ENHANCED BANDWIDTH MANAGEMENT MODEL USING SOFTWARE DEFINED NETWORKING

EMILIA ROSA JIMSON

THESIS SUBMITTED IN FULFILLMENT FOR THE DEGREE OF MASTER OF SCIENCE

FACULTY OF COMPUTING AND INFORMATICS
UNIVERSITI MALAYSIA SABAH
2019

DECLARATION

I hereby declare that the material in this thesis is my own except for certain quotations, equations, summaries, and references, which have been duly acknowledged.

05th MARCH 2019

EMILIA ROSA JIMSON

MI1521006T

CERTIFICATION

NAME : **EMILIA ROSA JIMSON**

MATRIC NO. : **MI1521006T**

TITLE : **ENHANCED BANDWIDTH MANAGEMENT MODEL USING SOFTWARE DEFINED NETWORKING**

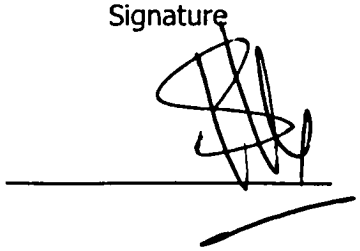
DEGREE : **MASTER OF SCIENCE (COMPUTER SCIENCE)**

VIVA DATE : **05th MARCH 2019**

CERTIFIED BY;

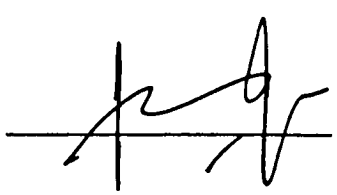
1. **MAIN SUPERVISOR**

Signature



Assoc. Prof. Dr. Kashif Nisar

2. **CO-SUPERVISOR**



Assoc. Prof. Ts. Dr. Mohd. Hanafi Ahmad Hijazi

ACKNOWLEDGEMENT

First and foremost, I am very grateful to God the Father in Heaven because I was given the opportunity to pursue my studies in Master Degree level. Praise to God, you have strengthened me to face all the challenges during my studies. I am extremely grateful to my beloved parents Jimson Majemal and Felicia Milin Untoi, for their love, prayers, and support. My biggest blessing has always been having parents that truly care for the wellbeing of their kids. I also want to express my thanks to my siblings Famela Rosa Jimson, Bachelor of Social Work (Hons), UMS; Dr. Lilyan Rosa Jimson, Bachelor in Medicine and Surgery, MAHE; Irenecia Rosa Jimson, Bachelor of Science in Biotechnology (Hons), UMS; and medical doctor to be Nathanieal Neo and Nathania Pearl for their support and valuable prayers. I also would like to express my special gratitude to my beloved late grandmother Kambuai Buris for her motivations and prayers towards me.

I would like to express my deep and sincere appreciation to my main supervisor, Assoc. Prof. Dr. Kashif Nisar and my co-supervisor Assoc. Prof. Ts. Dr. Mohd Hanafi Ahmad Hijazi for their advice, time and support in guiding me. Dr. Kashif has encouraged me to further my study in master level since my final year in bachelor degree. I am extending my heartfelt thanks to Professor Yong-Jin Park and Miss Nor Daliela Mohd. Rusli, I really appreciate their advices and comments in improving my master research during the semester progress presentation. Not forgotten to Assoc. Prof Dr. Awang Asri Awg Ibrahim who has been serving as the Dean in Faculty of Computing and Informatics, UMS and Dr. Jakaria Dasan for their motivation throughout my journey to finish my research study.

Finally, my gratitude goes to Universiti Malaysia Sabah for funding this research through UMSGreat and *Skim Pembantu Pengajar* scholarship UMS. The Almighty will not let you down; your efforts will not go to waste. Rest if you must, but do not quit! Because, for all the sad words of tongue or pen, the saddest are these: "It might have been!" (John Greenleaf). Thank you everyone!

EMILIA ROSA JIMSON
29th JANUARY 2018

ABSTRACT

Available bandwidth is the maximum unused bandwidth at a link, whereby it is measured in bits per second. However, since available bandwidth in network is limited, it is very critical to manage the network bandwidth efficiently. In this research, bandwidth management model based on Software-Defined Networking (SDN) architecture is examined. Through the proposed model, real-time traffic was given priority to access the limited bandwidth over non-real-time traffic. SDN promises the simplification of network management compared to the traditional network. SDN architecture breaks the vertically integrated current network design and it introduces centralized network control through the SDN controller, which is considered as the greatest contribution of SDN in networking area. SDN architecture is adopted in this research because it promotes centralized control features which enable network programmability and supports better network resources management. Simulation was conducted using the EstiNet network simulator. Two groups of experiments with different situations have been conducted. Each experiment consisted of five simulations with different number of sender and receiver nodes. The first experiment simulated the traffics in a traditional network; and the second experiment simulated the traffics in a proposed network model. In this research, most of the available bandwidth was reserved to real-time traffic and the remaining portion was reserved for non-real-time traffic. The real-time throughput results of the two different experiments have been compared to evaluate the performance of the proposed model. The experiment results showed that the proposed model has successfully given priority to real-time traffic to access the limited network bandwidth. As the number of nodes increases, the average real-time throughput of experiment one and experiment two decreases linearly. When nodes reaches 10, the real-time average throughput of experiment one and experiment two are 635KBps and 473KBps respectively.

