Lappeenranta University of Technology
School of Engineering Science
Erasmus Mundus Master’s Programme in Pervasive Computing & Communications for Sustainable Development (PERCCOM)

Furkat Gofurov

NEW MULTIMEDIA SERVICES IN SDN CONSIDERING ENERGY CONSUMPTION OF THE NETWORK

Examiners:  Professor Eric Rondeau (University of Lorraine)
                 Professor Jari Porras (Lappeenranta University of Technology)
                 Associate Professor Karl Andersson (Luleå University of Technology)

Supervisors:  Professor Eric Rondeau (University of Lorraine)
                  Associate Professor Jean-Philippe Georges (University of Lorraine)
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ABSTRACT

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New Multimedia Services in SDN Considering Energy Consumption of the Network

Master’s Thesis

68 pages, 20 figures, 8 tables, 3 appendix

Examiners: Prof. Eric Rondeau (University of Lorraine)
Prof. Jari Porras (Lappeenranta University of Technology)
Assoc. Prof. Karl Andersson (Luleå University of Technology)

Keywords: Green Software Defined Networking (SDN), energy consumption, carbon emission, Content Delivery Network (CDN), video streaming service, edge/fog computing, Mininet

Multimedia services getting more popular day by day, especially increasing demand for video streaming services resulting in huge amounts of data to be transferred every day. To handle such gigantic volumes of data, Content Delivery Network (CDN) plays a crucial role by geographically distributing servers in multiple locations. Edge computing is a new paradigm, promising to enable real-time communication and low latency and guaranteeing an adequate Quality of Experience (QoE) for end users by taking cache and processing resources closer to the end user at the edge of the network. Such complex architectures require centralized approach with programmability, where Software-Defined Networking
(SDN) addresses required capabilities. However, Quality in Sustainability (QiS) metrics, such as energy consumption and carbon emission of video streaming services using CDN and edge/fog computing technologies integrated with SDN are not considered in most of the prior works in the area. Therefore, in this paper, we propose new green services to manage and optimize an energy consumption as well as reduce carbon emission using server placement optimization. We performed set of experiments using various architectures based on Mininet network simulator and SDN controller to prove the efficiency of the solution. Moreover, we perform an evaluation of such green energy management services, present achieved high sustainability gains and present research challenges.
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Furkat Gofurov
Nancy, France
July 10, 2018
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABR</td>
<td>Adaptive Bitrate</td>
</tr>
<tr>
<td>APIs</td>
<td>Application Programming Interfaces</td>
</tr>
<tr>
<td>AWS</td>
<td>Amazon Web Services</td>
</tr>
<tr>
<td>BIP</td>
<td>Binary Integer Program</td>
</tr>
<tr>
<td>CDN</td>
<td>Content Delivery Networks</td>
</tr>
<tr>
<td>CNCE</td>
<td>Communication Network Carbon Efficiency</td>
</tr>
<tr>
<td>CNEE</td>
<td>Communication Network Energy Efficiency</td>
</tr>
<tr>
<td>DE</td>
<td>Germany</td>
</tr>
<tr>
<td>FR</td>
<td>France</td>
</tr>
<tr>
<td>GÉANT2</td>
<td>Gigabit Éuropean Advanced Network Technology</td>
</tr>
<tr>
<td>GCP</td>
<td>Google Cloud Platform</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communications Technology</td>
</tr>
<tr>
<td>ILP</td>
<td>Integer Linear Programming</td>
</tr>
<tr>
<td>ISP</td>
<td>Internet Service Provider</td>
</tr>
<tr>
<td>LUX</td>
<td>Luxembourg</td>
</tr>
<tr>
<td>MPLS</td>
<td>Multi-Protocol Label Switching</td>
</tr>
<tr>
<td>OTT</td>
<td>Over-the-top</td>
</tr>
<tr>
<td>QiS</td>
<td>Quality in Sustainability</td>
</tr>
<tr>
<td>QoE</td>
<td>Quality of Experience</td>
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<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RRL</td>
<td>Rectangle Rule List</td>
</tr>
<tr>
<td>SDN</td>
<td>Software Defined Networking</td>
</tr>
<tr>
<td>SSIM</td>
<td>Structural Similarity index</td>
</tr>
<tr>
<td>TCAM</td>
<td>Ternary Content Addressable Memory</td>
</tr>
<tr>
<td>VLC</td>
<td>VideoLAN Client player</td>
</tr>
<tr>
<td>VM</td>
<td>Virtual Machine</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

The increased usage of Internet and the enormous amount of energy consumption by communication networks and network devices have resulted to draw the attention of Information and Communications Technology (ICT) sector to the problem of power consumption optimization in today’s data networks. According to Smart 2020 [1] ICT sector’s emissions are expected to rise from 0.53 billion tonnes (Gt) carbon dioxide equivalent (CO$_2$e) in 2002 to 1.43 GtCO$_2$e in 2020. In [2] authors show that, the global electricity demand of ICT is on constant rise, accounting for 8% of overall produced electricity usage in 2010 and hitting a maximum demand of 51% by 2030. These are the obvious indications for the significance of managing energy consumption in ICT in order to move towards sustainability.

To be more precise, an increasing demand for video streaming services has been observed through past few years, based on the predictions from Cisco [3]. As shown in Fig. 1, IP video traffic will account for 82% of all consumer Internet traffic by 2021, rising from 73% in 2016.

![Fig. 1 Video traffic prediction by Cisco](image)

*Source: Adapted from [3]*
It is clear that, among the major ICT sectors, telco networks account for big share of ICT total energy consumption. Therefore, some of the ways to reduce energy footprint of ICT sector are accomplishing an energy saving in Internet Service Providers’ (ISP) backbone networks. Keeping that in mind, new multimedia services, especially Over-the-top (OTT) services also has gained a tremendous popularity in the recent years, thanks to the advancement of new technologies and huge amounts of data to be transferred every day traversing the networks every day. As this work focuses on video streaming services, popular OTT media streaming services are depicted in Fig. 2, including but not limited to Netflix, YouTube, Hulu and others being main platforms, that need to take rapid actions towards managing energy consumption and it’s carbon footprint awareness in order to attain a sustainability. OTT if simply put, is a way to deliver a content directly to users using a Content Delivery Networks (CDNs) or services that come in over the web [4]. To perform a delivery of the content, CDNs deploy clusters of servers globally in hundreds of datacenters, which are located at the “edge” of the Internet.

