

Performance Evaluation of Buffer Size for Access Networks in First Generation Optical Networks

Baruch Mulenga Bwalya*, Simon Tembo

Department of Electrical and Electronic Engineering, University of Zambia, Lusaka, Zambia

Abstract Enhancing network performance and reducing energy consumption by the routers are two very important design challenges faced by router manufacturers today. Routers require buffers to hold packets in times of delay. Therefore, buffer size plays a big role in router design. Network performance and router energy consumption is determined by the technologies employed to build the routers. Manufacturers use the rule of thumb to assign network buffer to routers, which increases buffer size linearly with an increase in network capacity. This results in large buffers that require a lot of power and board space, and are a challenge to router manufactures. In this paper, we use OPNET simulations to study buffer size in access networks, independent of network capacity, to come up with an optimal buffer size for the network. We propose and use a model to illustrate buffer size that is optimal for access networks. By having a buffer size that can hold at least fourteen packets, we illustrate that this results in reduced power consumption by the router and enhanced network performance.

Keywords Internetworking, Transmission Control Protocol, Buffer Size, Datagram Forwarding Rate

1. Introduction

All routers require buffers to store packets during times of delay in the network. The buffers should ideally be large enough to accommodate packets that are in queue but fast enough not to hold packets in queue longer than necessary. They should also be small enough to use fast memory technologies such as static random access memory (SRAM) or all-optical buffering [1, 20].

In an electrical packet-switched network, packet contention at the routers is resolved with a store and forward technique, where packets are stored in a buffer, and are sent out when random access memory (RAM) allows. The size and speed of electronic RAM are still bottlenecks as router manufacturers still use large, slow, off-chip dynamic random access memory (DRAM) chips, to satisfy large buffer requirements. Large buffers lead to large boards which are too hot and consume a lot of power. All-optical buffering currently does not have an equivalent to electronic RAM, so optical packet switches adopt a different approach to congestion control in the network [2, 9, 19].

While all-optical packet switching is regarded as a long term solution to increasing data rates in optical telecommunication networks, this has not yet been fully realized due to a number of factors; one of which is the

problem of contention resolution during times of congestion because of the extremely long lengths of fibre required to buffer several packets for various time delays when using fibre delay lines (FDL) [3]. However, optical packet switching has advanced from just using long lines of fibre to buffer packets, to include a switching fabric for switching packets optically. This kind of switching has lower power consumption and takes up less board space compared to electronic RAM and FDL. Shinya et al. [5] demonstrated a photonic crystal based all-optical bit memory operating at very low power, where each photonic cell could only buffer a single bit, with all wavelengths sharing the same buffer space, just like in electronic buffering. Such low buffer capacities make it difficult to buffer packets in a network that has an optical switching fabric with high data transmission rates [6].

Optical networks can be identified as first or second generation networks. First generation networks are point-to-point networks which use fibre as a faster substitute for copper cables. Wavelength Division Multiplexing (WDM) technology extended these systems to have more than one wavelength per fibre, thereby, increasing their capacity several times over. At each switching point in such networks, all wavelengths are terminated and converted to electrical form, and are remodulated onto the optical carrier at the output. Second generation networks obviate the need for conversion to the electronic domain by providing switching and routing services at the optical layer. Such networks are known as all optical networks [4].

Further to advances with WDM technology, dense wavelength division multiplexing (DWDM) has made it

* Corresponding author:

ruchiim2b@gmail.com (Baruch Mulenga Bwalya)

Published online at <http://journal.sapub.org/ijit>

Copyright © 2017 Scientific & Academic Publishing. All Rights Reserved

possible for networks to achieve ultra-high data transmission rates [6]. The role of optics in our study is to illustrate that with increasing data rates, calculations for buffer size must be made, independent of the capacity of the transmission links in the network.

In this paper, we simulate a first generation optical network, set in a multipath environment, using OPNET simulation software, although now known as Riverbed Academic Modeller, we will refer to it as OPNET in the rest of this paper.

Multipath routing has the potential of improving the throughput of traffic in the network but requires optimum buffers in the access network, as it is only available in the core of the network. The main disadvantage associated with multipath routing manifests as packet disordering at the receiver, since traffic is split into these multiple paths with different latencies creating jitter [16]. Solutions to these issues have been proposed in [17] and [18].

