

VIDEO DISTRIBUTION OVER IP NETWORKS

**A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF INFORMATICS
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY**

BY

MEHMET ÖZDEM

**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
THE DEPARTMENT OF INFORMATION SYSTEMS**

JANUARY 2007

Approval of the Graduate School of Informatics

Assoc. Prof Nazife BAYKAL
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Assoc. Prof. Yasemin YARDIMCI
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr.Y. Murat ERTEN
Supervisor

Examining Committee Members

Prof. Dr. Semih BİLGEN (METU, EE) _____
Assist. Prof. Dr. Y. Murat ERTEN (TOBB-ETU, CENG) _____
Dr. Ali ARİFOĞLU (METU, IS) _____
Dr. Altan KOÇYİĞİT (METU, IS) _____
Assoc. Prof. Dr. Ü.Erkan MUMCUOĞLU (METU, IS) _____

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Mehmet ÖZDEM

Signature : _____

ABSTRACT

VIDEO DISTRIBUTION OVER IP NETWORKS

ÖZDEM, Mehmet

M.S., Department of Information Systems

Supervisor: Assist. Prof. Dr. Y. Murat ERTEN

January 2007, 75 pages

As applications like IPTV and VoD (Video on demand) are gaining popularity, it is becoming more important to study the behavior of video signals in the Internet access infrastructures such as ADSL and cable networks. Average delay, average jitter and packet loss in these networks affect the quality of service, hence transmission and access speeds need to be determined such that these parameters are minimized.

In this study the behavior of the above mentioned IP networks under variable bit rate (VBR) video traffic is investigated. ns-2 simulator is used for this purpose and actual as well as artificially generated signals are applied to the networks under test. Variable bit rate (VBR) traffic is generated synthetically using ON/OFF sources with ON/OFF times taken from exponential or Pareto distributions. As VBR video shows long range dependence with a Hurst parameter between 0.5 and

1, this parameter was used as a metric to measure the accuracy of the synthetic sources. Two different topologies were simulated in this study: one similar to ADSL access networks and the other behaving like cable distribution network. The performance of the networks (delay, jitter and packet loss) under VBR video traffic and different access speeds were measured. According to the obtained results, minimum access speeds in order achieve acceptable quality video delivery to the customers were suggested.

Keywords: Long range dependency, Hurst parameter, VBR, Pareto distribution, exponential distribution.

ÖZ

IP ŞEBEKELER ÜZERİNDEN VIDEO DAĞITIMI

ÖZDEM, Mehmet

Yüksek Lisans, Bilişim Sistemleri Bölümü

Tez Yöneticisi: Yrd. Doç. Dr. Y.Murat ERTEN

Ocak 2007, 75 sayfa

IPTv, VoD gibi uygulamaların yaygınlaşması; ADSL veya kablo altyapısını kullanan şebekelerde video sinyalleri ile ilgili çalışmaların önemini artırmaktadır. Bu ağlarda video trafiğinin karşılaşacağı ortalama gecikme, ortalama gecikme değişimi ve paket kaybı servis kalitesini etkileyeceğinden, iletim ve erişim hızı gibi ağ parametrelerinin bunları en aza indirecek şekilde seçilmesi önem kazanmaktadır.

Bu çalışmada değişken hızda (VBR) video trafiği altında IP şebekelerinin davranışı incelenmiştir. Bu amaç için ns-2 simulatörü kullanılmış ve gerçek video sinyallerinin yanı sıra sentetik olarak üretilmiş sinyaller de test altındaki şebekelere uygulanmıştır. Değişken hızda (VBR) video trafiği sentetik olarak Üstel ve Pareto dağılımlarına göre ON/OFF zamanları belirlenmiş kaynaklar kullanılarak elde edilmiştir. VBR video sinyallerinin uzun süreli bağımlılık gösterdiği için Hurst parametresinin 0.5 ile 1 aralığında olduğu bilindiğinden bu parametre sentetik kaynakların doğruluğunu ölçmek amacıyla kullanılmıştır.

