCI International Conference, Florida, USA, pp. 79-229, July 26–31, 2019.
2. Jessie Y. C. Chen, Gino Fragomeni (Eds.), "Virtual, Augmented and Mixed Reality Design and Interaction Part I," HCI International Conference, Copenhagen, Denmark, pp. 18-285, July 19–24, 2020.
3. Jessie Y. C. Chen, Gino Fragomeni (Eds.), "Virtual, Augmented and Mixed Reality Industrial and Everyday life applications Part II," HCI International Conference, Copenhagen, Denmark, pp. 91-286, July 19–24, 2020.
4. Parsons T. D., Gaggioli A., Riva G., "Virtual Reality for Research in Social Neuroscience," *Brain Sciences*, vol. 7, pp. 1-21, Dec 2019.
5. Marco J. H., Perpina C., Botella C., "Effectiveness of Cognitive-Behavioural Therapy, Supported by Virtual Reality in the Treatment of Body Image in Eating Disorders: One-Year Follow-Up," *Psychiatry Research*, vol. 209, pp. 619-625, Oct 2013.
6. Tyrrell R., Sarig-Bahat H., Williams K., Williams G., Treleaven J., "Simulator Sickness in Patients with Neck Pain and Vestibular Pathology During Virtual Reality Tasks," *Virtual Reality*, vol. 22, pp. 211-219, Sep 2017.
7. Rothbaum B. O., Rizzo A. S., Difede J., "Virtual Reality Exposure Therapy for Combat-Related, Posttraumatic Stress Disorder, "*Annals of the New York Academy of Sciences*, vol. 1208, pp. 126-132, Oct 2010.
8. Bun P. K., Wichniarek R., Górski F., Grajewski D., Zawadzki P., "Possibilities and Determinants of Using Low-Cost Devices In Virtual Education Applications," *Eurasia Journal of Mathematics, Science and Technology Education*, vol. 13, pp. 381-394, 2017.
9. Slater M., Gonzalez-Liencres C., Haggard P., Vinkers C., Gregory-Clarke R, Jelley C, Watson Z., Breen G., Schwarz R., Steptoe W., Szostak D., Halan S., Fox D., Silver J., "The Ethics of Realism in Virtual and Augmented Reality," *Frontiers in Virtual Reality*, v1.1, pp. 1-13, Mar 2020.
10. Fauville G., Queiroz A., Bailenson J.," Virtual Reality as a Promising Tool To Promote Climate Change Awareness," *Technology and Health*, pp. 91-108, 2020.
11. Huawei iLab, "Cloud VR Network Solution White Paper," Huawei Technologies, Bantian, Shenzhen, China, Whitepaper, 2018.
12. Huawei iLab, "Cloud VR Solution Practice report," Huawei Technologies, Bantian, Shenzhen, China, Whitepaper, 2018.
13. *Information Technology, Coded Representation of Immersive Media Part 2: Omnidirectional Media Format*, Base no 23090-2, International Organization for Standardization, Vlinderweg, Holand, Jan 2019. [Online]. Available: https://www.iso.org/standard/73310.html
14. *Policy and Charging Control Architecture (release 15),* 3GPP TS 23.203 V15.4.0, 3rd Generation Partnership Project, Valbonne, France, Sep 2018. [Online]. Avalable: https://www.3 gpp.ore/ftp//Specs/archive/23_series/23.203/23203-f40.zip

15. *Multi-access Edge Computing (MEC); Framework and Reference Architecture*, ETSI GS MEC 003 V2.2.1, Mobile Edge Computing, Industry Specification Group, Sophia Antipolis, France, Mar 2016. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/02.02.01_60/gs_MEC003v020201p.pdf
16. Claudio P., Maddalena P., "Overview: Virtual Reality in Medicine., *Journal of Virtual Worlds Research*, vol. 7, pp. 2, Jan 2014.
17. McCloy R., Stone R., "Science, Medicine, and the Future: Virtual Reality In Surgery." BMJ (Clinical research ed.), vol. 323, pp. 912, Oct 2001.
18. Tidjane T., "Augmented Reality vs. Virtual Reality vs. Mixed Reality – An Introductory Guide," Toptal LLC, Delaware, USA. Accessed: Mar 7, 2021. [Online]. Available: https://www.toptal.com/designers/ui/augmented-reality-vs-virtual-reality-vs-mixed-reality
19. Ruan J.; Xie D., "Networked VR: State of the Art, Solutions, and Challenges," *Multidisciplinary Digital Publishing Institute, Electronics*, vol. 10, pp. 1-18, 2021. [Online]. Available: https://www.mdpi.com/2079-9292/10/2/166
20. Min-Chai H., Jia L., "Preliminary Study of VR and AR Applications in Medical and Healthcare Education," *Journal of Nursing and Health*, vol. 3, pp. 3-4, Jan 2018.
21. Lucas O., Rasmus B., Minh T.," Virtual Reality in the Healthcare Sector of Today: Gaining Allies or Making Adversaries through Immersive Virtual Environments and Technical Decisions," M.S. thesis, Aalborg University, Copenhagen, Denmark, June 2018.
22. Syrovatskyi O., Semerikov S., Modlo Ye., Yechkalo, Yu., Zelinska, S., "Augmented reality software design for educational purposes," Proceedings of the 1st Student Workshop on Computer Science & Software Engineering, presented at CEUR Workshop Proceedings, Kryvyi Rih, Ukraine, November 30, 2018. [Online]. Available: http://ceurws.org/Vol-2292/paper20.pdf
23. Kitchenham BA., Charters S., "Guidelines for Performing Systematic Literature Reviews in Software Engineering", vol. 2, Jan 2007.
24. Wieringa R., Maiden N., Mead N., Rolland C., "Requirements Engineering Paper Classification and Evaluation Criteria: A Proposal and a Discussion," Requirements Eng., vol. 11, no. 1, pp. 102-107, Mar. 2005.
25. Braun V., and Clarke V., "Using Thematic Analysis in Psychology," Qualitative Res. Psychol., vol. 3, no. 2, pp. 77-101, 2006.
26. Emilia M. (2019), Research methodology in Electrical Engineering with emphasis on Telecommunication Systems [PowerPoint slides]. Available: https://bth.instructure.com/courses/1999/files/157744?module_item_id=31910
27. Sebastian Weiß, "A Mobile Augmented Reality Application to Improve Patient Education in Urology,2 M.S. thesis, Dept Engineering and Info tech, Universität Magdeburg, Magdeburg, Germany, 2016. [Online]. Available https://www.researchgate.net/publication/310618970_A_Mobile_Augmented_Reality_Application_to_Improve_Patient_Education_in_Urology
28. Panteleimon P., Angeliki C., Ioanna P., Georgios P., Christos D., Thrasyvoulos P., Georgios L., and Michail S., "Virtual and Augmented Reality in Medical Education,