ABSTRAK

MODEL PENGURUSAN JALUR LEBAR MENGGUNAKAN RANGKAIAN PERISIAN YANG DITETAPKAN (SDN)

Jalur lebar yang tersedia adalah jalur lebar maksimum yang tidak digunakan pada pautan, dimana ia diukur dalam bit sesaat. Walaubagaimanapun, jalur lebar yang tersedia dalam rangkaian adalah terhad. Adalah sangat penting untuk menguruskan jalur lebar rangkaian dengan cekap. Dalam kajian ini, model pengurusan jalur lebar berdasarkan Rangkaian Perisian yang Ditetapkan (SDN) telah dicadangkan. Melalui model yang dicadangkan, trafik masa nyata diberi keutamaan untuk mengakses jalur lebar yang terhad berbanding trafik masa tidak nyata. SDN menjanjikan pengurusan rangkaian yang mudah berbanding rangkaian tradisional. SDN memecahkan rekabentuk rangkaian semasa secara vertikal dan memperkenalkan kawalan rangkaian berpusat melalui pengawal SDN yang dianggap sebagai sumbangan terbesar SDN dalam bidang rangkaian. Seni bina SDN disesuaikan dalam kajian ini kerana ia mempromosikan ciri-ciri kawalan terpusat yang membolehkan pemprograman rangkaian dan menyokong pengurusan sumber rangkaian yang lebih baik. Simulasi dijalankan menggunakan simulator EstiNet. Dua kumpulan eksperimen yang mempunyai situasi berbeza telah dijalankan. Setiap eksperimen terdiri daripada lima simulasi, dengan bilangan penghantar dan nod penerima yang berlainan. Eksperimen pertama mensimulasikan trafik dalam rangkaian tradisional; dan eksperimen kedua mensimulasikan trafik dalam model rangkaian yang dicadangkan. Dalam penyelidikan ini, majoriti jalur lebar yang tersedia dikhaskan untuk trafik masa nyata dan bahagian yang lain dikhaskan untuk trafik masa bukan nyata. Keputusan eksperimen masa nyata dari dua eksperimen yang berbeza telah dibandingkan untuk menilai prestasi model yang dicadangkan. Keputusan uji kaji menunjukkan model yang dicadangkan berjaya memberi keutamaan kepada trafik masa nyata untuk mengakses jalur lebar rangkaian terhad. Apabila nombor dari nod meningkat, purata masa sebenar purata percubaan satu dan eksperimen dua menurun secara linear. Apabila nod mencapai 10 keputusan purata trafik masa nyata untuk eksperimen satu dan eksperimen dua adalah masing-masing 635KBps dan 473KBps.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AP	-	Access Point
C	-	Controller
OFSw	-	OpenFlow Switch
OFCSw	-	OpenFlow Controller Switch
Ro	-	Router
R	-	Receiver
SDN	-	Software Defined Networking
S	-	Sender
Sw	-	Switch
TN	-	Traditional Network

CHAPTER 1

INTRODUCTION

1.1 Introduction

Bandwidth is referred to as the transmission medium in the network. According to Chaudhari and Biradar (2015), available bandwidth is referred as the maximum bandwidth at a link or a path, and it is measurable in bit per second which relates to the speed of bit transmission in a link. The amount of available bandwidth in a network influences the amount of data that is transmittable in the network per unit of time, for example, an internet connection that has large bandwidth can transmit a set amount of data faster than an internet connection with a lower bandwidth. The amount of data is known as network throughput, where the throughput is the rate of successful information delivery in a given period of time that goes through a communication link (Dordal, 2018). The effective bandwidth utilization is a crucial factor to be considered in order to improve the network performance (Deepika and Babu, 2014). Since the amount of bandwidth in the network is fixed based on what subscriber pays for, it is crucial to plan forwarding of data with specific priority to a specific traffic independently from the source to the destination. In other words, it is very significant to plan forwarding data with priority for a predefined traffic from the source to the destination.

Since the available bandwidth in network is fixed and as the number of sender nodes increased, there will be a situation in the network where the demand is beyond the bandwidth capacity (Deepika and Babu, 2014), so it is very important

to manage the bandwidth usage efficiently. This research has identified that the complex design of the current network architecture has resulted in the complexity of the network resources (e.g., Bandwidth) management. In this research, the current network architecture is known as traditional network. The network controls in current network architecture are distributed, where each device in the network has their own data plane and control plane which means all devices perform both control and forwarding data functions. Since the network controls in current network architecture are distributed, network administrator needs to make changes to every single device in the network in order to implement new idea or new protocols. This leads to error-prone and time consuming. Besides that, the current network also provides best-effort service, in best-effort network (Huston, 2001) all packets compete equally for network resources (e.g., Bandwidth) because best-effort network does not offer any resource guarantee to any packets in the network (Huston, 2001).