The rest of the paper is organized as follows. In section 2, we give an overview of buffer sizes and in section 3 we address buffer size and power consumption. In section 4, we look at simulation set up. Section 5 presents simulation results and discussion. We conclude the paper in section 6.

2. Overview of Buffer Sizes

Various proposals for calculation of buffer size have been made throughout the years. Here, we present some of the proposals made, to address the problem of buffer size in networks.

2.1. Bandwidth Delay Product

Bandwidth delay product or the rule-of-thumb gives a measure of required buffer size for a particular network based on its average round trip time and link capacity. The rule-of-thumb comes from a desire to keep the bottleneck link as busy as possible, so that the throughput of the network is maximized by providing a buffer size equal to the bandwidth delay product. This buffer size prevents the link from going idle and thereby losing throughput. However, Transmission Control Protocol (TCP) "sawtooth" congestion control algorithm is designed to fill any buffer, and deliberately causes occasional packet loss so as to provide feedback to the sender. Therefore, no matter how big we make the buffers at a bottleneck link, TCP will cause the buffer to overflow [19].

The bandwidth delay product, which is widely used in determining buffer size states that each link needs a buffer size:

$$B = \overline{RTT} \times C \quad (1)$$

where RTT is the average round trip time of the flow passing through the link and C is the capacity of the link. Using experimental measurements of at most eight TCP flows on a 40Mbits/s link, Vallamizar and Song [7] concluded that because of the dynamics of TCP's congestion control

algorithm, a router needs an amount of buffering equal to the average round-trip time of a flow that passes through the router, multiplied by the capacity of the routers network interfaces. This is the well-known rule-of-thumb, which network operators use to require router manufactures provide 250ms or more of buffering for a router [8].

2.2. A Case for Small Buffers

The rule-of-thumb complicates router buffer design due to the buffer sizes that can be required when the network capacity is large. For example, a 10Gbits/s router linecard needs approximately $250\text{ms} \times 10\text{Gbits/s} = 2.5\text{Gbits}$ of buffer. The amount of buffer required for a router will grow linearly with linerate.

Appenzeller et al. [9] conclude that buffers in backbone routers which use the rule-of-thumb, are much larger than they need to be, possibly by two orders of magnitude. They argue that the rule-of-thumb is now outdated and incorrect for backbone routers because of the large number of flows multiplexed together on a single backbone link. They go on to propose that a link with N flows requires no more than:

$$B = \overline{RTT} \times C / \sqrt{N} \quad (2)$$

where RTT is the average round trip time, C is the capacity of the link and N is the number of flows sharing the bottleneck link. The small buffers rule makes two assumptions. First is that utilization is the right metric for buffer sizing in a router and second that when there are many flows in a network, they are not synchronized. A link utilization of 100% is desired by the network operators as it means there is efficient utilization of resources, but this does not guarantee faster access times in access networks. Small buffers can reduce the network round trip time, which leads to a higher network throughput for each flow with TCP, as the flows will complete faster [21].

Avrachenkov et al. in [10] study an optimal choice for buffer size in internet routers. The objective of the study being to determine the minimum value of the buffer size required in order to fully utilize the link capacity. They propose a formula for buffer size as:

$$B = (\mu RTT)^2 / 32n^3 \quad (3)$$

where μ is the link capacity, RTT is the round trip time and n is the number of TCP connections.

In [10], the problem of router buffer size is formulated as a multi-criteria optimization problem. The solution to this problem provides further evidence that buffer size should be reduced in the presence of traffic aggregation. The study concludes that the minimum required buffer is smaller than what previous studies suggested.

Enachescu et al. [1], conducted a study on buffer sizes for backbone routers. Building on the work of Appenzeller et al. for the case of small buffers, Enachescu et al. explore how buffers in backbone routers can be significantly reduced even more, to as little as a few dozen packets, if we are willing to sacrifice a small amount of link capacity.

They [1] argue that if the TCP sources are not overly bursty, then fewer than twenty packets buffers are sufficient for high throughput. This network of tiny buffers can have buffer size of:

$$B = O(\log W) \quad (4)$$

where W is the window size of each flow.

2.3. A Case for Large Buffers

Dhamdhare and Dovrolis [22] raise some concerns about previous recommendations on small buffers in the network. They show that small buffers can lead to excessively high packet loss rates in congested access links that carry many flows. They argue that even if the link is fully utilized, small buffers lead to lower throughput for most large TCP flows.