Çalışmada ADSL türü bir ağ ve kablo internet altyapısı, ns-2 simulatörü kullanılarak benzetim yoluyla test edilmiştir. Bu ağların değişik hızlarda uygulanan video trafiği ve farklı erişim hızlarında performansları (gecikme, gecikme değişimi ve paket kaybı) ölçülmüştür. Bu sonuçlara göre abonelerin kabul edilebilir video kalitesine sahip olmaları için gerekli erişim hızlarıyla ilgili öneriler geliştirilmiştir.

Anahtar Kelimeler: Uzun süreli bağımlılık, Hurst parametresi, Değişen bit oranı, Pareto dağılımı, üstel dağılım.

ACKNOWLEDGEMENTS

I first thank my supervisor Assist. Prof. Dr. Y. Murat ERTEN for providing guidance and insight throughout this research.

I also want to thank my manager Hakan AYDIN for his patience and supports. I want to thank my cousin Ahmet T. SERİN for his help and suggestions. I also thank my friends Murat YÜCEL and Orhan KILIÇ for their invaluable support.

TABLE OF CONTENTS

ABSTRACT	iv
ÖZ	vi
ACKNOWLEDGEMENTS	viii
TABLE OF CONTENTS	ix
LIST OF TABLES	xi
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS AND ACRONYMS	xvi
CHAPTER	
1. INTRODUCTION.....	1
1.1 Background	1
1.2 Thesis Structure.....	3
2. SELF-SIMILARITY AND LONG RANGE DEPENDENCE.....	4
2.1 The Self-similarity.....	5
2.2 Long range dependence phenomenon	6
2.3 Short-range dependence vs. long-range dependence.....	7
2.4 Long range dependence on VBR.....	8
2.5 Hurst Parameter Estimation	9
2.5.1 Discrete Wavelet Transform.....	10
2.5.2 Wavelet-based Hurst Parameter Estimator.....	11
3. ON/OFF SOURCES.....	14
3.1 Video Traffic	14
3.2 ON/OFF Sources	14
3.2.1 Pareto ON/OFF Sources.....	15
3.2.2 Exponential ON/OFF Sources.....	19

4. NETWORK SIMULATIONS	21
4.1 Purpose and Scope.....	21
4.2 ns-2 Simulator	22
4.3 Simulation Setup 1.....	23
4.3.1 Results of simulation setup 1.....	28
4.4 Simulation Setup 2.....	39
4.4.1 Results of simulation setup 2.....	39
4.5 Simulation Setup 3.....	44
4.5.1 Results of simulation setup 3.....	44
4.6 Simulation Setup 4.....	45
4.6.1 Results of simulation setup 4.....	45
4.7 Network Performance	48
5. SIMULATION VERIFICATION.....	57
6. CONCLUSIONS	61
6.1 Future Work	62
REFERENCES	63
APPENDICES	67
A. OTHER HURST PARAMETER ESTIMATION APPROACHES.....	67
B. SAMPLE SCRIPTS AND CODES USED IN SIMULATIONS.....	69

LIST OF TABLES

Table 1- Hurst parameter for exponential distribution with different ON/OFF times (Simulation duration = 4 seconds and Number of nodes =10)	29
Table 2- Hurst Parameter for Pareto distribution with different ON/OFF times and shaping factors (Simulation duration=4 seconds Number of nodes=10)	30
Table 3- Hurst Parameter for exponential distribution for different number of nodes (Simulation duration = 4 seconds and ON/OFF =15 ms).....	31
Table 4- Hurst Parameter for Pareto distribution for different number of nodes (Simulation duration =4 seconds, ON/OFF =50 ms, Shaping factor=1.5).....	31
Table 5- Hurst Parameter for exponential distribution with different ON/OFF times (Simulation duration=1000 seconds and Number of nodes=10)	32
Table 6- Hurst Parameter for Pareto distribution with different ON/OFF times (Simulation duration=1000 seconds , Shaping factor=1.5 and Number of nodes=10)	33
Table 7- Hurst Parameter for exponential distribution with different simulation duration's (ON/OFF =5 seconds and Number of nodes=10).....	33
Table 8- Hurst Parameter for exponential distribution with different simulation duration's (ON/OFF =10 seconds and Number of nodes=10).....	34
Table 9- Hurst Parameter for Pareto distribution with different simulation duration's (ON/OFF =1 seconds and Number of nodes=10).....	34
Table 10- Hurst Parameter for exponential distribution with different packet sizes (Simulation duration=1000 seconds, ON/OFF =5 seconds and Number of nodes=10)	35