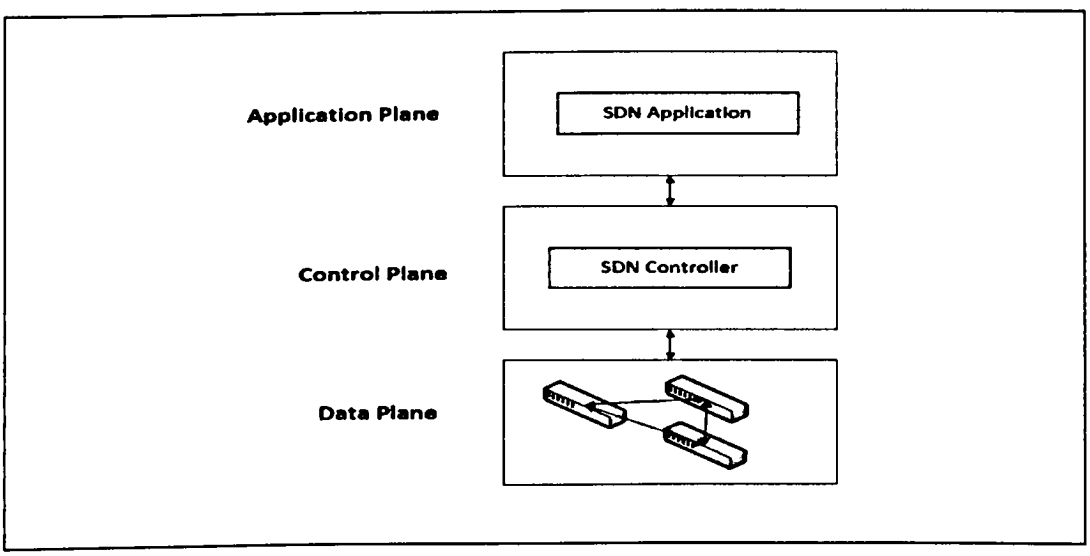


Figure 1.1 : Software Defined Networking Reference Model
Source : Open Network Foundation (2012)

Due to the complex design of the current network architecture, a model of bandwidth management based on architecture of the Software Defined Networking (SDN) has been proposed in this research (Astuto, Mendon, Nguyen, Obraczka, and Turletti, 2014). Figure 1.1 illustrated the SDN architecture proposed by the Open

Network Foundation Organization. Based on the proposed model, majority of the bandwidth is prescribed for real-time traffic; this means that real-time traffic is given priority to gain access of the limited bandwidth. This research adapted the SDN architecture in the proposed model because SDN promises the simplification of the network resources management through the centralization of the network control. Through this feature, all traffics in SDN are abstracted as flow, where flow abstraction allows network resources to be managed in a better way (Lara, Kolasani, and Ramamurthy, 2014).

Farhady, Lee, and Nakao (2015) agreed that SDN refers to a network design that offers some solutions to address the problem of traditional network architecture limitation in terms of network management. SDN breaks the vertically integrated architecture of the traditional network devices; it splits the control plane away from the hardware devices and makes it centralize in a software known as SDN controller (Kim and Feamster, 2013). This network architecture is totally different from the current network architecture as the centralization of the network control makes the network programmability possible (Kreutz, Ramos, Verissimo, Rothenberg, Azodolmolky, and Uhlig, 2015).

In SDN, the switch which is known as OpenFlow switch is connected with the SDN controller (Farhady *et al.,* 2015). The OpenFlow switch serves as a dumb switch, since it only performs data forwarding process following the decision made by the SDN controller. The SDN architecture will be discussed in more detail in Chapter 2.

1.2 Problem Statement

In this research, current network architecture is referred to as traditional network. As illustrated in Figure 1.2, it can be seen that the traditional network devices architecture are vertically integrated (Kreutz *et al.*, 2015), where it is observed that the control plane and the data plane are placed directly inside the network devices. Since these two planes are coupled tightly, the network management process become complicated especially in terms of network resources management (Kabir,

2013). It is very difficult to add new functionality in traditional network architecture (Kreutz *et al.*, 2015) since each of the network devices has their own control plane that is responsible in making decision on how to handle the network traffic. Due to this matter, every single device needs to be configured in order to implement new idea. Manually modifying the network devices setting is time consuming and leads to error-prone/high error rate.