![Logo of Netflix, YouTube, Hulu, Showtime, Sling, and HBO Now](image)

**Fig. 2 List of Streaming services**

*Source: Adapted from [4]*

To highlight the importance of CDNs, it is predicted that, by the year of 2019, 72 % of Web traffic will cross CDNs globally [3]. Talking again about Netflix, it makes use of three different CDNs – Akamai, OpenCDN and Level 3 to support its own subscribers. On top of that, Amazon Web Services (AWS) cloud-computing platform is deployed for operations, like sign up or searching videos. The main share of energy consumed by Netflix accounts
for AWS or Google Cloud Platform (GCP) including servers hosted in partner ISP networks. According to [5], total electricity footprint of Netflix was 140,000 MWhs in 2016. Furthermore, in case of CDNs, server deployment energy consumption has biggest share. However, energy consumption of above-mentioned platforms, consisting of thousands of servers running every day, consuming a huge amount of energy while emitting an immense amount of carbon dioxide, still brings up a concern of lacking a green energy management services. As a proof for the above statement, based on Fig. 3, we can observe that, companies like Apple, Facebook and Google are investing a lot on sustainability aspect and their footprint, trying to run their platforms on close to 100% renewable energy [6].

![Fig. 3 List of companies with Clean Energy Index](image)

**Source**: Adapted from [6]
On the other hand, OTT service, Netflix in this case, falls behind in the race towards the race to build a green internet with least percentage of clean energy index of just 17% among others. As it is highlighted, video traffic travelling through the Internet will sharply increase in the near future and it means that, OTT streaming services must take into account sustainability aspects, such as energy consumption and carbon footprint as their immediate action plan for the near future.
1.1 Research Goals

Video streaming platforms will result in a huge energy consumption savings in the long run. Therefore, new green services and novel approaches are needed to maximize the energy efficiency. The main motivation behind this work is to propose a new green energy efficient management services based on server placement optimization horizontally and vertically in all layers of the CDN/SDN network architectures. Bandwidth varying and server placement, taking into account CO$_2$ factors in different countries analyzed later in the paper. As main contributions, architecture and implement green services to achieve a sustainability in terms of energy efficiency and carbon emission are outlined. The implementation part of the study is based on the simulation of network and compute resources in Mininet simulation tool, considering different scenarios, using Three Tire Network Architecture with Access, Distribution and Core network layers and GÉANT2 network architecture leveraged by CDN/SDN for video streaming case. Evaluation of proposed green energy management services and their high gains in sustainability metrics, namely energy consumption and CO$_2$ emission, are elaborated along with presenting research challenges to conclude a research.

1.2 Research Questions and Objectives

I. How to minimize energy consumption of video streaming services?

➢ What parameters are important to collect?
➢ What are the constraints?

II. How do we test our services?

➢ What tools to be used?
➢ What type of architectures to choose and why?
➢ What are the key challenges?

The objectives are as follows:

➢ Propose new green energy efficiency services in terms of Quality of Sustainability (QiS) focused mainly on energy consumption and CO$_2$ emission of video streaming networks
➢ Ensure the appropriate level of Quality of Experience (QoE) and Quality of Service (QoS) of the video streaming service
1.3 Structure of the Thesis

The remainder of the manuscript is organized as follows: Chapter 1 presents a key subject – an overview, the research goals, motivations, and objectives. Chapter 2 highlights the workflow of the study and the steps or to put it in other words, methodology of the research to complete the whole research. In Chapter 3, previous works and findings to improve energy efficiency of SDN, CDN/SDN framework and approaches as well as Edge Computing integrated for multimedia services in SDN case scenario are analyzed. Chapter 4 explains system architecture and requirements including benchmarking of various experimental architectures and their evaluation. In Chapter 5, the analysis and findings of the study will be discussed and sustainability aspects outlined. Finally, in Chapter 6 we will wrap up our study with conclusion and recommendations for future works.
2 METHODOLOGY

2.1 Agile Development Methodology

This chapter describes an Agile Development Methodology [7] which is divided into macro and micro levels along with important metrics that have been chosen to be used in the research. Definition and relative equations of Quality in Sustainability (QiS), Quality of Experience (QoE) and Quality of Service (QoS) metrics are presented, as comparison and efficiency of the services will mainly depend on these parameters.

The key appealing feature of Agile Development Methodology is - changes to requirements during any stage of the Software Development Life Cycle can be applied making it more easy and highly flexible to dynamic environments. We present our methodology in two levels, macro and micro. The macro level of methodology depicts whole general process as shown in Fig. 4, consisting of six stages as following: requirement analysis, plan, design, implementation, testing and evaluation.

![Agile Development Methodology](image)

**Fig. 4** Macro level Agile Development Methodology

**Source:** Adapted from [7]
On the other hand, the micro level of methodology explains details of techniques, tools, configuration and experimental setup parts.

1. Requirement analysis - includes functional and non-functional requirements of the system;
2. Plan - finding gaps in energy consumption and excessive CO$_2$ emission of the networks offering video streaming services. Thus, the bandwidth shaping as a preliminary step to justify our arguments and optimization of server placement technique as the main solution will be used to achieve the energy efficiency and CO$_2$ emission reduction overall;
3. Design - incorporated tools, metrics and approaches with SDN technology, choosing network topologies for experimental setup to propose new multimedia services are examined and work feasibility is confirmed;
4. Implementation - new energy efficient services are implemented using a Mininet [8] simulation environment. Mininet is an open-source tool to create a realistic virtual network, with few lines of code. Our solution is leveraged by CDN/SDN technologies for video streaming case and simple to complex network topologies configuration setup implemented;
5. Testing - Quality in Sustainability (QiS), Quality of Experience (QoE) and Quality of Service (QoS) metrics are collected for testing viability of the approach as well as benchmarking of architectures to test Energy consumption and Carbon emission metrics are tested;
6. Evaluation - evaluation of Server Placement Optimization solution in terms of QiS, QoE and QoS carried out and gains or claims mainly in terms of energy consumption and CO2 are presented.
2.2 Metrics

The main metrics chosen for this research are following: Quality in Sustainability (QiS), Quality of Experience (QoE) and Quality of Service (QoS).

A. Quality in Sustainability (QiS) metrics:

➢ Total Power consumption – is a computational calculation of the power consumed by the analyzed network architecture in a specific time period and task execution in Watts. For calculations, measured definite values in [9] are used;

➢ Total CO$_2$ – is a computational calculation of the CO$_2$ emission in tons of carbon dioxide (tCO$_2$e) according to CO$_2$ factors [10], as shown in Table 1.