Table 11- Hurst Parameter for Pareto distribution with different packet sizes (Simulation duration =1000 seconds, ON/OFF =1 second, Shaping factor =1.5 and Number of nodes=10)	35
Table 12- Hurst Parameter for exponential distribution with different bit rates (Simulation duration= 1000 seconds, ON/OFF =5 seconds and Number of nodes=10)	37
Table 13- Hurst Parameter for Pareto distribution with different bit rates (Simulation duration=1000 seconds, ON/OFF =1 seconds and Number of nodes=10)	37
Table 14- Hurst Parameter for Starwars trace with different simulation duration's (Number of nodes=10)	38
Table 15- Hurst Parameter for exponential distribution with different ON/OFF times (Simulation duration =4 seconds, Number of nodes=10)	40
Table 16- Hurst Parameter for Pareto distribution with different ON/OFF times and shaping factor. (Simulation duration=4 seconds, Number of nodes=10).....	40
Table 17- Hurst Parameter for exponential distribution for different number of nodes (Simulation duration=4 seconds and ON/OFF=15 ms).....	41
Table 18- Hurst Parameter for Pareto distribution for different number of nodes (Simulation duration=4 seconds, ON/OFF =50 ms, Shaping factor=1.5).....	41
Table 19- Hurst Parameter for exponential distribution with different ON/OFF times (Simulation duration=1000 seconds and Number of nodes=10).....	42
Table 20- Hurst Parameter for Pareto distribution with different ON/OFF times (Simulation duration=1000 seconds and Number of nodes=10)	42
Table 21- Hurst Parameter for exponential distribution with different bit rates (Simulation duration =1000 seconds, ON/OFF =5 seconds and Number of nodes=10)	43
Table 22- Hurst Parameter for Pareto dist with different bit rates (Simulation duration=1000 seconds, ON/OFF =1 second and Number of nodes=10)	43
Table 23- Hurst Parameter for Starwars for different queue size (Simulation duration=100 seconds and Number of nodes=100)	44

Table 24- Hurst Parameter for exponential distribution for different queue size and different bit rates (ON/OFF =300 ms, Simulation duration=100 seconds and Number of nodes=100).....	46
Table 25- Hurst Parameter for Pareto distribution for different queue size and different bit rates (ON/OFF = 50 ms, Simulation duration=100 seconds and Number of nodes=100).....	47
Table 26- Hurst Parameter for Par. and exponential distribution for different bit rates (Simulation duration=100 seconds and Number of nodes=100)	48
Table 27- The loss rate comparison	58

LIST OF FIGURES

Figure 1 - SRD & LRD autocovariance	8
Figure 2 - Logscale diagram of $y_j = \log_2 E \{d(j,k)q\}$ and j	13
Figure 3 - Distribution network topology used in the simulations	24
Figure 4 - Cable access network assumed in the simulations	24
Figure 5 - VBR simulation using Pareto distribution (Simulation duration=1000 seconds)	25
Figure 6 - VBR like signal generated using exponential distribution (Simulation duration=1000 seconds).....	26
Figure 7 - VBR Simulation using Pareto distribution for single traffic at Node 1 (Simulation duration=100 seconds)	27
Figure 8 - VBR Simulation using exponential distribution for single traffic at Node1 (Simulation duration=100 seconds)	28
Figure 9 - Hurst Parameter when ON/OFF sources are applied to Figure 3 with different packet size.....	36
Figure 10 - Hurst Parameter when ON/OFF sources are applied to Figure 3 with different bit rates.	37
Figure 11 - Hurst Parameter when synthetic sources and Starwars are applied to Figure 3 with different simulation duration's	38
Figure 12 - Packet loss when synthetic ON/OFF sources and Starwars are applied to Figure 3 with different number of nodes.	49
Figure 13 - Delay when synthetic ON/OFF sources and Starwars are applied to Figure 3 with different number of nodes	49
Figure 14 - Packet loss vs. bit rate for ON/OFF sources generated using Pareto distribution for simulation setup 2	50