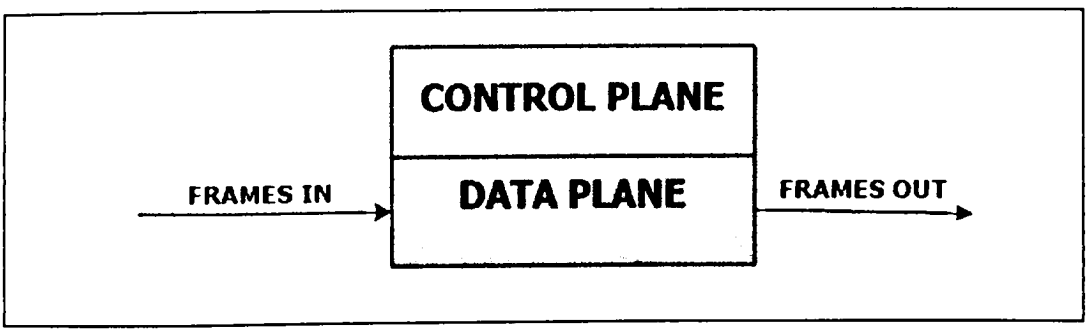


Figure 1.2: Control Plane and Data Plane Located on the Network Device

The network bandwidth in Internet is limited, either in wired or wireless link. Several types of traffic may flow through the same link, where each flow is competing to use the bandwidth available in the link which leads to bandwidth bottleneck at the congested link. The current network architecture provides best-effort service (Huston, 2001). In best-effort service, any packets in the network are not equipped with resources guarantee and due to that, all packets that are sent, will compete equally to gain network resources (e.g., Bandwidth). Besides that, the best-effort service does not meet the needs of a real-time application that requires sufficient bandwidth to operate effectively.

1.3 Research Motivation

The motivation of the work presented in this thesis is to simplify the network resources management process in the traditional network architecture. Through the reviews in Chapter 2, this research has identified SDN architecture as the solution to make the management process simpler in the traditional network. This research

aims to propose a network model based on SDN architecture since the design of the current network architecture is complex and very hard to manage. The proposed model is used to manage the limited bandwidth by giving priority to real-time over the other traffics to access the limited bandwidth.

1.4 Research Questions

In order to attain the motivation that are stated in the previous section, three research questions were acknowledged:

i. What key characteristics are required to simplify the network resources management in traditional networks?
ii. How does SDN simplify bandwidth management process in the traditional networks?
iii. How is the proposed model performance in networks evaluated and validated?

The first research questions is answered and explained in Chapter 2, while the second research question is explained in Chapter 3 and third research question is answered in Chapter 4 and Chapter 5.

1.5 Objectives

Based on the stated research questions, three research objectives were derived:

i. To identify the SDN features that can simplify network bandwidth management;
ii. To propose a resources management network model based on the Software Defined Networking (SDN) architecture to manage the available bandwidth; and
iii. To evaluate the performance of the SDN-Based Model (proposed model) through simulation by comparing the network throughput results

obtained in the traditional network with the throughput results obtained in the proposed model.

1.6 Research Objectives Overview

To ensure that the research objectives of the work in this research are achieved, a methodology of three phases is proposed. Each phase explains the steps taken to achieve the three objectives. The overall methodology is illustrated in Figure 1.3.

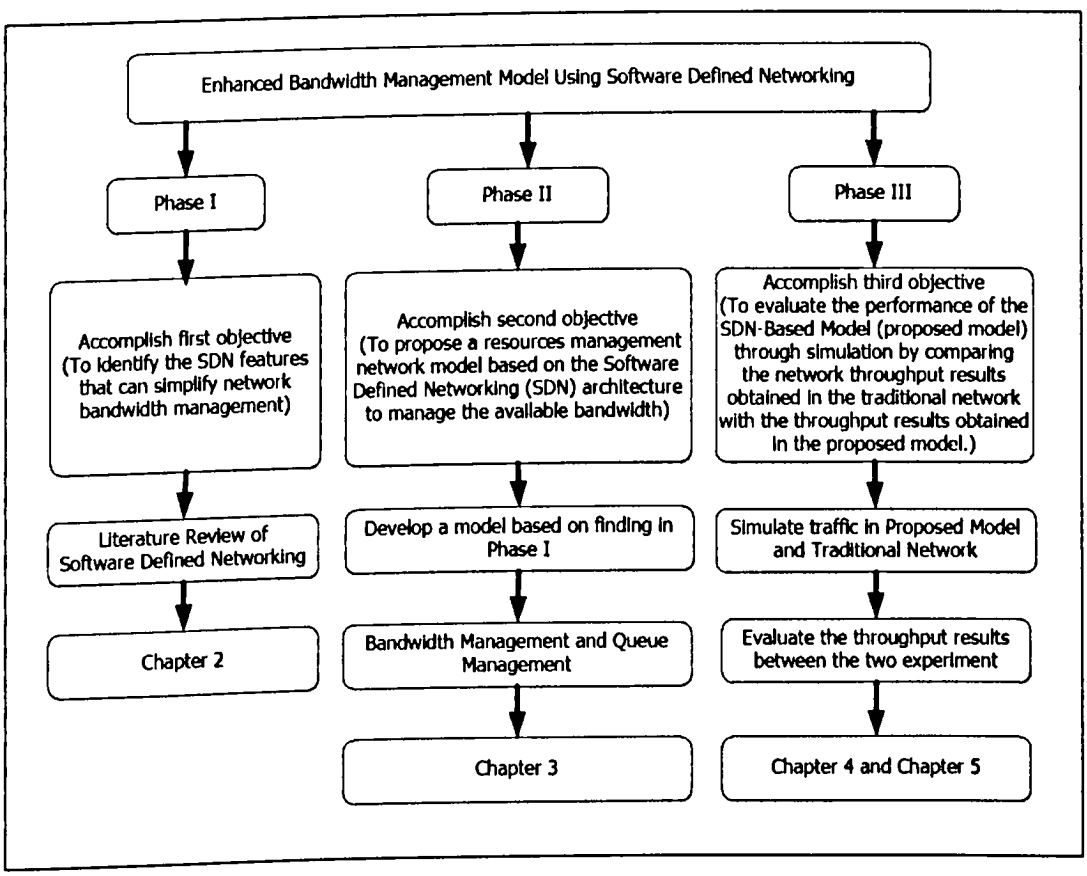


Figure 1.3 : Proposed Research Method

Phase I: To identify the SDN features that can simplify network bandwidth management. Reviews of previous works were conducted to identify the SDN features that can be used to simplify the network bandwidth management. Details of this phase are presented in Chapter 2.