In [22], they state that when using small buffers, there is packet loss rate of up to 15% in congested access links that carry many flows. Such frequent packet losses can negatively affect certain applications, making application layer performance less predictable. The study recommends an increase in buffer sizes to improve network performance.

Avrachenkov *et al.* in [11] studied the effect of the Internet Protocol (IP) router buffer size on the sending rate, the goodput and the latency of a TCP connection. They analysed short TCP transfers as well as persistent TCP connections.

In [11], they conclude that small buffers increase packet loss resulting in a poor sending rate and goodput. In the case of large buffers, the queuing delays and round trip times cause a poor sending rate and goodput.

Therefore, for a given TCP connection, there must be an optimal value of the buffer size for the bottleneck IP router, which must be different for each TCP connection due to propagation delays. They note several reasons for the buffer size to be increased, as opposed to being reduced. They suggest that for a system to be robust, buffers must be set larger, rather than smaller.

2.4. A Case for an Optimal Buffer

From the foregoing reviews, it is clear there is no one agreement on what the buffer size should be. Gorinsky *et al.* [12] attempted to reconcile the different approaches by arguing that the problem of buffer sizing needs a new approach other than the traditional bandwidth delay product; over-square-root or small buffer rule; and connection-proportional allocation, which support increased buffer size.

The suggestion in [12] is for a new formulation to address the problem of buffer size by designing a buffer sizing algorithm that accommodates the needs of all Internet applications; that does not involve the routers in any additional signalling. This, they argue, keeps the network queues short by setting the buffer size to $2L$ datagrams, where L is the number of input links.

To find an optimal buffer size for a network carrying both TCP and User Datagram Protocol (UDP) traffic, Vinoth and Thiruchelvi [13] proposed an equation:

$$Q \geq RTT \times C[1 + k_1]/2 - W_{UDP} \quad (5)$$

where RTT is the long lived TCP flow, C is the bottleneck link, k is a constant i.e. $k_1 + k_2 = 1$ and W_{UDP} is the total number of UDP packets.

However, we note in [10] that UDP does not use any congestion control and reliable retransmission and it is mostly employed for delay sensitive applications such as Internet telephony. UDP traffic does not contribute much in terms of the load in IP networks.

3. Buffer Size and Power Consumption

Router design has a significant impact on the cost of the router, power consumption and the cost of memory.

Small buffers can significantly reduce power consumption, the amount of fast memory required to build the buffer of the router and size of the buffer; thereby reducing the cost of the router. Small buffers also have the advantage of reducing queuing delays, while maintaining full link utilization at the target link; a design that comes with the cost of high loss rate of packets [14].

To compare power utilization of an optical router with a traditional electronic router, Gu *et al.* [15] designed an optical router and an electronic router to deliver the same maximum throughput. They used a moderate 12.5Gbit/s for each port on the routers. The electronic router was simulated in Cadence Spectre. The simulation results show that for the electronic router, on average, the crossbar consumes 0.07pJ/bit, the input buffer consumes 0.003pJ/bit and the control unit consumes 1pJ to make decisions for each packet. The optical routers implemented the same routing algorithm and had no input buffers. This made the optical buffers under study consume one or two orders of magnitude lower power than the electronic routers. A particular Cygnus only consumed 3.8% power of the high performance electronic router while routing 512 bit packets.

4. Simulations

We use OPNET to set up a network to evaluate buffer size. The network is simulated with Abilene backbone network, where low and heavy traffic scenarios are routed through the network.

The objectives of the simulation are to find an optimal buffer size for the network with minimal packet loss, independent of link capacity, due to an increase in data transmission rates. The links of the future are projected to be higher and it is improbable that such links will be utilized one hundred percent during data transmission. Packets must, therefore, spend as little time as possible at the routers by switching faster with small buffers.

4.1. Network Setup

The network simulation was setup with Abilene

backbone network [21], shown in Figure 1, as a first generation optical network, using OC-192 links, which have a capacity of well over 9 Gbps. This setup is in a multipath environment, where packets can take the shortest available route. A server was placed on the Seattle side of the network, as shown in Figure 2, and all client or host machines were placed on the New York side of the network, as shown in Figure 3. The server and hosts were set up to have direct connection to the access routers. Throughout the simulations, network hosts were varied from six to forty-eight, directly connecting to an access router.