Medical and Surgical Education - Past, Present and Future”, *IntechOpen*, DOI: 10.5772/intechopen.71963, Dec 2017 [Online]. Available https://www.intechopen.com/books/medical-and-surgical-education-past-present-and-future/virtual-and-augmented-reality-in-medical-education
29. Viglialoro, Rosanna M., Sara C., Giuseppe T., Marina C., Vincenzo F., and Marco G., "Augmented Reality, Mixed Reality, and Hybrid Approach in Healthcare Simulation: A Systematic Review", *Applied Sciences*, vol. 11, no. 5: 2338, 2021. [Online]. Available: https://doi.org/10.3390/app11052338
30. Mayowa P., David B., Temitope D., Oluwaseun E., and Iyanuoluwa G., “Augmented Virtual Reality in Education and the Field of Medicine for Global Impact”, *International Journal of Advanced Research*, Vol. 7, no. 12, pp.344-353, 2019. [Online]. Available: http://dx.doi.org/10.21474/IJAR01/10160
31. Sarah A ., Graham R., “Virtual Reality Technology and Surgical Training - A Survey of General Surgeons In Ireland”, *Irish Journal Of Medical Science*, vol. 175, no. 1, Mar 2006. [Online]. Available: https://www.researchgate.net/publication/7165465_Virtual_reality_technology_and_surgical_training_-_A_survey_of_general_surgeons_in_Ireland
32. Herpich, Fabrício and Nunes, Felipe and Petri, Giani and Tarouco, Liane, “How Mobile Augmented Reality is Applied in Education”, *Creative Education*, vol. 10, no. 7, pp 1589-162, 2019. [Online]. Available: https://www.scirp.org/journal/paperinformation.aspx?paperid=93878
33. An, Brian and Matteo, Forrest and Epstein, Matt and Brown, Donald., “Comparing the Performance of an Immersive Virtual Reality and Traditional Desktop Cultural Game”, Proceedings of the 2nd International Conference on Computer-Human Interaction Research and Applications (CHIRA 2018), Seville, Spain, September 19-21, 2018 pp. 54-61. [Online]. Available: https://www.scitepress.org/Papers/2018/69228/69228.pdf
34. Prasanna K., “Effectiveness of Virtual Reality Based Immersive Training for Education of Health Professionals: A Systematic Review”, M.S Thesis, Health Sciences, University of Canterbury, Christchurch, New Zealand, 2011. [Online]. Available: http://hdl.handle.net/10092/6721
35. Manisha B., “Investigation of Interaction Metaphors for Augmented and Virtual Reality on Multi-Platforms for Medical Applications”, M.S Thesis, Department of Electrical, Mechanical and Industrial Engineering, 2020. [Online]. Available: https://www.hs-anhalt.de/fileadmin/Dateien/FB6/personen/tuemler_j/Final_Thesis_Copy_ManishaSureshBalani.pdf
36. Orraryd P., “Exploring the Potential Use of Augmented Reality In Medical Education”, M.S Thesis, Department of Science and Technology, Linköping University, Linköping, Sweden,2017. [Online]. Available: http://www.diva-portal.se/smash/get/diva2:1147159/FULLTEXT01.pdf2017.
37. Dorota K., Tomasz S., Sławomir W., Toomas T., Rain Eric H., Egils A., Ahmed H., Cagri O. and Gholamreza A., “Virtual Reality and Its Applications in Education: Survey”, *Multidisciplinary Digital Publishing Institute*, Vol. 10, no. 10, 2019. [Online]. Available: https://doi.org/10.3390/info10100318