➢ Total cost of electricity – is calculated based on electricity price per country in euros cents, based on Table 1.

➢ Communication Network Energy Efficiency (CNEE) – measures the efficiency of a packet delivery process in data center network. The unit used for CNEE is watts/bit/second, which is equal to joules/bit, or the energy required to send a single bit of information by the network [11]:

$$CNEE = \frac{Power \ Consumed \ by \ Network \ Equipment}{Effective \ Network \ Throughput \ Capacity}$$ (1)

➢ Communication Network Carbon Efficiency (CNCE) – measures the efficiency of carbon emission for a packet delivery process in data center network. The CNCE unit is measured in kg/bit which is the amount of carbon emission emitted to send a single bit of information by the network:
\[
CNCE = \frac{\text{Total Carbon Emission}}{\text{Effective Network Throughput Capacity}}
\] (2)

B. Quality of Experience (QoE) metrics:

➢ The Structural Similarity (SSIM) index – is a metric to compare the similarity between two images. The SSIM score range is 0 to 1 for simulated video in all experiments as in Table 2. The SSIM score of 1 means that the received video is 100% the same as in the source point video without any loss in quality. The measure between two windows \( x \) and \( y \) of common size \( N \times N \) is:

\[
SSIM(x, y) = \frac{(2\mu_x \mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}
\] (3)

where:

- \( \mu_x \) is the average of \( x \);
- \( \mu_y \) is the average of \( y \);
- \( \sigma_x^2 \) is the variance of \( x \);
- \( \sigma_y^2 \) is the variance of \( y \);
- \( \sigma_{xy} \) is the covariance of \( x \) and \( y \);
- \( c_1 = (k_1L)^2 \), \( c_2 = (k_2L)^2 \) two variables to stabilize the division with weak denominator;
- \( L \) is the dynamic range of the pixel-values;
- \( k_1=0.01 \) and \( k_2=0.03 \) by default.
Video Packet loss – is defined as chunks of video file failing to reach the client-side player while streaming and asking for retransmission request, measured in a percentage scale.

C. Quality of Service (QoS) metrics:

- Average throughput – is a rate of effective content delivery over a communication channel, measured in bits per second (bps);
- Packet delay – is an amount of time for the content to reach client-side player and measured in milliseconds (ms);
- Jitter – is a measure of variation in delay and measures how consistent is a delay, measured in milliseconds (ms).

Moreover, Table 1. presented to calculate CO₂ emissions and electricity price, Table 2. from [12] shows power consumption for constant link rate and link rate switching and lastly Table 3. for reference video file size used in all simulations.

**Table 1.** National and European emission factors and price for consumed electricity

<table>
<thead>
<tr>
<th>Country</th>
<th>Standard emission factor (t CO₂/MWhₑ)</th>
<th>Electricity price (euro cents per kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>0.056</td>
<td>14.72</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>1.08</td>
<td>16.15</td>
</tr>
<tr>
<td>Germany</td>
<td>0.624</td>
<td>29.42</td>
</tr>
</tbody>
</table>
**Table 2.** Power Consumption for Constant Link Rate and Link Rate Switching

<table>
<thead>
<tr>
<th>Energy</th>
<th>10Mb/s</th>
<th>100Mb/s</th>
<th>1Gb/s</th>
<th>100Mb/s/10Mb/s</th>
<th>10Mb/s/1Gb/s</th>
<th>1Gb/s/100Mb/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (W)</td>
<td>0.1</td>
<td>0.4</td>
<td>3.6</td>
<td>0.8</td>
<td>1.05</td>
<td>1.6</td>
</tr>
</tbody>
</table>

**Table 3.** Reference Video file size used in simulations (values obtained from video properties)

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Size</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>720x480p</td>
<td>5 MB (5,243,244 bytes)</td>
<td>27 seconds</td>
</tr>
</tbody>
</table>
3 REVIEW OF RELATED WORKS

This chapter is divided into three parts that will cover following: (a) Energy Efficiency in SDN, (b) SDN based CDN video streaming, (c) Edge computing for video streaming integrated with SDN. All previous works, studies and approaches towards sustainability and QoE as well as QoS related to this research will be discussed.

3.1 Green Service and Energy Efficiency in SDN

A service is considered “green,” when it is deployed in computing systems, which targeted to reduce energy consumption and increase energy efficiency as well as cause a minimal environmental impact. Generally, these types of services usually function by relaxing traditional performance-based parameters for creating opportunities to save energy. In our case, proposed new green services for managing energy consumption in video streaming scenarios will be evaluated in the next chapters.

Software Defined Networking (SDN) [13] is a novel approach, which is dynamic, adaptable and configurable. The general idea of the SDN is decoupling the switch control plane from the data plane. This means that network devices can be programmed and managed by the SDN controller directly.

Some of the key elements of the SDN architecture as in Fig. 5 are following:

- **The network controller** in the control layer is attached to Application Layer using Northbound Application Programming Interfaces (APIs) and linked to data plane by Southbound APIs, which are used to configure switches and handle fast packet processing. The main task of the controller is to install packet processing rules onto the OpenFlow switches in the network and handle overall communication between switches
- **Control-plane APIs** of OpenFlow switches used to receive instructions from the controller as well as perform very basic updates to the data plane without contacting the controller
- **Infrastructure layer or Data plane** comprised of Programmable switches which handle the actual packet processing and carries user traffic.
Adding to this, as shown in Fig. 6, from practical example of deploying OpenFlow switches in a data center resulted in 80% energy consumption reduction making SDN technology as a novel approach for most of the huge ICT companies in the sector [14].

It proves that, SDN helps to make existing processes and devices function properly as needed, even do more work but consume less energy.
There are various approaches for achieving energy efficiency using SDN. In one of the papers, authors study principles, advantages versus disadvantages of recent SDN techniques focusing on energy minimization. Full comparison of existing approaches in terms of energy gain ratios are presented showing possible sustainability aspects [15]. In another study presented by Danda, et. al (2017), fixed list of almost all energy efficient techniques are collected together. To the best of our knowledge according to [16], Energy Efficiency techniques through SDN implementation are following:

- Energy Efficiency with optimal network resource utilization
- Energy Efficient Traffic Engineering/Management
- Energy Efficient SDN Policy Updating
- Energy Efficient Monitoring of Traffic Conditions
- Ternary Content Addressable Memory (TCAM) Compression for Energy Efficiency
- Proper Placement of SDN Devices for Energy Efficiency.