Figure 15 - Delay vs. bit rate for ON/OFF sources generated using Pareto distribution for simulation setup 2	51
Figure 16 - Packet loss vs. bit rate for ON/OFF sources generated using Pareto distribution for simulation setup 3.....	52
Figure 17 - Packet loss vs. bit rate for ON/OFF sources generated using exponential distribution for simulation setup 3.....	52
Figure 18 - Delay vs. bit rate for ON/OFF sources generated using Pareto distribution for simulation setup 3.....	53
Figure 19 - Delay vs. bit rate for ON/OFF sources generated using exponential distribution for simulation setup 3.....	53
Figure 20 - Jitter vs. bit rate for ON/OFF sources generated using Pareto distribution for simulation setup 3	54
Figure 21 - Jitter vs. bit rate for ON/OFF sources generated using exponential distribution for simulation setup 3	54
Figure 22 - Packet loss vs. bit rate for ON/OFF sources applied to Figure 4 for simulation setup 4.....	55
Figure 23 - Delay vs. bit rate for ON/OFF sources applied to Figure 4 for simulation setup 4.....	56
Figure 24 - Jitter vs. bit rate for ON/OFF sources generated using Pareto and exponential distributions for simulation setup 4.....	56
Figure 25 - Simulated topology to verify the simulations.....	57
Figure 26 - Packet loss and delay measurement using Trace graph tool	59
Figure 27 - Packet loss and delay measurement using awk scripts	60

LIST OF ABBREVIATIONS AND ACRONYMS

ADSL	: Asymmetric Digital Subscriber Line
ATM	: Asynchronous Transfer Mode
AVC	: Advanced Video Coding
CBR	: Constant Bit Rate
CPE	: Customer Premises Equipment
DSLAM	: Digital Subscriber Line Access Multiplexer
DVD	: Digital Versatile Disc
DWT	: Discrete Wavelet Transform
FIFO	: First In First Out
FTP	: File Transfer Protocol
GBPS	: Gigabits Per Second
H	: Hurst Parameter
HTTP	: Hyper Text Transfer Protocol
IP	: Internet Protocol
IPTV	: Internet Protocol Television
KB	: Kilobyte
KBPS	: Kilobits Per Second
LAN	: Local Area Network
LRD	: Long Range Dependence
MATLAB	: Matrix Laboratory
MBPS	: Megabits Per Second
MS	: Millisecond
MPEG	: Motion Picture Experts Group

NAM	: Network Animator
NS-2	: Network Simulator 2
POO	: Pareto On/Off
PSD	: Power Spectral Density
QL	: Queue Length
S	: Second
SD	: Simulation Duration
SRD	: Short Range Dependence
TCL	: Tool Command Language
TCP	: Transmission Control Protocol
UDP	: User Datagram Protocol
VBR	: Variable Bit Rate
VCD	: Video Compact Disk
WWW	: World Wide Web

CHAPTER 1

INTRODUCTION

1.1 Background

Services like IPTV are intended to be deployed over access networks such as ADSL and cable; hence it is important to understand the behavior of video traffic over these networks.

In this study the delay, jitter and packet loss were analyzed for ADSL and cable networks under video traffic. The simulation was used in the study and adopted Network Simulator 2 (ns-2) which is a popular simulator commonly utilized to simulate different network types and topology was used for simulations. The publicly available Starwars trace [1] as well as artificially generated inputs were applied to simulate the networks under test.