Phase II: To propose a resources management network model based on the Software Defined Networking (SDN) architecture so as to manage the available bandwidth. By using the findings in phase I, this research was proposed a resource management network model based on SDN. Details of this phase are described in Chapter 3.

Phase III: To evaluate the performance of the SDN-Based Model (proposed model) through simulations by comparing the network throughput results obtained in the traditional network and the throughput results obtained in the proposed model. Details of this phase are described in Chapter 4 and 5.

1.7 Research Scope

This research aims to find a solution to simplify the resources management in the current network architecture. The Software Defined Networking (SDN) paradigm has been identified as a solution to solve the research problem. Based on the surveys and studies done by researches (Lara *et al.,* 2014; Deepika and Babu, 2014; Xia, Wen, Foh, Niyato, and Xie, 2015; Kreutz *et al.*, 2015; Shu, Wan, Foh, Niyato, and Xie, 2016), SDN has been shown to be more effective in simplifying the network management because it has introduced lots of benefits to improve the network management in traditional network which were discussed in details in Chapter 2. In this research SDN-Based Network model has been proposed to ensure the bandwidth management process in traditional network is simplified, simulations were conducted to evaluate the performance the proposed model. After that the throughput results obtained in simulation of data in the traditional network and in the proposed model were compared. In the proposed model the available bandwidth in network is utilized by assuring priority to the real-time traffic to access the bandwidth.

1.8 Research Contribution

The main contributions of this research can be summarized as stated below:

i. A review of Software Defined Networking architecture were conducted and presented in Chapter 2. Through the review this research has identified the features/characteristics that the network management must have in order to simplify the network resources management in the traditional network.

ii. The SDN-based model was proposed with explanation provided in Chapter 3 and Chapter 4.

iii. This research has proposed SDN-Based Model which successfully improved the bandwidth management process in traditional network. Simulations were conducted to test the performance of the proposed model. The throughput results of the simulations of the traditional network, and the proposed model are compared. Based on the result obtained the proposed model successfully gives priority for the real-time traffics to access the limited bandwidth in the network.

1.9 Published Work

The work described in this thesis has been published in a number of refereed publications as itemized below:

i. Conference

a. Emilia Rosa Jimson, Kashif Nisar, and Mohd. Hanafi bin Ahmad Hijazi. (2017). *Bandwidth Management using Software Defined Network and Comparison of the Throughput Performance with Traditional Network.* 2017 International Conference on Computer and Drone Applications (2017IConDA). This paper won the "Best Paper Award" in IConDA2017 conference. Available electronically on IEEE Xplore.

REFERENCES

Akyildiz, I. F., Lee, A., Wang, P., Luo, M., & Chou, W. (2014). A Roadmap for Traffic Engineering In Software Defined Networks. *Computer Networks*, *71*, 1–30. http://doi.org/10.1016/j.comnet.2014.06.002

AlSaeed, Z., Ahmad, I., & Hussain, I. (2018). Multicasting in software defined networks: A comprehensive survey. *Journal of Network and Computer Applications*, *104*, 61–77. http://doi.org/10.1016/j.jnca.2017.12.011

Alto, P. (2012). Software-Defined Networking: The New Norm for Networks [white paper]. Retrieved from https://www.opennetworking.org/images/stories/downloads/sdn-resources/white-papers/wp-sdn-newnorm.pdf

Arbettu, R. K., Khondoker, R., Bayarou, K., & Weber, F. (2016). Security analysis of OpenDaylight, ONOS, Rosemary and Ryu SDN controllers. In *17th International Telecommunications Network Strategy and Planning Symposium, Networks 2016 - Conference Proceedings* (pp. 37–44). http://doi.org/10.1109/NETWKS.2016.7751150

Astuto, B. N., Mendon, M., Nguyen, X. N., Obraczka, K., & Turletti, T. (2014). A Survey of Software-Defined Networking : Past , Present , and Future of Programmable Networks. *IEEE Communications Society*, *16*(3), 1617–1634.

Cai, Z., Cox, A. L., & Ng, T. S. E. (2011). *Maestro: A System for Scalable OpenFlow Control. Rice University.* Retrieved from https://www.cs.rice.edu/~eugeneng/papers/TR10-11.pdf

Casado, M., Freedman, M. J., Pettit, J., Luo, J., McKeown, N., & Shenker, S. (2007). Ethane: Taking Control of the Enterprise. *SIGCOMM '07 Proceedings of the 2007 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications*, *37*(4), 1–12. http://doi.org/http://doi.acm.org/10.1145/1282380.1282382

Casado, M., Garfinkel, T., Akella, A., Boneh, D., Mckeown, N., & Shenker, S. (2006). SANE : A Protection Architecture for Enterprise Networks. In *15th USENIX Security Symposium* (pp. 137–151).