Similarly, authors in [17] tried to collect all recent Energy efficiency approaches in SDN and improved the research that was carried out by previous researchers paper. On of the main difference is it discusses weaknesses of proposed techniques for energy efficiency in SDN and tries to give a feedback on drawbacks of each strategy. Table 2. lists full and recent table of energy-efficient SDN strategies.
Table 4. Summary of Energy-efficiency techniques in SDN

<table>
<thead>
<tr>
<th>Category</th>
<th>Approach</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic aware</td>
<td>Elastic Tree</td>
<td>Elastic Tree, based on traffic, Mixed IP, re-computation cost</td>
</tr>
<tr>
<td></td>
<td>CARPO</td>
<td>Fat Tree, based on correlation analysis among flows</td>
</tr>
<tr>
<td></td>
<td>REsPoNse</td>
<td>Fat Tree, identify energy-critical path to optimize</td>
</tr>
<tr>
<td></td>
<td>Carrier Grade</td>
<td>MLTE implementation, topology-aware heuristic</td>
</tr>
<tr>
<td></td>
<td>Integrated</td>
<td>Combined sleep and turning off, recovery from failure</td>
</tr>
<tr>
<td>Compacting TCAM</td>
<td>Rectilinear</td>
<td>Rectangle Rule List (RRL) minimization, geometric model</td>
</tr>
<tr>
<td></td>
<td>TCAM Razor</td>
<td>Decision diagrams, dynamic programming, and redundancy algorithm</td>
</tr>
<tr>
<td></td>
<td>Bit Weaving</td>
<td>Non-prefix based compression</td>
</tr>
<tr>
<td></td>
<td>Compact TCAM</td>
<td>Usage of short tag</td>
</tr>
<tr>
<td>Rule Placement</td>
<td>Big Switch</td>
<td>Heuristics for endpoint policy, routing policy and rule placement</td>
</tr>
<tr>
<td></td>
<td>Palette</td>
<td>Graphs, algorithms, heuristics</td>
</tr>
<tr>
<td></td>
<td>Optimizing Rule Placement</td>
<td>Meaning of rules, Integer linear programming formulation of the problem</td>
</tr>
<tr>
<td>End Host Aware</td>
<td>Honeyguide</td>
<td>Virtual Machine (VM) migration, fault tolerance, easy deployment</td>
</tr>
<tr>
<td></td>
<td>EQVMP</td>
<td>Virtual Machine, load balancing</td>
</tr>
</tbody>
</table>

The formulation of optimization problem to identify appropriate set of active links for optimal resource utilization and conservation of energy consumption, while satisfying traffic demands is discussed and a computational efficient heuristic algorithm has been introduced in [18], [19]. A. Maleki et al conducted a research on energy consumption of core networks and saved 41% links in peak traffic time in GÉANT network, by managing the routing and forwarding decisions properly [20].
Furthermore, [21] presents a new traffic management and routing framework, called SDGTE (Software Defined Green Traffic Engineering), which adapts network energy consumption based on dynamics of network demands online without foregoing assumption of traffic in the network. The efficiency of framework saving energy while utilizing most of the links at the same time has been achieved by simulating realistic case studies. Energy-aware routing algorithms are proposed, determined by the active number of OpenFlow switches and Open Virtual Switch Node Connectors in the switches to achieve maximum energy efficiency in [22], [23] respectively.

It is known that heuristic algorithms will enable to achieve energy efficiency of the network enormously while degrading network performance slightly. Thus, there has been done an extensive research in the algorithmic approach proposed in various papers. [24] Proposes a heuristic algorithm named Strategic Greedy Heuristic with four various strategies to deal with problem of scaled networks while [25] presents two heuristic algorithms, namely Constant Weight Greedy and Dynamic Weight Greedy algorithms implemented to save energy in the network.

Furthermore, energy efficient placement of SDN devices, in particular, the placement of the Controller is an important problem. The problem can be solved by modeling approach of Binary Integer Program (BIP), where energy consumption of network can be minimized taking into account load of controllers and delay of control path along with the heuristic algorithm to overcome the issue of large networks [26].

Authors in [27] claim to achieve a high speed and reduction of energy consumption coupled with carbon emission by designing OpenFlow based network using simple network set-up and replacing the traditional network of Georgia Southern University. Despite significant reduction in terms of CO$_2$ and budget saving for energy consumed, paper seems to be not properly and lacks technical details of how implementation was carried out, specifications and further guidance for the solution.
3.2 SDN based CDN video streaming

In order to run OTT services we make use of CDN [Fig. 7] nowadays. Handling a gigantic volumes of data is not an easy task and CDN plays a crucial role by geographically distributing servers in multiple locations to solve this issue. As mentioned in previous chapters, CDN deploys clusters of servers globally in hundreds of datacenters, which are located at the “edge” of the Internet. The logic behind CDN is “shopping locally” and it is not always sustainable as believed. As so this work is a motivational work to try to propose new energy efficiency services in CDN/SDN networks, where SDN is used to manage network in a centralized manner.

Authors in [28], [29] studied video streaming services provided by SDN-based Content Delivery Networks (CDN) and SDN-based streaming multicast video frameworks respectively. Both research papers mainly concentrate on Quality of Experience (QoE) and Quality of Service (QoS) metrics, providing video streaming services with high availability.
CDN distributes content among different locations and consists of a caching mechanism, which keeps popular content on the edge servers without a global view of the network infrastructure. Adding to this, DNS servers used to redirect users to the closest server in CDN. There has been number of works which concentrated on improving Quality of Service (QoS) and Quality of Experience (QoE) perceived by the user. For example, in [30] they proposed optimal server selection which results in the reduction of link delay between servers and users, while [31] proposes an algorithm to decide routing strategy and selection of server at the same time while achieving bandwidth satisfaction and acceptable response time. Paulo A. L. Rego et al [32] proposed an elastic approach to handle a customer demand for video streaming service using OpenFlow-based load balancer and elasticity management mechanism which controls the number of active streaming servers (by increasing or decreasing). Experiments were carried out in OpenNebula (open source software for altering current data centers infrastructure into an Infrastructure as a Service Cloud) testbed.