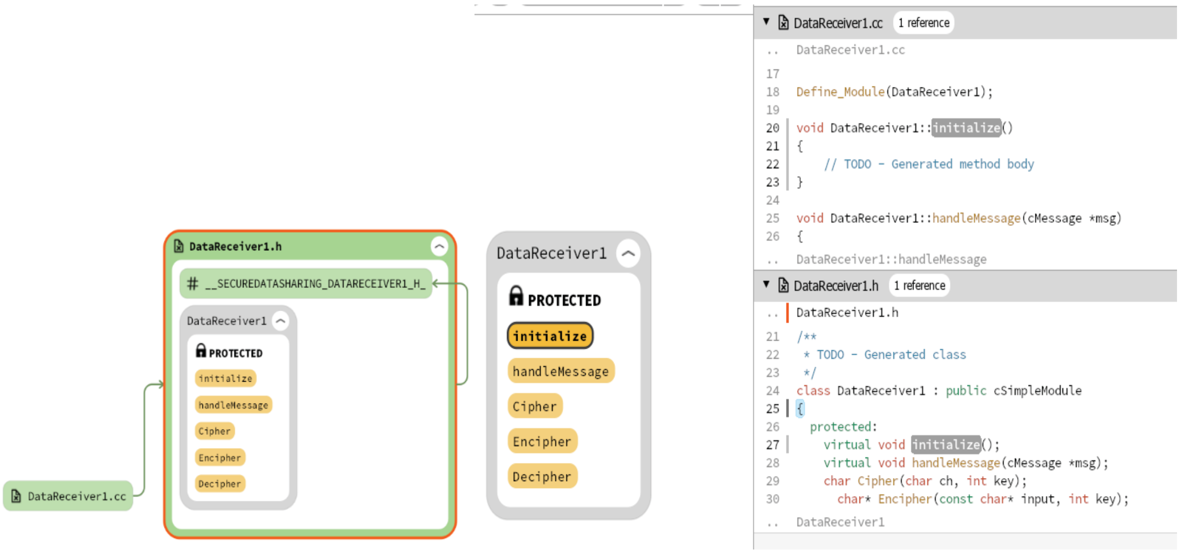
38. Vishal P.," The Application of Innovative Virtual World Technologies to Enhance Healthcare Education", PhD Thesis, Department of Surgery and Cancer, Imperial College, London, United Kingdom,2014. [Online]. Available: https://spiral.imperial.ac.uk:8443/handle/10044/1/25270
39. MauraS. and NinaS., "Perspectives of Extended Reality in Nursing — A Literature Review", M.S Thesis, Department of Nursing, Laurea University of Applied Sciences, Finland, 2020. [Online]. Available: https://www.theseus.fi/handle/10024/346282
40. Brian V., "The effectiveness of an Augmented reality training paradigm", M.S Thesis, Department of Human Factors and Systems, Embry-Riddle Aeronautical University, Daytona Beach, Florida, USA, 2002. [Online]. Available: https://commons.erau.edu/cgi/viewcontent.cgi?article=129 1 &context=db-theses
41. Nesenbergs, Krisjanis, Valters A., Juris O. and Artis M., "Use of Augmented and Virtual Reality in Remote Higher Education: A Systematic Umbrella Review", *Multidisciplinary Digital Publishing Institute*, Vol. 11, no. 1, 2021. [Online]. Available: https://doi.org/10.3390/educsci11010008
42. Sankalp M., "Use Of Virtual Reality Technology In Medical Training And Patient Rehabilitation", M:S Thesis, Department of Computer Science and Engineering, Wright State University, Ohio, USA, 2019. [Online]. Available: https://corescholar.libraries.wright.edu/etd_all/2151/
43. Mohd J., Abid H., "Virtual reality applications toward medical field", Science Direct, Vol. 8, no. 2, Pages 600-605, 2020. [Online]. Available: https://doi.org/10.1016/j.cegh.2019.12.010.pg.
44. Anderson, James and Chui, Chee-Kong and Cai, Yiyu and Wang, Yaoping and Li, Zirui and Ma, Xin and Nowinski, Wieslaw and Solaiyappan, Meiyappan and Murphy, Kieran and Gailloud, Philippe and Venbrux, Anthony, "Virtual Reality Training in Interventional Radiology", presented at the Johns Hopkins and Kent Ridge Digital Laboratory Experience seminar, Singapore, Vol. 19, no. 2, pg. 179-186, (2002). [Online]. Available: https://www.thieme-connect.de/products/ejournals/abstract/10.1055/s-2002-32796.
45. de Boer I., "VR As Innovation In Dental Education: Validation Of A Virtual Reality Environment: Collecting Evidence 'on-the-fly' During Development and Implementation", European Journal Of Dental Education , Vol. 22, no. 4,pg 215-222, March 2018. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1111/eje.12331
46. Peng X., "Enhancing Healthcare with Virtual Reality", M.S Thesis, School of Engineering, Computer and Mathematical Sciences, Auckland University of Technology, New Zealand, May 2018. [Online]. Available: https://openrepository.aut.ac.nz/handle/10292/11787
47. "INET 2.2.0 Framework," [Online]. Available: https://inet.omnetpp.org/Download.html

APPENDIX

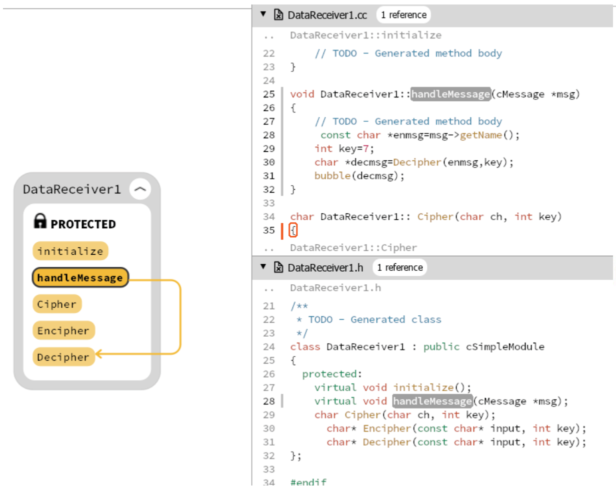
Appendices A

Cloud VR Terminals (Data Receivers)