Chase, J., Kaewpuang, R., Yonggang, W., & Niyato, D. (2014). Joint virtual machine and bandwidth allocation in software defined network (SDN) and

cloud computing environments. *2014 IEEE International Conference on Communications, ICC 2014*, 2969–2974. http://doi.org/10.1109/ICC.2014.6883776

Chaudhari, S. S., & Biradar, R. C. (2015). Survey of Bandwidth Estimation Techniques in Communication Networks. *Wireless Personal Communications*, *83*(2), 1425–1476. http://doi.org/10.1007/s11277-015-2459-2

Cui, H., Ma, C., Lai, W., Zheng, L., & Liu, Y. (2015). Accurate Network Resource Allocation in SDN according to Traffic Demand. In *4th International Conference on Mechatronics, Materials, Chemistry and Computer Engineering (ICMMCCE 2015)* (pp. 1166–1175).

De Turck, F., Boutaba, R., Chemouil, P., Bi, J., & Westphal, C. (2015). Guest Editors' Introduction: Special Issue on Efficient Management of SDN/NFV-Based Systems—Part II. *IEEE Transactions on Network and Service Management*, *12*(1), 1–3. http://doi.org/10.1109/TNSM.2015.2403775

Deepika, M. S., & Babu, K. N. R. M. (2014). An Approach to Effective Bandwidth Utilization using Software Define Networking. *International Journal of Computer Science and Information Technologies*, *5*(4), 5571–5574.

Dordal, P. (2018). *An Introduction To Computer Networks*. 3rd ed. [ebook] Chicago: Loyola University Chicago, p.11-12. Available at: https://ecommons.luc.edu/cs_facpubs/announcements.html [Accessed 5 Jan. 2018].

Erickson, D. (2013). The beacon openflow controller. In *Proceedings of the second ACM SIGCOMM workshop ...* (pp. 13–18). http://doi.org/10.1145/2491185.2491189

Farhady, H., Lee, H., & Nakao, A. (2015). Software-Defined Networking: A survey. *Computer Networks*, *81*, 79–95. http://doi.org/10.1016/j.comnet.2015.02.014

Feamster, N., & Balakrishnan, H. (2005). Detecting BGP configuration faults with static analysis. In *Proceedings of the 2nd conference on Sympo- sium on Networked Systems Design & Implementation* (pp. 43–56). Retrieved from http://www.usenix.org/event/nsdi05/tech/feamster/feamster_html/

Feamster, N., Rexford, J., & Zegura, E. (2013). The road to SDN. An intellectual history of programmable networks. *ACM SIGCOMM Computer Communication*

Review, *11*(12), 1–14. Retrieved from http://delivery.acm.org/10.1145/2570000/2560327/p20-rexford.pdf?ip=1.9.184.253&id=2560327&acc=OPEN&key=4D4702B0C3E38B35.4D4702B0C3E38B35.4D4702B0C3E38B35.6D218144511F3437&CFID=658464597&CFTOKEN=97205956&__acm__=1471833325_2a0f236c017c7d51d071fc81ff6a32d7

Fernando, J., Orrego, G., Pablo, J., & Duque, U. (2017). Throughput and delay evaluation framework integrating SDN and IEEE 802 . 11s WMN. In *IEEE 9th Latin-American Conference on Communications (LATINCOM)* (pp. 1–6).

Foukas, X., Marina, M. K., & Kontovasilis, K. (2015). *Software Defined Mobile Networks (SDMN): Beyond LTE Network Architecture*. (M. Liyanage, A. Gurtov, & M. Ylianttila, Eds.) (First). John Wiley & Sons, Ltd.

Greene, K. 2009. TR10: software-defined networking. MIT Technology Review (March/April); http:// www2.technologyreview.com/article/412194/tr10-software-defined-networking/.37.

Gude, N., Koponen, T., Pettit, J., Pfaff, B., Casado, M., Mckeown, N., & Shenker, S. (2008). NOX: Towards an Operating System for Networks. *ACM SIGCOMM Computer Communication Review*, *38*(3), 1–6.

Hilmi, E. E., Seyhan, C., & Murat, T. A. (2013). An Optimization Framework for QoS-Enabled Adaptive Video Streaming Over OpenFlow Networkse. *IEEE Transactions on Multimedia*, *15*(3), 710–715.

Hu, F., Hao, Q., & Bao, K. (2014). A Survey on Software Defined Networking (SDN) and OpenFlow: From Concept to Implementation. *IEEE Communications Surveys & Tutorials*, *16*(4), 2181–2206. http://doi.org/10.1109/COMST.2014.2326417

Huang, K., Liu, C., Gan, C., Wang, M., & Huang, C. (2014). SDN-based Wireless Bandwidth Slicing. In *International Conference on Software Intelligence Technologies and Applications* (pp. 77–81).