On the other hand, multicast has been used as a promising solution in [33], for both Internet Service Providers (ISP) and CDNs live video streaming service. The paper proposes a framework between CDNs and ISPs to allow mCast for live video streaming emulated in Mininet. Collected results show that used links can be decreased almost twice compared to IP unicast while QoE metrics such as video frame loss and start-up delay can be improved. Moreover, Adaptive Bitrate (ABR) streaming where a video player adjusts resolutions based on end-to-end network conditions along with CDN can be used to improve user-perceived video quality in nowadays OTT video service providers.

However, the problem of congestion in the network in times of high demand and peak traffic hours still remains as bottleneck for video streaming services. Mathias Wichtlhuber et. al [34] proposed a new way to encourage CDN and ISP (Internet Service Provider) collaboration based on OpenFlow enabled network architectures in the ISP’s network. In [35], authors propose SDN application to constantly check behavior of network in real time and dynamically re(route) flows using Multi-Protocol Label Switching (MPLS) traffic engineering in order to deliver best QoE for the end user, while [36] offers a load balancer application implemented in the SDN controller, which controls real time link statistics for
required video and provides end users with a list of available servers using three different algorithms for comparison scenarios in SDN-based CDN networks.

As one of the popular applications that makes use of CDNs is YouTube Video Streaming [37]. In this paper, the evaluation of SDN-based Application-Aware Networking approaches are compared and simulated to see how various sorts of information gathered from application can be used to improve QoE in YouTube Video Streaming. The most interesting of this study is that they used YouTube quality monitoring tool YoMo, to identify impact of approaches, which shows Deep Packet Inspection and Application-Aware Path Selection methods overperform traditional ones such as Bandwidth-based or Round Robin, making Application-Aware SDN approach to be the most viable.
3.3 Edge Computing and Video streaming using Load Balancing

In contrast to CDN, where content has to go through transit network from CDN to ISP, following data delivery from ISP to end-users, edge technologies use a different approach of storing and processing elements at the edge of the network [38]. Furthermore, authors highlight huge potentials of edge computing in multimedia services and video streaming. In [39] the problem of massive amount of carbon footprint for video streaming service is the main challenge that solved by the paper, proposing a new multimedia services including sustainability parameters. Authors in [40], discussed and evaluated the performance of service migration from the cloud to multi-tier fog computing based on SDN to distribute video services with QoE support in the testbed. Nevertheless, the discussion of sustainability part still lacks on the video streaming services, mostly concentrating on QoE. Therefore, this work addresses these shortages and focuses on sustainability, to be precisely energy efficiency and carbon emission reduction of the multimedia offering services. While QoE is important factor for video streaming services, it is worth to remind that QoS for cloud applications and services need to be taken into account. [41] discusses SDN-based QoS technique which can provide end-to-end QoS routing for each cloud user service, resulting in improving traditional QoS metrics like delay, throughput.

Load balancing technique has been used for quite some time to handle traffic demand coming from users in case of server overloading. An interesting study has been done in [42] using a real-time path load condition strategy, so that network QoS metrics will be collected and integrated with Artificial Neural Network to show path load condition. This strategy is ultimately effective as transmission path for new incoming demands can be chosen by prior knowledge as well as achieving load balancing. [43] proposes a new application to improve the QoS for video streaming over single operator OpenFlow networks in case of server overload. Server load balance is achieved by continuous monitoring of the load of each server and dynamically redirecting ongoing or new service requests to available servers in such a manner that the end user experiences the lowest delay and distortion when one or more servers are overloaded. Similarly, authors in [44] presents an application that implements three load balancers using SDN, when compared to previous study, this paper more of evaluation of selected algorithms and their performance evaluation in specific SDN based case scenario.
4 IMPLEMENTATION AND EVALUATIONS

We have carried out various types of experiments depending on the research goals and objectives. In the early stages of the research main intention was to make sure the feasibility of the proposed solutions are achievable due to the time constraints. In this chapter we presented only three main experiments that were considered important and . To be precise, in this chapter we will be discussing mainly three experiments as listed in Fig. 8

**Experiment 1 and Objectives:**
it is a preliminary experiment to observe the impact of bandwidth variation & impact of number of servers to the sustainability

**Experiment 2 and Objectives:** to analyze SERVER PLACEMENT OPTIMIZATION solution in CDN/SDN architecture and observe energy efficiency in all three layers of Three tier architecture

**Experiment 3 and Objectives:** placement of servers considering carbon emission in 3 different countries using GÉANT2 network topology

*Fig. 8 Description for list of Experiments in flow chart*
4.1 System Architecture and Technical Specifications

Fig. 9 System Architecture

The system architecture as depicted in Fig. 9 is built in simulation environment Mininet. POX SDN controller was used due to the some advantages, such as reusable sample mechanisms for selecting path, topology discovery and simplicity in building and implementing network topologies using Python scripting, it is way more practical when designing related matter is a concern due to the time constraints. When topology is built depending on the benchmarking scenarios, any client demanding a video file from a server will be sending request to SDN controller. The main function of SDN controller is to optimize server placement as such server which is capable of meeting QoS, QoE and QiS metrics will be met during the video streaming process. Some of the known tools like VLC Media Player [45] for broadcasting video from the server to clients, FFmpeg tool [46] to collect QoE metric and Wireshark network packet analyzer [47] are used. The solution proposed to use a server located in the Three tier network topology choosing it horizontally.
or vertically in any case broadcasting a video to end user with maximum QoE while minimizing energy consumption of the whole network architecture.

An experimental setup for all above-mentioned experiments in flow chart was developed using following list of elements:

- ➢ Client PC (running Ubuntu 14.04 LTS)
- ➢ VMware Workstation 12 Pro
- ➢ All-in-one SDN App Development Starter VM [48].

The 64-bit Ubuntu 14.04 image is preinstalled with various software and tools:

- Controllers: POX, OpenDaylight, Trema, RYU, Floodlight, ONOS
- Open VSwitch 2.3, which also supports OpenFlow 1.2, 1.3, and 1.4, LINC Switch
- Mininet
- Pyretic
- Wireshark 1.12.1 used to obtain QoS and QoE metrics (throughput, delay, video packet loss and etc.)
- JDK 1.8, Maven 3.3 and Eclipse Luna
- FFMpeg tool
- Xterm: standard terminal emulator to start stream a video from server to end-host
- VLC media player
4.2 Experiment 1. A preliminary experiments and results

As a proof of concept to support our motivation, we run simple network topology scenarios to observe how video streaming service will impact networks. We came up with simple scenarios 1 to 4 as shown in Fig. 10 with some hosts and servers, which were used to broadcast a video in a simultaneous manner.