The server generated traffic for the network. Table 1 shows the low traffic that was generated and simulated in the network. Table 2 shows the high traffic that was generated and simulated in the network. Six different kinds of traffic were generated across the network, with buffer size and datagram forwarding rates being varied during the simulations. IP packet drops were observed across the network and the buffer size and datagram forwarding rate observed and recorded, focusing on points where there was no packet loss. A graph was then plotted, showing the relationship between buffer size and datagram forwarding rate.



Figure 1. Abilene backbone network [21]

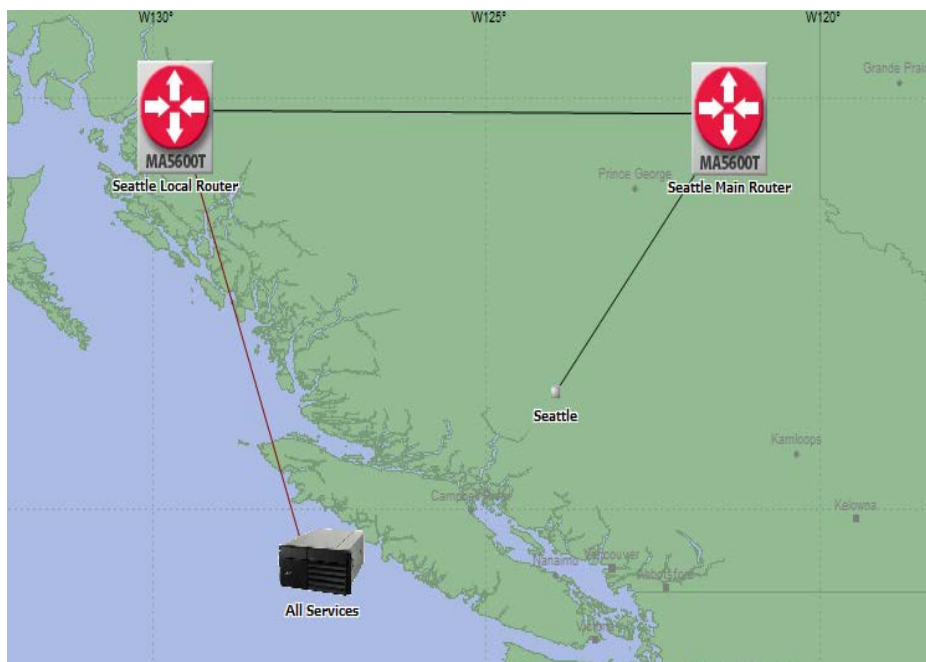


Figure 2. Server side setup at Seattle

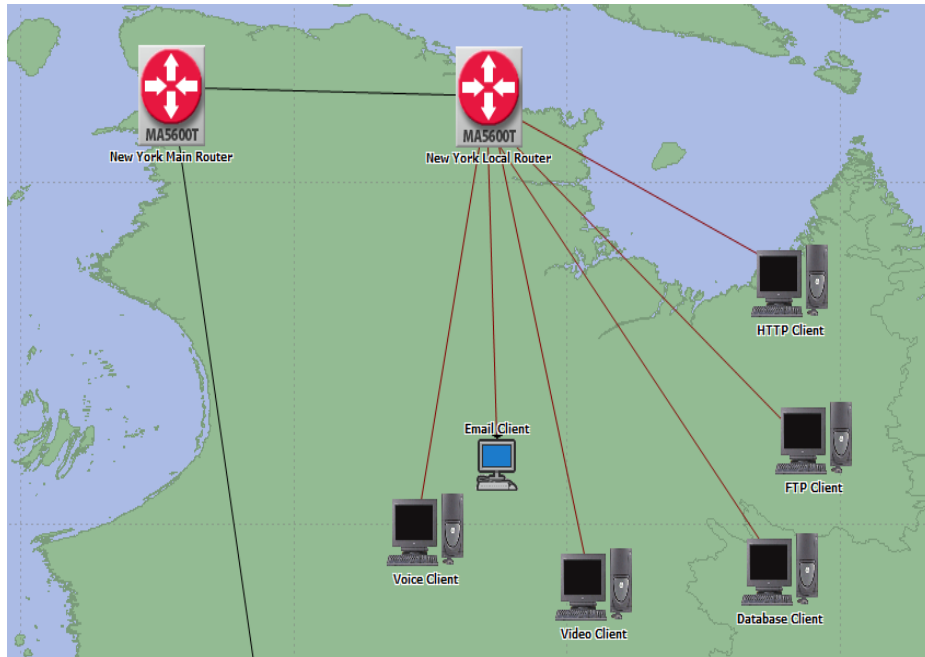


Figure 3. Host setup for New York subnet with six host connections to an access router