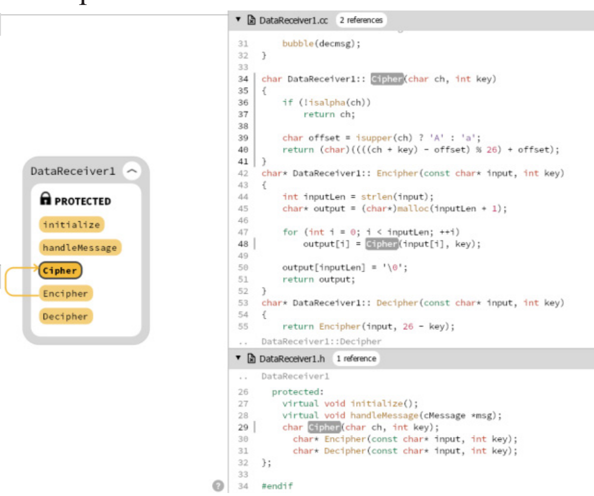
1. Initialize



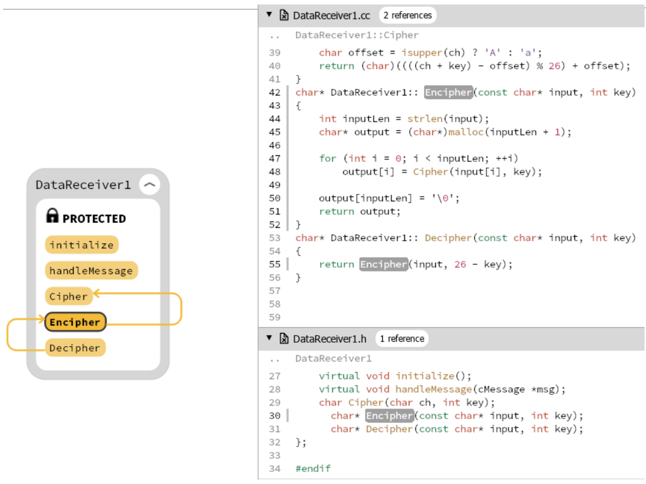
2. Handle Message



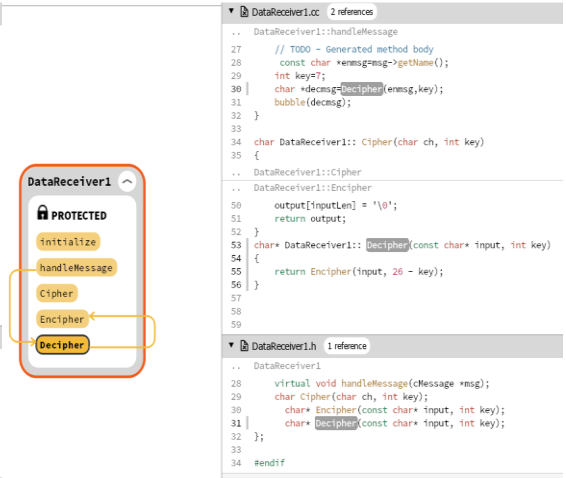
3. Cipher



4. Encipher

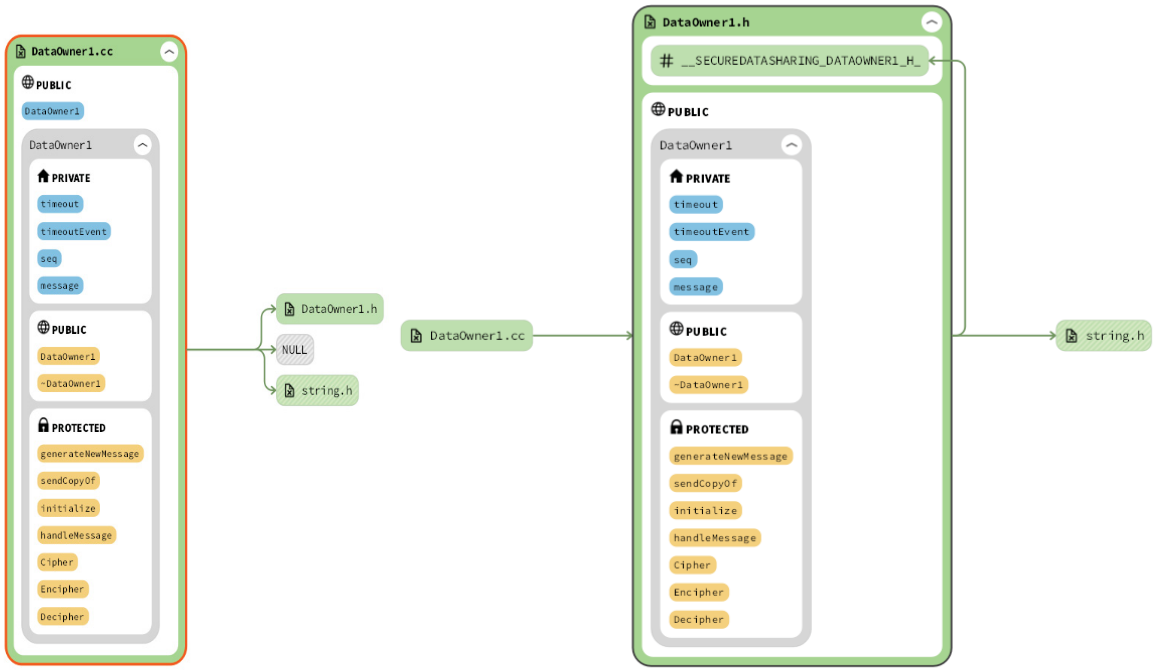