**Scenario 1**

![Scenario 1 Network Architecture](image1)

**Scenario 2**

![Scenario 2 Network Architecture](image2)

**Scenario 3**

![Scenario 3 Network Architecture](image3)

**Scenario 4**

![Scenario 4 Network Architecture](image4)

**Fig. 10 Network architecture topologies for a preliminary experiment**

Tools like xterm standard terminal emulator and VLC player were used to generate a video (Table 3.) traffic from the server(s) to host(s) in the Mininet environment. Network topology was set up using a simple python script which assigns different bandwidth to the links based on scenarios simulated. All metrics from the previous sections were obtained using various
tools and methods. CNEE metric was calculated using energy consumption values obtained and system throughput from the experiments. CNCE results obtained using Table 1. standard emission factor values for France specifically. The Wireshark packet analyzer is used to obtain the statistics for average throughput and delay, The SSIM was obtained using a FFmpeg tool, which is a collection of libraries and tools to process multimedia content while the packet loss metric results are shown in output console of the system when experiments run.

**Table 5.** Experiment 1. Network architecture topologies for a preliminary experiment

<table>
<thead>
<tr>
<th>METRICS</th>
<th>Quality in Sustainability (QiS)</th>
<th>Quality of Experience (QoE)</th>
<th>Quality of Service (QoS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Energy (kW h)</td>
<td>Total CO₂ (kg)</td>
<td>CNEE (µJoule/bit)</td>
</tr>
<tr>
<td>Scenario 1 (a)</td>
<td>0.000279</td>
<td>0.0019</td>
<td>4.7</td>
</tr>
<tr>
<td>Scenario 2 (b)</td>
<td>0.00028</td>
<td>0.0018</td>
<td>8</td>
</tr>
<tr>
<td>Scenario 3 (c)</td>
<td>0.000281</td>
<td>0.0019</td>
<td>1.7</td>
</tr>
<tr>
<td>Scenario 4 (d)</td>
<td>0.000279</td>
<td>0.002</td>
<td>6.9</td>
</tr>
</tbody>
</table>

**Summary:** Results in Table 5. prove that multimedia video streaming services have a huge impact on networks. If we compare Scenario 2 and Scenario 3 in Fig. 10, by varying bandwidth from 10Mbps to 100Mbps, based on our results we achieve 64% gain in terms of CNEE, 62% less CNCE carbon amount.

Moreover, 32% better SSIM result is attained by architecture in Scenario 3. As for Scenario 4 it emits more CO₂ but it delivers best QoE to the end user. Once again this preliminary experiments prove the motivation of our research interest and intend to further experiment other more complex and real life architectures in the next phases of research.
4.3 Experiment 2. CDN/SDN based video streaming

The use of CDNs in video streaming is extremely adopted and deployed nowadays by multimedia delivery content providers. To make it simple, CDN uses a logic of “shopping locally,” meaning any request from the user must be handled by the closest server. By doing so, low latency, high availability and reliability parameters achieved by CDN technology. To have a better understanding of CDN/SDN based architecture and see its advantages and drawbacks we simulated a CDN/SDN based architecture consisting of three-tier, namely access, distribution and core. The main idea behind these experiments is to see how server placement affects the overall energy consumption and carbon emission of the network. Therefore we simulated a video streaming case in the following three-tier architectures depicted in Fig. 11. Reference video was streamed using 10 Mbps bandwidth using the same tools and techniques as it was described in the preliminary experiments.

![SDN based CDN three-tier architectures](image)

**Fig. 11** SDN based CDN three-tier architectures
In these experiments, we used computational values of power consumption of network devices in architectures using a specific tool in [49], which calculates ICT energy use, Energy Cost and Carbon Emission. As the architectures are different so the number of devices used varies for each architecture. The energy consumption and overall CO₂ emission of reference video for one day has been calculated to obtain results and it can be calculated for one month or months, years, if needed. The only constrain here is that we are considering only one size of video streamed in the architecture, but values can change based on demands from end users if number of hosts/servers increase.

Based on the results in Table 6, we can analyze and see the effect of the server placement. When CDN 1 and CDN 2 are compared it is observed that as the location of the server has not changed and the number of hosts increased, it impacted an overall energy consumption of the system and influenced sustainability metrics negatively. Moreover, user experience has also decreased experiencing some stall and delays in the playback. However, it is acceptable and video service can be served for both hosts at the same time using the only one server rather than multiplying the number of servers, that would probably increase energy consumption.

<table>
<thead>
<tr>
<th>METRICS</th>
<th>Quality in Sustainability (QiS)</th>
<th>Quality of Experience (QoE)</th>
<th>Quality of Service (QoS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Energy (KWatt/h per day)</td>
<td>Total CO₂ (kg per day)</td>
<td>Total cost of electricity (euros)</td>
</tr>
<tr>
<td>CDN 1</td>
<td>0.000262</td>
<td>1.763328</td>
<td>4.635</td>
</tr>
<tr>
<td>CDN 2</td>
<td>0.000264</td>
<td>1.779456</td>
<td>4.677</td>
</tr>
<tr>
<td>CDN 3</td>
<td>0.000264</td>
<td>1.779456</td>
<td>4.677</td>
</tr>
<tr>
<td>CDN 4</td>
<td>0.000325</td>
<td>2.182656</td>
<td>5.737</td>
</tr>
</tbody>
</table>

On the other hand, if we compare CDN 3 and CDN 4 architectures, QoS and QoE statistics has a slight difference making CDN 4 desired architecture. This is due to two servers running at the same time in CDN 4 architecture. Nevertheless, we see that, QoS and QoE metrics in CDN 3 architecture are also acceptable and can support video streaming with slight decrease
in overall performance than the latter case scenario. On the other hand, we can see that, in terms of QiS metrics, CDN 3 architecture is more sustainable compared to all three different metrics. CDN 1 is the best architecture as server serves only one host. To continue, both CDN 3 and CDN 2 have the values for QiS metrics, while overall the latter is more desirable. The interesting part of this experiment is the comparison of CDN topologies 3&4.

The server placed on the top of the architecture compared to the one servers placed on both sides is sustainable by 20% as shown in Fig. 12 using Radar Chart for all parameters of QiS. Adding to this we have to mention that, in the first case, QoE metric SSIM was degraded by 14% along with noticeable long delay. However, we consider both those parameters as acceptable, due to during the streaming process it was not a big concern for a perceptible view of the content.