Huang, K., Wang, M., & Huang, C. (2015). Bandwidth Management for SDN-enabled Wireless Networks. *ICT Journal*, (167), 62–69.

Huston, G. (2001). Best Efforts Networking, (July).

Jammal, M., Singh, T., Shami, A., Asal, R., & Li, Y. (2014). Software defined networking : State of the art and research challenges. *COMPUTER NETWORKS*, *72*, 74–98. http://doi.org/10.1016/j.comnet.2014.07.004

Jarschel, M., Wamser, F., Hohn, T., Zinner, T., & Tran-Gia, P. (2013). SDN-based application-aware networking on the example of youtube video streaming. In *Proceedings - 2013 2nd European Workshop on Software Defined Networks, EWSDN 2013* (pp. 87–92). http://doi.org/10.1109/EWSDN.2013.21

Kabir, M. H. (2013). Software Defined Networking (SDN): A Revolution in Computer Network. *IOSR Journal of Computer Engineering (IOSR-JCE)*, *15*(5), 103–106. Retrieved from http://www.iosrjournals.org/iosr-jce/papers/Vol15-issue5/Q0155103106.pdf?id=7557

Karia, D. C., & Kolekar, U. D. (2008). Performance analysis of real and non real time traffic over WLAN using connection admission control policy. In *Proceedings - EMS 2008, European Modelling Symposium, 2nd UKSim European Symposium on Computer Modelling and Simulation* (pp. 548–554). http://doi.org/10.1109/EMS.2008.25

Kim, H., & Feamster, N. (2013). Improving network management with software defined networking. *IEEE Communications Magazine*, *51*(2), 114–119. http://doi.org/10.1109/MCOM.2013.6461195

Koponen, T., Casado, M., Gude, N., Stribling, J., Poutievski, L., Zhu, M., ... Shenker, S. (2010). Onix: A Distributed Control Platform for Large-scale Production Networks. *Proceedings of the 9th USENIX Conference on Operating Systems Design and Implementation*, 1--6. http://doi.org/10.1.1.186.3537

Kreutz, D., Ramos, F. M. V, Verissimo, P., Rothenberg, C. E., Azodolmolky, S., & Uhlig, S. (2015). Software-Defined Networking : A Comprehensive Survey. *IEEE Journals & Magazines*, *103*(1), 14–76. http://doi.org/10.1109/JPROC.2014.2371999

Lara, A., Kolasani, A., & Ramamurthy, B. (2014). Network Innovation using OpenFlow: A Survey. *IEEE Communications Surveys & Tutorials*, *16*(1), 1–20. http://doi.org/10.1109/SURV.2013.081313.00105

Levin, D., Wundsam, A., Heller, B., Handigol, N., & Feldmann, A. (2012). Logically Centralized ? State Distribution Trade-offs in Software Defined Networks. In Proceedings of the first workshop on Hot topics in software defined networks, HotSDN '12, (pp. 1–6).

Li, K., Guo, W., Zhang, W., Wen, Y., Li, C., & Hu, W. (2014). QoE-based bandwidth allocation with SDN in FTTH networks. In *IEEE/IFIP NOMS 2014 - IEEE/IFIP Network Operations and Management Symposium: Management in a Software Defined World* (pp. 1–8). http://doi.org/10.1109/NOMS.2014.6838418

Li, Y., Li, D., Cui, W., & Zhang, R. (2011). Research based on OSI model. In *IEEE 3rd International Conference on Communication Software and Networks, ICCSN 2011* (pp. 554–557). http://doi.org/10.1109/ICCSN.2011.6014631

McKeown, N., Anderson, T., Balakrishnan, H., Parulkar, G., Peterson, L., Rexford, J., ... Turner, J. (2008). OpenFlow: Enabling Innovation in Campus Networks. *ACM SIGCOMM Computer Communication Review*, *38*(2), 69–74. http://doi.org/10.1145/1355734.1355746

Morales, L. V., Murillo, A. F., & Rueda, S. J. (2016). Extending the floodlight controller. In Proceedings - 2015 IEEE 14th International Symposium on Network Computing and Applications, NCA 2015 (pp. 126–133). http://doi.org/10.1109/NCA.2015.11

Morzhov, S., Alekseev, I., & Nikitinskiy, M. (2016). Firewall application for Floodlight SDN controller. In *International Siberian Conference on Control and Communications, SIBCON 2016 - Proceedings* (pp. 1–5). http://doi.org/10.1109/SIBCON.2016.7491821

Ns-3. (2017). ns-3. [online] Available at: https://www.nsnam.org/ [Accessed 2 Apr. 2017].

OpenDaylight. (2016). Home - OpenDaylight. [online] Available at: https://www.opendaylight.org/ [Accessed 6 Mar. 2017].

Open Networking Foundations (ONF). (2012). OpenFlow Switch Specification Version 1.3.1, *0*, 1–36. http://doi.org/10.1002/2014GB005021

Open Networking Foundation. (2017). *Software-Defined Networking (SDN) Definition - Open Networking Foundation*. [online] Available at: https://www.opennetworking.org/sdn-definition/ [Accessed 4 Mar. 2017].