5. Decipher

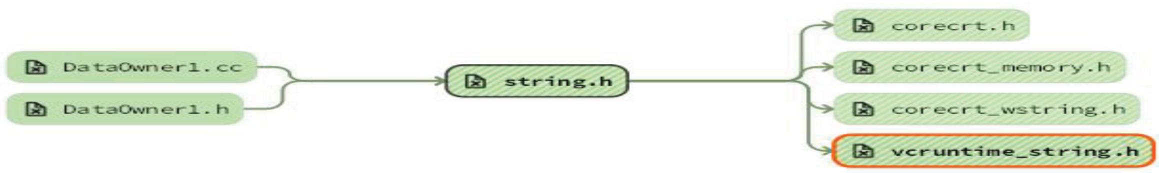


Data Owner

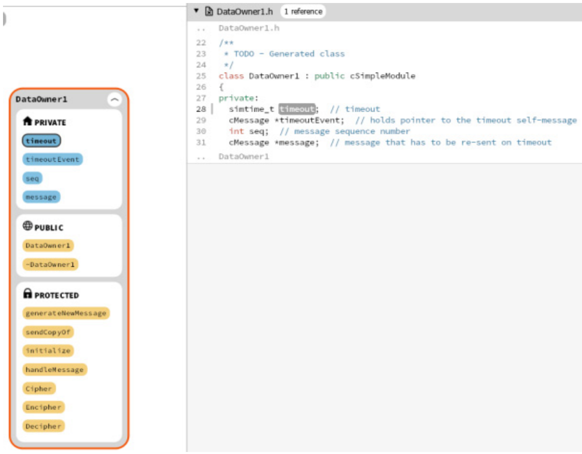
1. C++ and header file



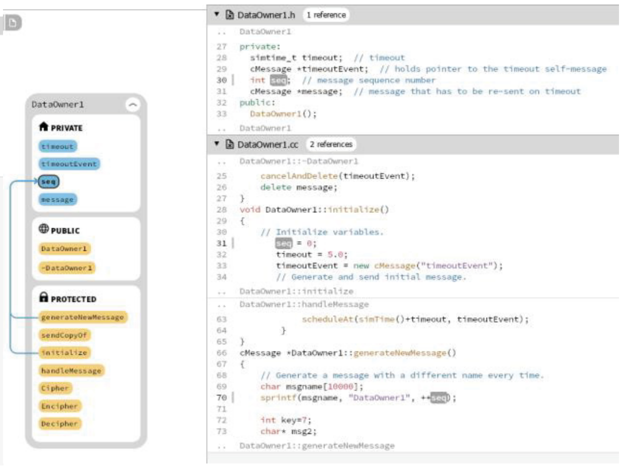
2. Interaction between the main C++ and other header files