![CDN based Benchmarking](image)

**Fig. 12** CDN/SDN based Benchmarking Radar chart
To see more clearly achieved gains in percentages we plotted QiS metrics (Fig. 13) comparing two case scenarios for explanation purposes. The scenarios where we achieved noticeable sustainability gains were CDN3 and CDN 4 architectures, so we decided to compare these scenarios.

**Fig. 13 CDN3 Efficiency Gain**

**Summary:** By placing the server on the Core layer or on the Cloud of ISP, we can save a bit more of 1 euro per day to serve the demands from the end hosts, resulting in 18.5% economical profit annually. The takeaway from the experiment is that vertical and horizontal placement of server in any layer of the network should be managed by SDN controller dynamically, taking into consideration sustainability indicators which lacks in today’s most used video content delivery technologies.
4.4 Experiment 3. GÉANT2 network topology based video streaming

GÉANT2 (Gigabit Éuropean Advanced Network Technology) is pan-European research and a network interconnecting Europe’s National Research and Education Networks (NRENs). The unrivaled geographical coverage of the GÉANT2 marks it at the most advanced research network in the earth. To give some numbers, it connects 50 million users at 10,000 higher education and institutions across the Europe. Technically speaking, it operates at speeds of up to 500 Gbps [50].

Fig. 14 GÉANT2 backbone topology network

Source: Adapted from [50]
To make our experiments more realistic, we decided to build a topology based on GÉANT2 backbone network as shown in Fig. 14. Three countries were chosen to build a topology network for benchmarking of video streaming scenarios between countries. These countries are following: France, Luxembourg and Germany. For simplification, we use abbreviations of countries such as FR, LUX and DE respectively.

In this benchmarking scenarios, we will focus on Carbon Emission efficiency of networks based on countries as provided in Table 1. CO₂ emission of different network scenarios will be calculated based on the corresponding country and CNCE metric will be considered as one of the parameters for placement of server among three countries. Adding to this, this time we considered some background traffic to flow in the network in order to make it more congested. In the real network, data traveling will not only consist of packets carrying video but other user-generated data would be flowing as a natural process. For that, simple tool in Mininet - Iperf is used to generate UDP packets and help to congest a network to see how it might impact the network performance and keep experiments natural to that of real video streaming platforms.

We have tested two different benchmarking architectures consisting of scenarios, servers placed in interchangeable positions:

- The first benchmarking scenario (3.1) architectures are depicted in Fig. 15, where we simulated one Server Placement for whole network architecture – in France (a), Luxembourg (b) and Germany (c), serving Receiver Hosts locally and outside of their network
- Second benchmarking scenario (3.2) architecture is shown in Fig. 17, where Server Placement for multimedia service to serve only Receiver Host in Luxembourg, using different servers in different countries were tested
Fig. 15 One Server Placement for whole network architecture
Reference video size of 5 MB is streamed for both benchmarking architectures, results based on metrics measured and sorted out in tables Table 7. and Table 8. for Fig. 15 and Fig. 17 accordingly.

**Table 7.** Experiment 3.1 Experimental Results one Server for whole Architecture

<table>
<thead>
<tr>
<th>METRICS</th>
<th>Quality in Sustainability (QiS)</th>
<th>Quality of Experience (QoE)</th>
<th>Quality of Service (QoS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Total Energy (KW h)</strong></td>
<td><strong>Total CO₂ (kg)</strong></td>
<td><strong>CNEE (µJoul /bit)</strong></td>
</tr>
<tr>
<td>Server FR</td>
<td>0.0021</td>
<td>0.13</td>
<td>0.42</td>
</tr>
<tr>
<td>Server LUX</td>
<td>0.002</td>
<td>0.172</td>
<td>0.42</td>
</tr>
<tr>
<td>Server DE</td>
<td>0.00215</td>
<td>0.153</td>
<td>0.42</td>
</tr>
</tbody>
</table>

To clearly notice the efficiency of the optimal server placement we plotted figures in Radar charts using 0 to 100% scale, meaning that approaching 0% is sustainable from QiS point of view, better experience for video content viewer as it offers better QoE and lastly stable network performance from QoS metric perspective.

The first architecture scenarios (a), (b) and (c), where the only server placed in the country serves whole architecture. By placing the server in France to take care of all users in neighbor countries, Luxembourg and Germany, will be an efficient and most sustainable solution based on Fig. 16. It is undeniable that the server placed in the country where receiver resides resulted in better QoE and QoS metrics, as to reach the content is few hops away from the end-host. However, choosing a server to serve a host from a different countries, such as the server in France, serving a host in Luxembourg or Germany will have almost the same quality for content and network availability for the user, while reducing the share of overall video streaming service.
All carried out experiments in this section were intended to prove mainly carbon emission efficiency of different network architectures by multiple server placements per country or only server for whole architecture.

**Summary:** By doing so, we can cut total carbon emission by 24% and 15% in Luxembourg and Germany in accordance, delivering the most green and carbon freed video streaming service among countries. CNEE metrics remain almost the same for all countries, while CNCE metric for France is 25% less than compared to that of Luxembourg and 16% for Germany.
In the second benchmarking scenarios illustrated in Fig. 17 main intention was to explore whether it is better to stream a video locally for the host in Luxembourg or it would be an ideal solution to deliver a content from neighboring countries.

**Fig. 17** Multimedia service to serve Receiver in Luxembourg

**Table 8.** Experiment 3.2 Experimental Results for Multimedia Service to serve a Receiver in Luxembourg

<table>
<thead>
<tr>
<th>METRICS</th>
<th>Network elements</th>
<th>Quality in Sustainability (QiS)</th>
<th>Quality of Experience (QoE)</th>
<th>Quality of Service (QoS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of SWs</td>
<td># of Links</td>
<td>Total Energy (KW h)</td>
<td>Total CO2 (kg)</td>
</tr>
<tr>
<td>Server FR</td>
<td>4</td>
<td>4</td>
<td>0.00123327</td>
<td>0.084</td>
</tr>
<tr>
<td>Server LUX</td>
<td>3</td>
<td>3</td>
<td>0.000924958</td>
<td>0.1199</td>
</tr>
<tr>
<td>Server DE</td>
<td>4</td>
<td>4</td>
<td>0.00123327</td>
<td>0.126</td>
</tr>
</tbody>
</table>
The most energy efficient and best QoE offered solution to serve a client would be choosing a server locally as the content is delivered using fewer switches in the network. However, the main purpose of conducting this experiment is to compare CO₂ efficiency. We can observe that as illustrated in radar chart Fig. 18, delivering content from Server placed in France is 28% and 33% greener in terms of total CO₂ emitted compared to servers placed in Luxembourg and Germany respectively. Likewise, if we compare another metric like CNCE, we can achieve 17% and 33% efficiency respectively.