Table 1. Low Traffic in the Network

Application Definition	Value
Voice Server	PCM Quality and Silence Suppressed
Video Server	Low Resolution Video
HTTP Server	Light browsing
Email Server	Low Load
Database Server	Low Load
FTP Server	Low Load

Table 2. High Traffic in the Network

Application Definition	Value
Voice Server	GSM Quality and Silence Suppressed
Video Server	High Resolution Video
HTTP Server	Web TV
Email Server	High Load
Database Server	High Load
FTP Server	High Load

5. Simulation Results and Discussion

The objective of our simulation was to find an optimal buffer size. The focus of our study is not on link utilization or its relationship to buffer size.

5.1. Packet Drops across the Network

Packet drops were observed when the buffer size and datagram forwarding rates were not sufficient for traffic routing. This was observed both in low and high traffic scenarios as shown in Figure 4 and Figure 5. With such an observation, the buffer size was adjusted further to find an optimal buffer size.

Figure 4 shows packet drops in a low traffic environment with buffer size set at 17975 bytes and datagram forwarding rate (DFR) at 300 packets per second. Figure 5 shows packet drops in a high traffic environment with buffer size set at 40975 bytes and DFR set at 300 packets per second. With these settings, we observed packet drops at the edges of the network with one server and six hosts.

5.2. No Packet Drops across the Network

By simulation, we adjusted the buffer size until we found values for buffer size and DFR where packets were not dropping. This occurred at buffer size 17975 bytes and DFR of 390 packets per second for the low traffic environment as shown in Figure 4. For a high traffic environment, we set buffer size at 40975 bytes and DFR at 16000 packets per second as shown in Figure 5. Theoretically, this means that all packets are being delivered across the network with no packet drops. This scenario also means that the buffer size is optimal and sufficient for packet transfers.

As we varied the buffer size alone, while keeping DFR constant, we found the minimum buffer size required where no packets could drop across the network. From the point of the minimum buffer size, we adjusted the DFR downwards, to find the minimum forwarding rate at which no packets were dropping across the network for buffer size we had set. Minimums for a pair of datagram forwarding rate and buffer size were noted.

Next, we adjusted both the DFR and the buffer size and we discovered that doing so causes excessive packet loss. We then increased one value and reduced the other. As we increased the buffer size, we reduced the DFR. This is what we state as an inverse relationship between the buffer size and DFR. We have depicted this relationship by graphing

buffer size against DFR as shown in Figure 6 and Figure 7. Though we might not have found the accurate points or values for this relationship, we are satisfied that when buffer size is increased and DFR is reduced, a minimum value is found at which both these values can sustain network routing with minimal or no packets dropping across the network. We did this for low and high traffic scenarios in the network.