Owens, H., & Durresi, A. (2015). Video over Software-Defined Networking (VSDN). *Computer Networks*, *92*(2), 341–356. http://doi.org/10.1016/j.comnet.2015.09.009

Pakzad, F., Portmann, M., Tan, W. L., & Indulska, J. (2014). Efficient Topology Discovery in Software Defined Networks. In *International Conference on Signal Processing and Communication Systems (ICSPCS)* (pp. 1–8).

Prete, L. R., Shinoda, A. A., Schweitzer, C. M., & De Oliveira, R. L. S. (2014). Simulation in an SDN network scenario using the POX Controller. In *2014 IEEE Colombian Conference on Communications and Computing, COLCOM 2014 - Conference Proceedings* (pp. 1–6). http://doi.org/10.1109/ColComCon.2014.6860403

Qasmarrogy, G. A., Qasmarrogy, E. S., & Ali, A. Y. (2014). Performance Analysis of Real and Non-real Time Traffic under MANET Routing Protocols. *International Journal of Engineering Development and Research*, *2*(4), 3522–3530.

Ramadona, S., Hidayatulloh, B. A., Siswanto, D. F., & Syambas, N. (2016). The simulation of SDN network using POX controller: Case in Politeknik Caltex Riau. In *Proceeding of the 2015 9th International Conference on Telecommunication Systems Services and Applications, TSSA 2015* (pp. 1–6). http://doi.org/10.1109/TSSA.2015.7440463

Shalimov, A., Zimarina, D., Pashkov, V., Zuikov, D., & Smeliansky, R. (2013). Advanced Study of SDN / OpenFlow controllers. In *Proceeding CEE-SECR '13 Proceedings of the 9th Central & Eastern European Software Engineering Conference in Russia* (pp. 1–6). http://doi.org/10.1145/2556610.2556621

Sherwood, R., Gibb, G., Yap, K., Appenzeller, G., Casado, M., Mckeown, N., & Parulkar, G. (2010). Can the Production Network Be the Testbed? In *Proceedings of the 9th USENIX conference on Operating systems design and implementation* (pp. 1–14).

Shu, Z., Wan, J., Li, D., Lin, J., Vasilakos, A. V, & Imran, M. (2016). Security in Software-Defined Networking: Threats and Countermeasures. *Mobile Netw Appl*, *21*, 764–776. http://doi.org/10.1007/s11036-016-0676-x

Stancu, A. L., Halunga, S., Vulpe, A., Suciu, G., Fratu, O., & Popovici, E. C. (2015). A comparison between several Software Defined Networking controllers. In *12th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services, TELSIKS 2015* (pp. 223–226). http://doi.org/10.1109/TELSKS.2015.7357774

Tomovic, S., Prasad, N., & Radusinovic, I. (2014). SDN control framework for QoS provisioning. In *22nd Telecommunications Forum, TELFOR 2014 - Proceedings*

of Papers (pp. 111–114). http://doi.org/10.1109/TELFOR.2014.7034369

Tuncer, D., Charalambides, M., Clayman, S., & Pavlou, G. (2015). Adaptive Resource Management and Control in Software Defined Networks. *Network and Service Management, IEEE Transaction on 12.1*, *12*(1), 18–33. http://doi.org/10.1109/TNSM.2015.2402752

Turck, F. De, Chemouil, P., Boutaba, R., Yu, M., Rothenberg, C. E., & Shiomoto, K. (2016). Guest Editors' Introduction: Special Issue on Management of Cloud Services. *IEEE Transactions on Network and Service Management*, *13*(3), 362–365. http://doi.org/10.1109/TWC.2011.09.001-tnsm1403-editorial

Wang, S.-Y., Chou, C.-L., & Yang, C.-M. (2013a). EstiNet OpenFlow Network Simulator and Emulator. *IEEE Communications Magazine*, *51*(9), 110–117.

Wang, S.-Y., Chou, C.-L., & Yang, C.-M. (2013b). OpenFlow Controllers over EstiNet Network Simulator and Emulator: Functional Validation and Performance Evaluation. In *Ns1.Estinet.Com* (pp. 1–21). Retrieved from http://ns1.estinet.com/fckimages/1361023696265156168.pdf

Wang, S. Y. (2014). Comparison of SDN OpenFlow network simulator and emulators: EstiNet vs. Mininet. In *IEEE Symposium on Computers and Communications (ISCC)* (pp. 1–6). http://doi.org/10.1109/ISCC.2014.6912609

Xia, W., Wen, Y., Foh, C. H., Niyato, D., & Xie, H. (2015). A Survey on Software-Defined Networking. *IEEE COMMUNICATION SURVEYS & TUTORIALS*, *17*(1), 27–51. http://doi.org/10.1007/978-3-319-28430-9_9

Xie, J., Guo, D., Hu, Z., & Qu, T. (2015). Control Plane of Software Defined Networks: A Survey. *Computer Communications*, *67*, 1–10. http://doi.org/10.1016/j.comcom.2015.06.004

Yiakoumis, Y., Yap, K., Katti, S., Parulkar, G., & Mckeown, N. (2011). Slicing Home Networks. In *ACM SIGCOMM Work Home networks* (pp. 1–6).