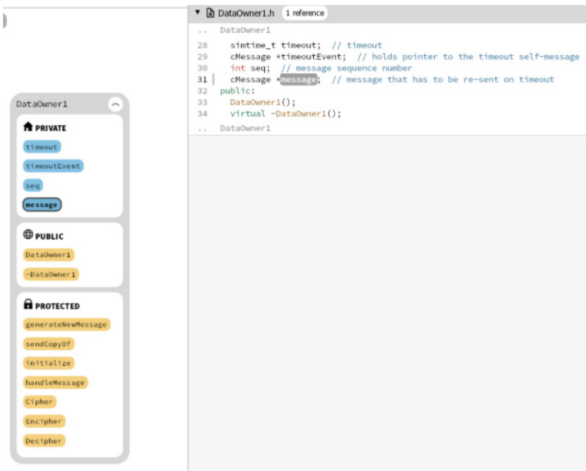
3. Timeout



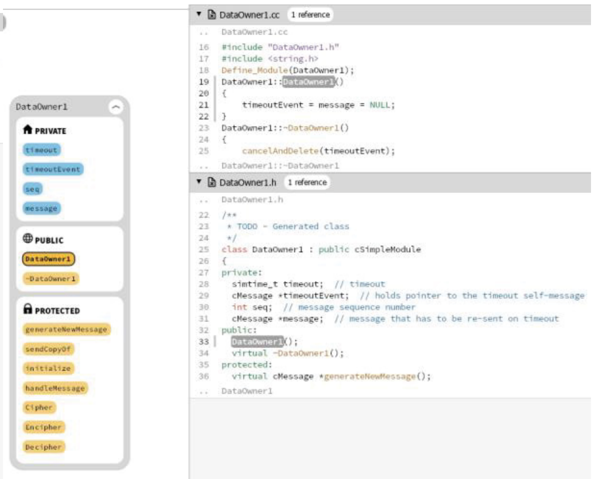
4. Sequence



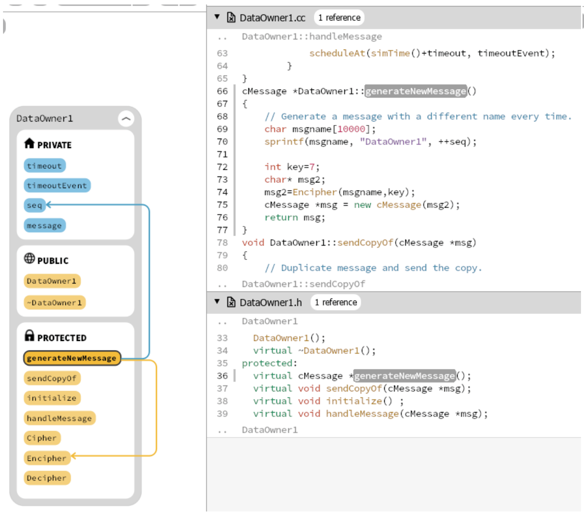
5. Message



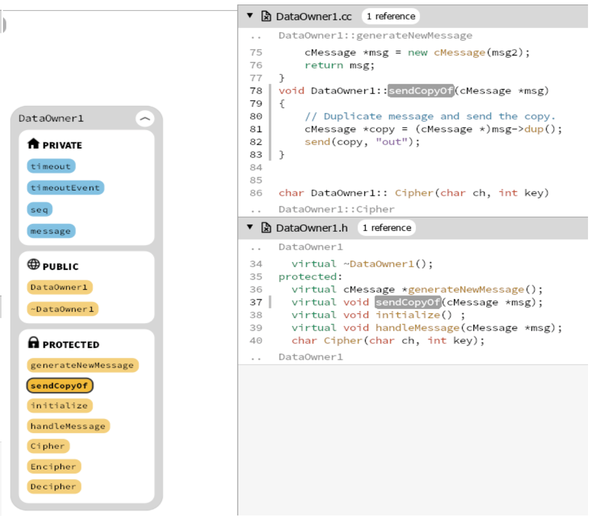
6. Data Owner 1



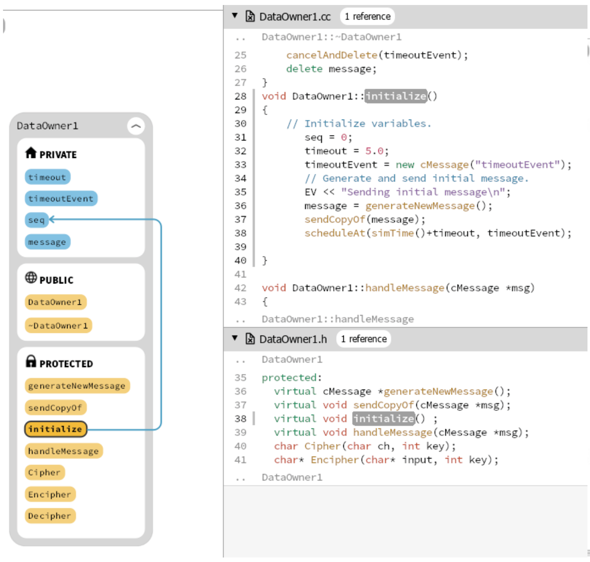
1. Generated Contents