Video delivery over IP networks has been studied in many previous researches. In [2] a similar study was conducted on the challenges of delivering IP based residential television services over an IP networks. It was stated in that article that at least 1 Mbps video channels should be allocated for television on the PC. In [3] the network under study was similar to simulated ADSL network topology but they only used actual video traces in their simulations.

Their results show that buffer sizes of about 150 KB are required to deliver Starwars video with a packet loss less than 1%. Starwars trace was used in these and many other studies to measure the network characteristics such as delay and throughput. As the rate of this source can not be changed, however, delay, jitter and packet loss parameters can not be measured against rate when this source is used. Therefore research using actual video traces usually measures packet loss and delay against buffer size [3].

To avoid this, variable bit rate (VBR) video is generated artificially in this work using the built in functions of ns-2 and ON/OFF source models was adopted with ON and OFF times taken from exponential or Pareto distributions. These sources transmit at fixed rates during the ON periods and are silent during OFF periods. Signals generated in this manner provide more flexibility to test the different performance parameters of the networks and the independent variable may be chosen more freely when this approach is deployed.

To make sure that these artificially generated signals generate a realistic environment when used in these simulations their parameters have to be chosen correctly. It has been shown that VBR video exhibits long range dependence [4] and a precise marginal distribution with a heavy tail [5] hence it is reasonable to assume that traffic generated artificially using the superposition of ON/OFF sources should also possess self-similarity if to be used in place of actual video traces [4],[6].

To measure the degree of self similarity (in general long range dependence also implies self similarity) shown by the video signals, Hurst parameter (H) is used as a metric. A signal which exhibits long range dependence has an H parameter between 0.5 and 1.0 [4] and it shows stronger self similarity if this parameter is closer to 1.0 without exceeding it [7]. The H parameter of the artificially generated ON/OFF sources were measured using a wavelet based estimator. This is similar to a study reported in [6] but a larger network topology was used and this work also

includes processes with exponential ON/OFF times to identify their behavior. It is expected that distributions with finite variance such as exponential distribution will show correlations in the short range. Simulations for different periods of time to test the suitability of different distributions were also performed. Based on the results of H parameter measurements, different parameters of the ON/OFF sources were selected and these were applied as inputs to the networks. Similar measurements were also made on the same networks applying data from the Starwars sequence and the results were compared. The results show that both actual and synthetic sources produce similar results and that the access networks should have at least 1 Mbps speeds to support acceptable quality video transmission.

1.2 Thesis Structure

This text is organized as follows:

Chapter 2 includes information about long range dependency and self-similarity concepts. It also explains Hurst parameter and the method adopted to calculate it.

Chapter 3 provides background about Pareto and exponential ON/OFF sources. It covers how ns-2 creates the ON/OFF source traffics.

Chapter 4 covers the network simulations and presents the results of network performance for different inputs.

Chapter 5 presents the conclusions.

Appendix A explains approaches for estimating the Hurst parameter such as R/S, variance-time and periodogram estimators.

Appendix B includes the sample scripts and Tcl codes. ns-2 simulator was used in the study which uses Tcl as a command and configuration interface and awk scripting language was used to calculate the delay, jitter and packet loss.

CHAPTER 2

SELF-SIMILARITY AND LONG RANGE DEPENDENCE

Multimedia network applications, such as video streaming and video conferencing, have gained popularity in the past years. Video traffic possesses two major characteristics: high bandwidth requirements and high variability [8]. In order to model and analyze the impact of the network performance on the quality of the received video, it is important to develop adequate models for the video sources.

Analyses of the statistical properties of video sequences compressed by employing various encoding algorithms (MPEG-2, MPEG-4, H.263, and several proprietary algorithms) [4], [9], [10] have shown that long-range dependence is an inherent property of the video traffic. The property is independent of the scene (e.g., video phone, video conference, motion picture video, codec). Long-range dependent processes are characterized by the Hurst parameter (H) which is a measure of the degree of self-similarity of a data stream because it allows the evaluation of the bursty nature of a data flow.