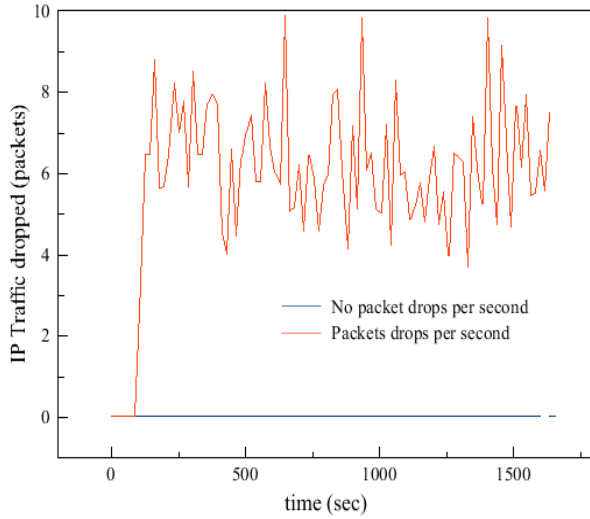


Figure 4. IP traffic flow in low traffic environment

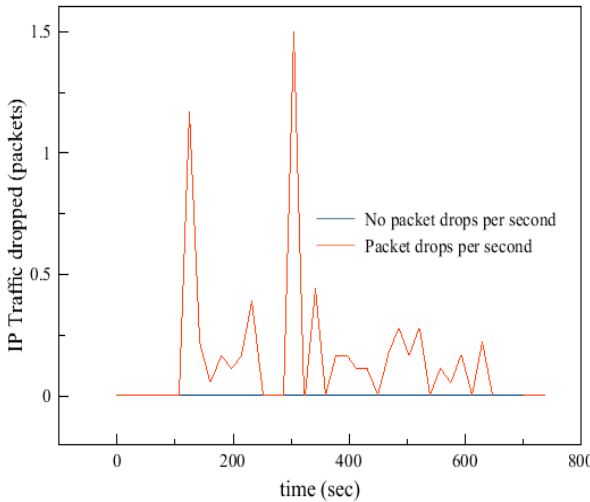


Figure 5. IP traffic flow in high traffic environment

Based on the relationship we found from our simulations, we came up with equation (6), having two known values which determine the constant k :

$$B = k/D \tag{6}$$

Where B is the buffer size and k is the constant of proportionality and D is the DFR.

To find the constant k , we ran simulations, where buffer size was increased and DFR rate was reduced. k was arrived at by taking the minimum value for the buffer and the maximum value for the DFR. This was done for both low and high traffic scenarios across the network.

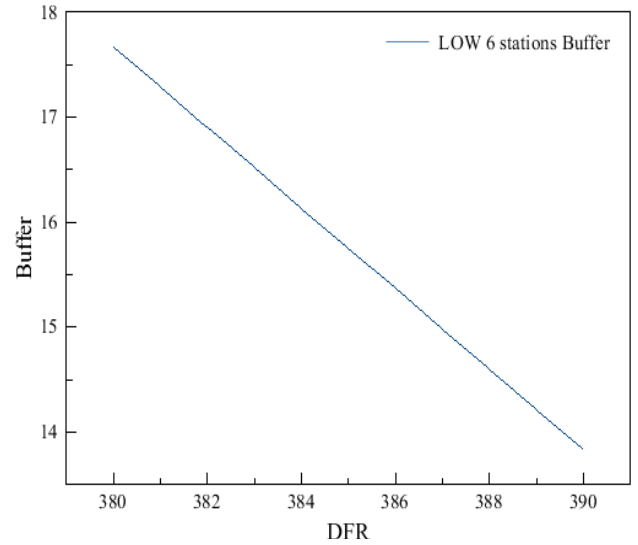


Figure 6. Buffer size plotted against datagram forwarding rate adjusted at intervals in low traffic environment

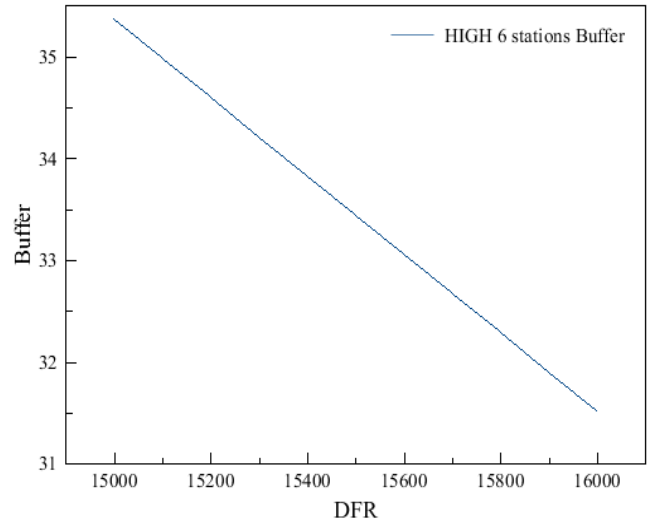


Figure 7. Buffer size plotted against datagram forwarding rate adjusted at intervals in high traffic environment

In a low traffic environment, we found that the minimum values for buffer size and DFR were 17975 bytes and 390 packets respectively. These values did not induce any packet drops. In our study, we take packet size to be equal to 1300 bytes. This, therefore, means that our minimal buffer size is 13.38 packets.

To find the value of k from equation (6), we have $B = 13.83$ and $D = 390$, therefore $k = 5393.70$, rounded off to 5400.

We observed that buffer size on access router needs to be doubled at most, from the minimum value we found, when hosts are twenty-four or more on the access network. Therefore, our new equation for low traffic networks and with more than twenty-four hosts is:

$$B = (5400/D) + 28 \tag{7}$$

where D is non-zero and 28 is the minimum buffer at the access routers where client connections are more than twenty-four. It can be noted that this value can be halved to 14 packets, for networks with less than twenty-four connections.