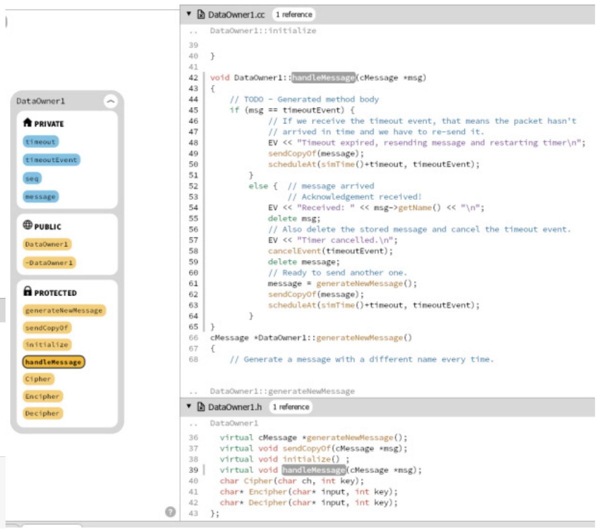
7. Contents Output



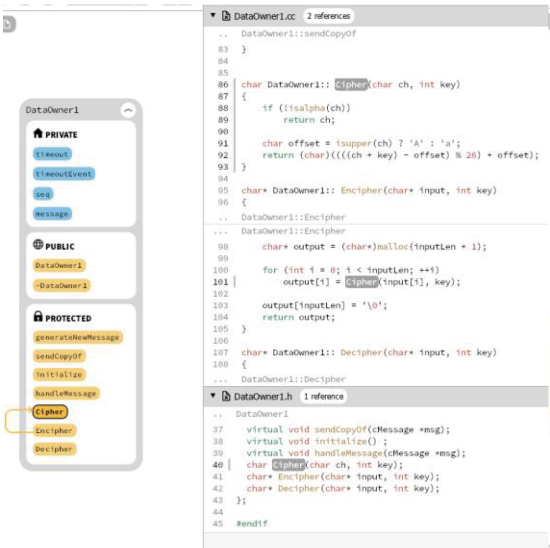
2. Initialize



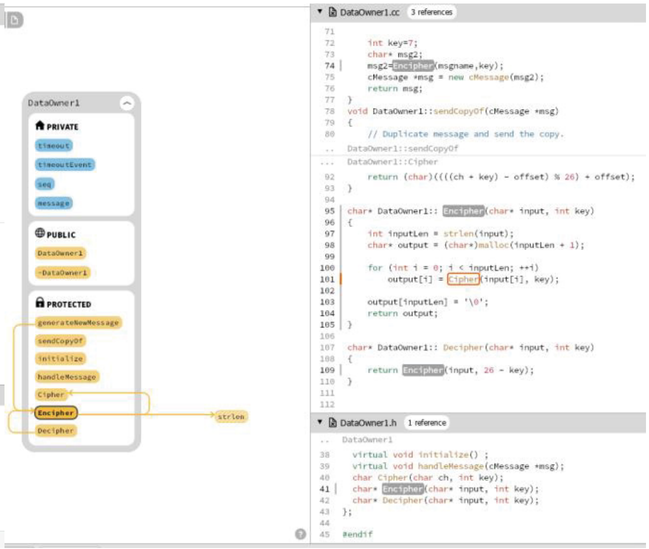
9. Message Handling



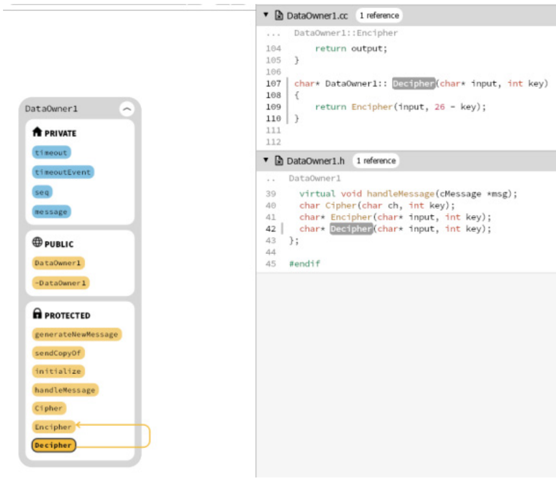
10. Cipher



11. Encipher



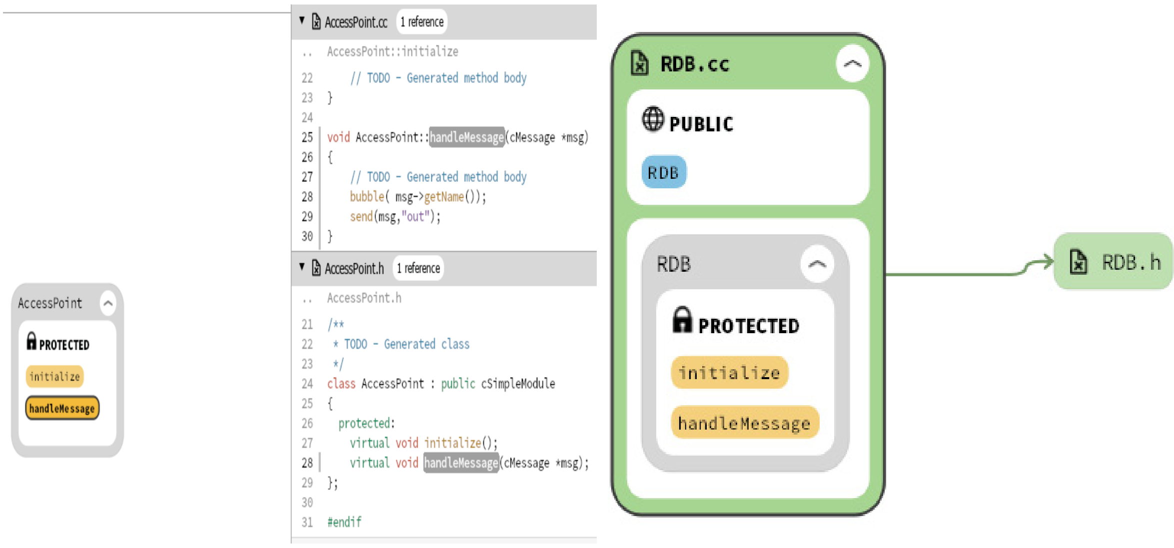
12. Decipher



Access Point.