This chapter introduces main properties of self-similarity, long range dependency and methods which are used to estimate H value.

It also includes some research in the literature on the long range dependence (LRD) properties of discrete signals.

2.1 The Self-similarity

Self-similarity implies a “fractal” behavior which means that no matter what time scale is used to examine the data, similar patterns are seen. Burstiness exists across many time scales in self-similar processes. Unlike the Poisson traffic, traffic does not get “smoother” when it is aggregated. Self-similar object is exactly or approximately similar to a part of itself, the whole has the same shape as one or more of the parts.

There are many studies in the literature which show that the following traffic types exhibit self similar characteristics

- Ethernet traffic

The study in [7] shows that Ethernet traffic is self-similar with typical parameter values of $H = 0.9$, $\alpha = 1.2$ where α is shaping factor.

- Signalling System No. 7 traffic

In [11] the control signal protocol signaling System Number 7, used in ISDN and other digital networks is investigated. The study shows that self-similar traffic models provided a much better fit than Poisson based models.

- TCP, FTP and TELNET traffic

In [12] it is indicated that TCP traffic exhibited self-similar characteristics.

- VBR Video

Many studies have shown that digitized video of the type that is transmitted over networks is self-similar [4], [5], [9], [10], [13], [14].

Fractals and the corresponding self-similarity phenomena were originally introduced by B. Mandelbrot [15] to explain the mathematical objects whose properties get preserved when scaled in space or in time. Such phenomena (fractals) are generated by using deterministic functions or procedures. The self-similarity property of such fractals was a deterministic one, implying that their structure remained the same regardless of time or space scales.

Mathematical definition of self-similarity is represented in [16] as follows.

Given a zero-mean, stationary time series $X = (X_t; t=1,2,3,\dots)$, m -aggregated series are defined as $X^{(m)} = (X_k^{(m)}; k=1,2,3,\dots)$ by summing the original series X over nonoverlapping blocks of size m . Then it can be said that X is self-similar, if for all positive m , $X^{(m)}$ has the same distribution as X rescaled by m^H . That is,

$$X_t = m^H \sum_{i=(t-1)m+1}^{tm} X_i \quad \text{for all } m \in \mathbb{N}. \quad (\text{Equation 1})$$

If X is self-similar, it has the same autocorrelation function

$$r(k) = E[(X_t - \mu)(X_{t+k} - \mu)] / \sigma^2 \quad (\text{Equation 2})$$

as the series $X(m)$ for all m where σ^2 represents variance of X series and μ represents mean of X series .

2.2 Long range dependence phenomenon

Another important property of the Internet traffic processes is long-range dependency (LRD) [17]. Bursty traffic patterns generated by data sources and VBR real-time applications such as compressed video and audio tend to exhibit certain degrees of correlation between arrivals, and show long-range dependence in time (self-similar traffic) [13].

In [18] it has been stated that given $X(n)$, $n = 0, 1, \dots$ be a wide sense stationary stochastic process with an autocorrelation function $r(k)$ with time lag k , the process

$X(n)$ is called long-range dependent if the sum of $r(k)$ over all k 's is infinite [19]. For large lags k , $r(k)$ is modeled as a hyperbolic (power law) decaying function:

$$r(k) = c_r k^{-(2-2H)}, k \rightarrow \infty, \quad (\text{Equation 3})$$

where c_r is a positive constant and H ($0.5 \leq H < 1$) is the Hurst parameter. The power spectral density (PSD) $f(v)$ of $X(n)$ satisfies equation 4.

$$f(v) = c_f |v|^{-\alpha}, |v| \rightarrow 0, \quad (\text{Equation 4})$$

where c_f is a positive constant and α is the scaling exponent. For LRD process, $0 < \alpha < 1$. The relationship between H and α is linear:

$$H = 0.5(1 + \alpha) \quad (\text{Equation 5})$$

The Hurst parameter measures the degree of LRD of a process. Values of $H \approx 1$ indicate a process with strong LRD. For example, bursty network traffic has large H [19]. In [4] it is stated that a process with long-range dependence exhibit a much smaller decay of the correlations.