**Server Placement results for 1 Flow towards Receiver in LUX**

![Radar chart plotting multimedia service to serve Receiver in Luxembourg](image)

**Fig. 18** Radar chart plotting multimedia service to serve Receiver in Luxembourg
Based on above statements, we can say that, by placing the server in the right place, in France in our case, taking into account CO₂ factors, would be greener and assures carbon free content delivery to end-hosts. However, delay values for the server located in Luxembourg are much less compared to other countries as the server is located close to the host in this case, making QoE of the user much better.

**Summary:** To conclude, we can observe that in this experiment streaming of the video from the server located in France is sustainable even having a possibility managing a demand from the receiver in Luxembourg locally. This means there is a trade-off between QiS and QoS metrics in this scenario. We can achieve an ideal CO₂ efficiency using Server in France while QoS metrics degrade eventually. Therefore, we have to take into account all QiS, QoE and QoS metrics while choosing a server placement to serve a demand and try to deliver a multimedia service, which can solve trade-off between metrics achieve a certain level of sustainability in any network architecture.
4.5 Sustainability

Based on a recent study by Becker, et.al [51] on classifying the different requirements to further analyze sustainability in software engineering, and ICT systems, the sustainability analysis pentagon was derived. Five interrelated dimensions are investigated: individual dimension, social dimension, economic dimension, technical dimension, and environmental dimension, across three different effective layers, namely immediate, enabling and structural as shown in Fig. 19 for this research case.
In Fig. 20 shows in brief all Sustainability gains in terms of QiS metrics, to be specifically energy consumption and carbon emission are demonstrated, which are the main aims described in [52]. It is obvious that we can say the efficiency of the bandwidth variation & server placement optimization solutions enables greening and leads towards the sustainability in video streaming networks. Hence, all obtained results in terms of Energy efficiency and Carbon emission are very promising to ensure our research results and statements.
5 DISCUSSIONS

Multimedia services like video streaming is a big concern to take major steps to save energy and run sustainable networks. CDN is a tool to deliver video streaming service but it is missing mechanisms or techniques, to be more eco-friendly, sustainable and carbon-free. To reduce an overall carbon footprint and energy consumption share of IT in the world, new ways or green services to mitigate above-mentioned problems should be proposed and tested. As we propose, CDN merged with SDN would be a solution to overcome mentioned issues. Firstly, CDN providers can benefit from collaboration of their underlying network infrastructure and secondly, SDN will enable them to have a global view of overall network infrastructure by gathering a real-time message from SBI and NBI. OpenFlow is used for rewriting all flows directly to OpenFlow switches which helps to reroute traffic to best available server dynamically and choose best paths towards the destination. We simulated and tested different architectures varying from simple to mid complex, to see how our proposed solutions will impact an overall energy consumption and carbon emission. All experiments run in the virtual environment using Mininet and other tools needed to carry out research. After a set of benchmarking experiments, it is clear that server placement optimization is a viable and sustainable method to solve the research issues of this study.
6 CONCLUSION

6.1 Summary

Most of the experiments run were motivational for further research in the area of multimedia services, specifically video streaming case. The gaining in terms of energy efficiency and carbon emission are noticeable and interesting to take into consideration. In this work, the proposed solutions of server optimization placement, bandwidth variation were validated using various experiments, testing new green multimedia services, assuring the extra savings and efficiency in energy and carbon emission when different approaches implemented. As the number of viewers to request a content from content providers on the rise every year, it is very appealing to work on this research domain.

6.2 Future Works

As a future work, architecture dynamicity must be implemented and integrated with the system. The solution could be expanded orchestrating security capabilities as it is one of the vital metrics to take into account in all networks. Moreover, based on the results of the experiments an algorithm that will automatically allocate the video over servers across the network and allocate the resources such as routing and bandwidth over the network devices can be defined.
REFERENCES


Conference and Workshops (NetSoft), Seoul, pp. 73-77, 2016.


### APPENDIX 1. Literature review in tables

**Table of papers considering QoS in video streaming service**

<table>
<thead>
<tr>
<th>Paper</th>
<th>Delay (Ms)</th>
<th>Jitter (Ms)</th>
<th>Packet Loss Ratio (%)</th>
<th>Throughput (bit/s)</th>
<th>Bit rate (bit/s)</th>
<th>Availability</th>
<th>Bandwidth (Mbps)</th>
</tr>
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<tbody>
<tr>
<td>Video streaming over software defined networks with server load balancing</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streaming Multicast Video over Software-Defined Networks</td>
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<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Software Defined Networking for Reducing Energy Consumption and Carbon Emission</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
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<tr>
<td>SDN-based Application-Aware Networking on the Example of YouTube Video Streaming</td>
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<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
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<td>Research on Load Balance Method in SDN</td>
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APPENDIX 1. Literature review in tables (continues)

Table of papers considering QoE in video streaming service

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### Table of papers considering QoS in video streaming service

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APPENDIX 2. Additional experiment screenshots and plotted results

**Screenshot 1** Network topology with four hosts

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Screenshot 2 Streaming video from Server to Hosts

Screenshot 3 Streaming video complete output of 4hosts
Screenshot 4 Throughput vs Number of hosts video streaming case (360x240p video resolution)

Screenshot 5 Delay vs Number of hosts video streaming case (360x240p video resolution)

(continues)
Screenshot 6 Throughput vs Number of hosts video streaming case (720x480p video resolution)

Screenshot 7 Delay vs Number of hosts video streaming case (720x480p video resolution)

(continues)
Screenshot 8 SSIM vs Number of hosts video streaming case (360x240p video resolution)

Screenshot 9 SSIM vs Number of hosts video streaming case (720x480p video resolution)

(continues)
Screenshot 10 Video Packet Loss vs Number of hosts video streaming case (360x240p and 720x480p video resolution)

Screenshot 11 Jitter vs Number of hosts video streaming case (360x240p video resolution)

(continues)
Screenshot 12 Jitter vs Number of hosts video streaming case (720x480p video resolution)