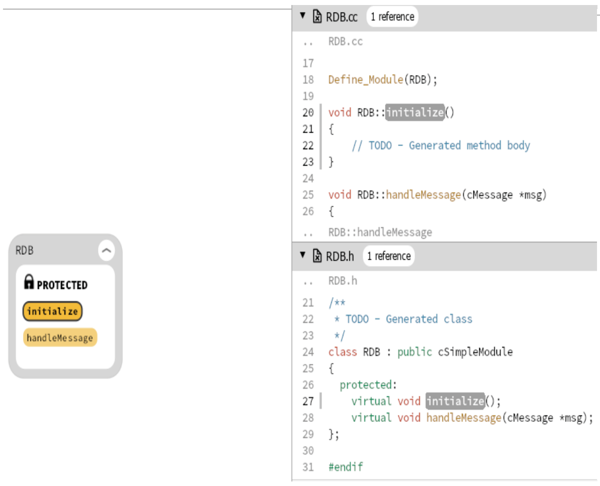
1. Initialize

2. Handle message

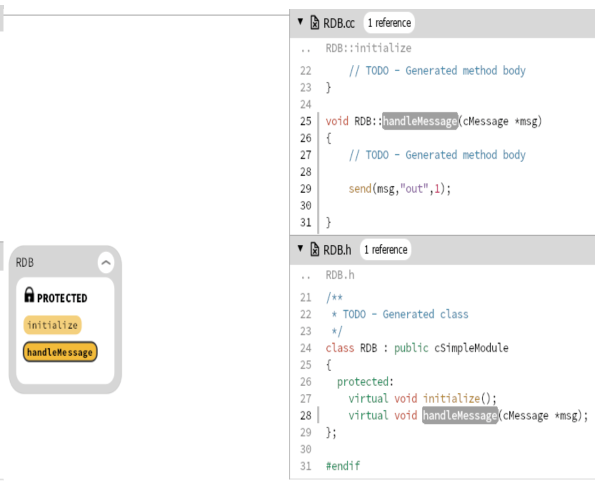


4.3.5.4 Relational Databases

1. Initialize

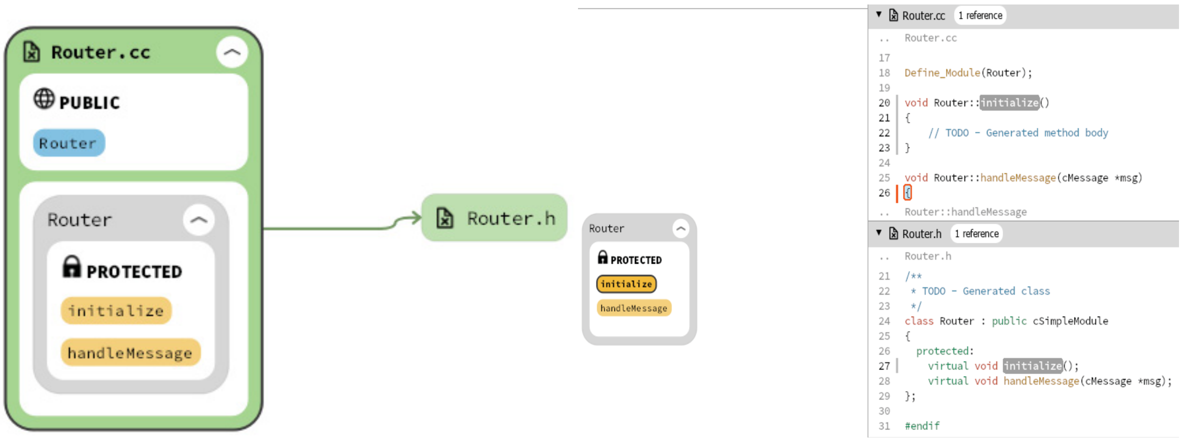


2. Handle Message

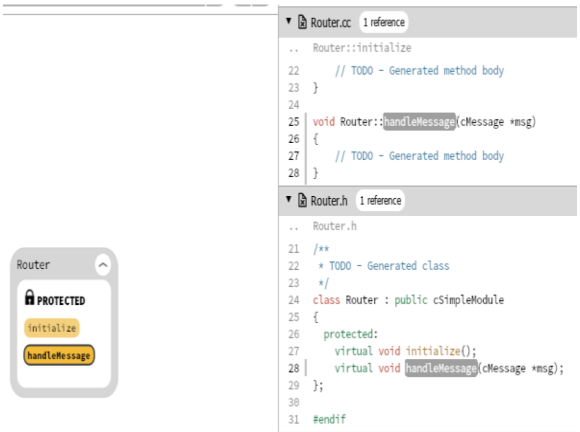


Routers.

1. Initialize

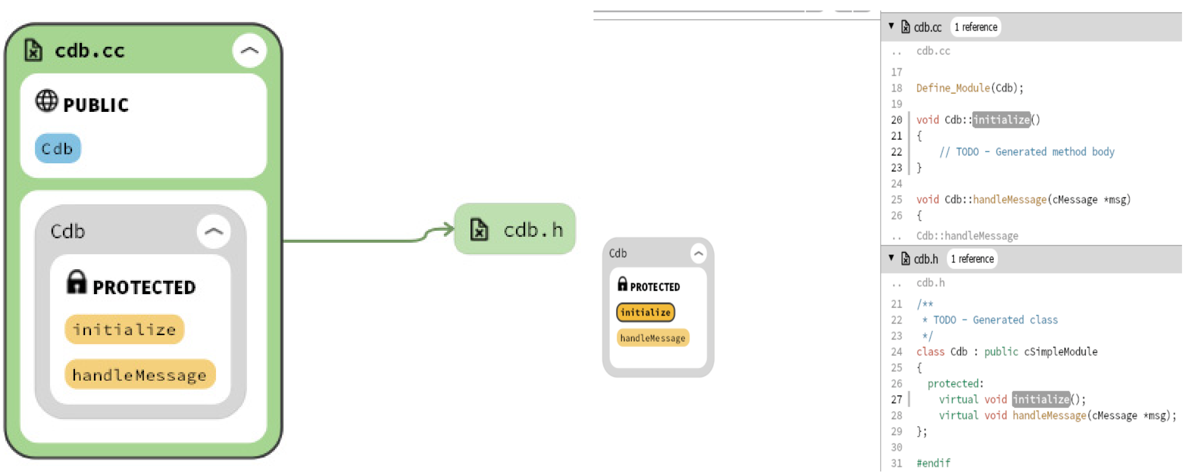


2. Handle Message



Cloud and Software Defined Network Database.

1. Initialize



2. Handle Message