In high traffic networks, we found that the minimum values for buffer size and DFR were 40975 and 16000 packets respectively. This means the buffer size was 31.52 packets.

To find the value of k from equation (1), we have $B = 31.52$, $D = 16000$, therefore $k = 504320$, rounded off to 504000.

Our equation for high traffic in a network is:

$$B = (504000/D) + 32 \quad (8)$$

where D is non-zero and 32 is the minimum buffer at the access routers where client connections can be up to forty-eight.

5.3. Discussion

This paper summarizes a study of the feasibility of small buffers in first generation optical networks. With increasing link capacities, especially optical links, buffer sizes will increase linearly if the bandwidth delay product is used to come up with buffer sizes. Large buffers are not ideal for fast networks as they add to the delay of packets being routed.

In this study, we have observed that a network can reach a point where no packets are dropped and all packets are delivered between the two end-points of the network. The absence of packet drops theoretically means that buffer size is optimal and packets deliveries and acknowledgments are happening in the network without any need for TCP to drop packets in its transmission.

Buffer size and DFR were set to the same value all across the network, while adjusting the number of hosts on the client side of the network for both the low and high traffic environments. We noted that for the low traffic environment, packets were dropped when we increased the number of hosts to twenty-four. This prompted us to double the buffer size at the edge of the network, which is the New York local router; which had direct connection to the network hosts on the client side. This meant that the buffer size for traffic in low traffic environment needed to be doubled when more than twenty-four ports were being used at the router. This was not the case for high load traffic.

The optimal buffer size, for both low and high traffic environment can, therefore, be calculated from equation (8), which we present as the main equation from our study. Thus:

$$B = (504000/D) + 32$$

The formula we present from our study reduces the buffer size significantly from the traditional bandwidth delay product. This, in turn, reduces power consumption and board space when building the routers. The result is smaller, power efficient routers; which enhance network performance on networks with high link capacities.

In our simulations with OPNET, we used 100Gbps

Ethernet duplex link on the access network. The core of the network used OC-192. The RTT was observed at 0.055s, which was the highest RTT from our simulations.

With these values, we can calculate the buffer size that would be required for our router using the bandwidth delay product and come up with a buffer size of 5.5GB. Contrast this value with the buffer size we get from our simulation, which is 40975 bytes or simply 50KB in high traffic scenario.

A router with 5.5GB of buffer will require a lot of power and board space, resulting in a large router, that will hold packets longer during times of delay as it will queue up more packets compared to a router that has less buffer. A router with 50KB of buffer will require less power to run, take up less board space, compared to a router with 5.5GB of buffer. A 50KB router will hold fewer packets in times of delay, compared to a large buffer of, say, 5.5GB. This makes the smaller router more efficient by utilizing less power and holding packets for a shorter time in comparison to a large buffer. The result is enhanced network performance.

We also noted in our simulations with OPNET that we could only simulate not more than 50,000,000 events. This gave us the difference in simulation times we observed in Figure 4 and Figure 5, even though the simulation time was set as the same in both scenarios. This did not affect our results in any negative way except that the time of simulation is shorter as more events or data is flowing during the simulation.

6. Conclusions

As link capacity is increasing with improvements in optical technology, buffer size calculated from the rule of thumb increases linearly. This in turn increases router power consumption and board space due to the routers increased size. We have also noted that multipath routing in the core of the network reduces the load in the core of the network, leading to the possibility of employing small buffers in the core of the network. Such buffers can be as small as 7 packets.

Small buffers improve network performance. Consequently, we propose the equation $B = (504000/D) + 32$ as an alternative to big buffers, where D is the DFR and is non-zero.

Our proposed equation will make access networks more efficient, use less power and reduce the router size. Small buffers are ideal for networks with fast links like a first generation optical network.

Our further work will involve developing an interface on a router where network administrators can set buffer size and DFR based on their networking needs and also trying our proposed model on a real world network.

ACKNOWLEDGEMENTS

I wish to acknowledge Dr. S. Tembo, Dr. M.

Sumbwanyambe and Dr. D. Banda for the valuable guidance.

REFERENCES

- [1] M. Enachescu, Y. Ganjali, A. Goel, N. McKeown and T. Roughgarden, "Part III: Routers with very small buffers," *ACM SIGCOMM Computer Communication Review* 35, 2005, 83-90.
- [2] B. Mukherjee, "Optical packet switching," in *Optical WDM Networks*, Davies, CA: Springer Science and Business Media, Inc., 2006, p. 807.
- [3] R. Geldenhuys and F. W. Leuschner, "Buffering in All-Optical Packet-Switching," *University of Pretoria, SATNAC 2003*.
- [4] R. Ramaswami and K. N. Sivarajan, "Introduction to optical networks," in *Optical Networks: A Practical Perspective*. San Francisco, CA: Morgan Kaufman Publishers, Inc., 1998, pp1-40.
- [5] A. Shinya, M. Shinji, T. Takasumi, K. Eiichi, S. Tomonari, K. Takaaki and N. Masaya, "All Optical on chip bit memory based on ultra-high Q in Gasp photonic crystal," *Optics Express* 16 (23), 2008, 19382-19387.
- [6] O. Alparslan, S. I. Arakawa and M. Murata, "Buffer scaling for optical packet switching networks with shared RAM," *Optical Switching and Networking 8.1 (2011): 12-22*.
- [7] C. Villamizar and C. Song, "High Performance TCP in ANSNET," *ACM Computer Communications Review*, 24 (5): 45-60, 1994.
- [8] CISCO Line Cards [Online]. Available: http://www.cisco.com/en/US/products/hw/modules/ps2710/products_data_sheets_list.html.
- [9] G. Appenzeller, I. Keslassy and N. McKeown, "Sizing router buffers," In *SIGCOMM 2004: Proceedings of the 2004 conference on Applications, technology and architecture and protocols for computer communications*, pp. 281-292, New York, NY, 2004, ACM Press.
- [10] K. Avrachenkov, U. Ayesta, and A. Piunovsky, "Optimal choice of the buffer size in the internet routers," In *Proceedings of IEEE conference on decision and control*, 2005, pp 1143-1148.
- [11] K. Avrachenkov, U. Ayesta, E. Altman, P. Nain and C. Barakat, "The effect of router buffer size on TCP performance," In the proceedings of LINIIS workshop, St. Petersburg, Jan 29-Feb 1 2002.
- [12] S. Gorinsky, A. Kantawala and J. Turner, "Link buffer sizing: A new look at an old problem," Technical report WUCSE-2004-82, Department of Computer Science and Engineering, Washington University in St. Louis, December 2004.
- [13] R. S. Vinoth and G. Thiruchelvi, "Buffer Size for mixed TCP and UDP traffic," Technical report IJARCC-2015-04, University of India, vol. 4, Issue 4, 2015.
- [14] A. Dhamdhere and C. Dovolis, "Open issues in router buffer sizing," *ACM SIGCOMM Computer Communication Review* 36 (1):87-92, 2006.
- [15] H. Gu, K. H. Mo, J. Xu and W. Zhang, "A low-power low-cost optical router for optical networks-on-chip in multiprocessor systems-on-chip," In *VLSI proceedings of IEEE computer society annual symposium on VLSI*, 2009.
- [16] T. Anjali, A. Fortin, G. Calinescu, S. Kapoor, N. Kirubanandan and S. Tongngam, "Multipath network flows: bounded buffers and jitter," In *proceedings of IEEE INFOCOM 2010*.
- [17] S. Bohacek, J. Hespanha, J. Lee, C. Lim and K. Obraczka, "A new TCP for persistent packet reordering," *IEEE/ACM Transactions on networking*, vol. 14, No.2, 2006.
- [18] H. Han, S. Shakkottai, C. V. Hallot, R. Srikant and D. Towsley, "Multipath TCP: A joint congestion control and routing scheme to explore path diversity in the internet," *IEEE/ACM Transactions on networking*, vol. 14, pp.1260-1271, Dec. 2006.
- [19] G. Patil, S. McClean and G. Raina, "Drop Tail and RED queue management with small buffers: stability and hope bifurcation," *ICTACT Journal on Communication Technology: Special Issue on Next Generation Wireless Networks and Applications*, vol.2, no. 2, June 2011.
- [20] Y. Ganjali and N. McKeown, "Update on buffer sizing in internet routers," *ACM SIGCOMM Computer Communication Review*, vol. 36(5), 2006.
- [21] E. Roberts (2003). *Internet2Architecture* [Online]. Available: <https://cs.stanford.edu/people/eroberts/courses/soco/projects/2003-04/internet-2/architecture.html>.