2.3 Short-range dependence vs. long-range dependence

Long-range (LRD) and short-range dependent (SRD) processes are characterized by their autocovariance functions as shown in Figure 1 [11].

In short-range dependent (SRD) processes, the coupling between values at different times decreases rapidly as the time difference increases [11].

- Near zero, there exists an exponential decay.
- The area under it is finite.

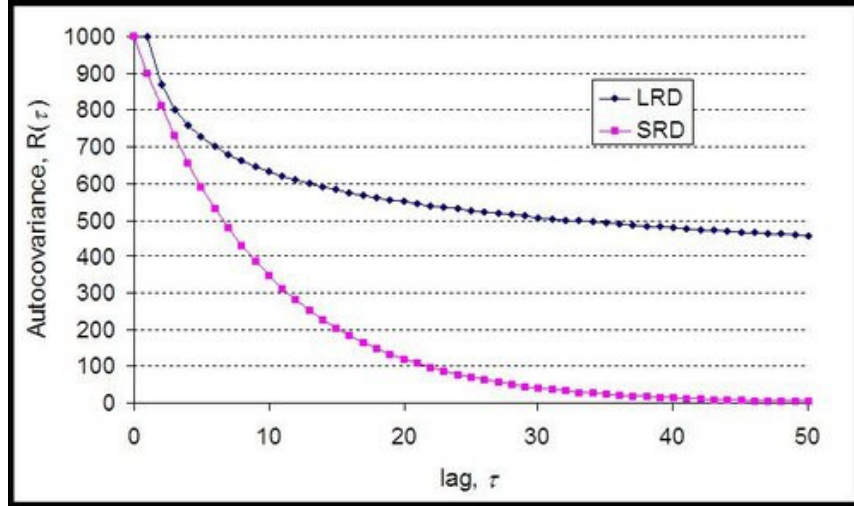


Figure 1 - SRD & LRD autocovariance

In long-range processes there is much stronger coupling.

- The decay of the autocovariance function is hyperbolic and decays slower than exponentially.
- The area under it is infinite.

2.4 Long range dependence on VBR

In [20] it is stated that currently, most digital video broadcasting systems use MPEG-2, MPEG-4, H-264, AVC video compression standards to encode raw video into a constant bit rate (CBR) bit stream. The major advantage of CBR coding is that its bit rate is constant so that it is easily transported over conventional communication channels. For many video broadcasting or transmission applications, higher bit rate is usually used to guarantee the acceptable video quality for the most complex video content segments.

At the same time, more bits are unnecessarily wasted for simple video content segments. The same reference suggests to improve the information throughput of digital broadcasting networks, and states that migration of digital video coding

technology from CBR to VBR encoding is the next step that could achieve substantial bit savings without sacrificing encoded video quality. The high compression ratio of VBR coding has been evidenced by such applications such as DVD, VCD and video server etc. Depending on the application configuration and encoder and multiplexer design, coding efficiency improvements of up to 40% or more could be reached.

The principle of VBR coding is to encode the video content as much as possible to have a constant quality. The number of bits used for coding each frame is a function of spatial and temporal frame content complexity. This results in VBR bit stream.

In [4] it is stated that the most important inherent feature of VBR video traffic is long-range dependence. This feature is independent of scene (e.g. video phone, video conference, motion picture video) and codec. Additional studies show that VBR video traffic shows long-range dependence characteristics and hence are of the self-similar in nature [9], [10], [14].

2.5 Hurst Parameter Estimation

Self-similarity can be expressed by using the Hurst Parameter [21]. In the same reference it is stated that the H value is suggested as a measure of the degree of self-similarity of a data stream because it allows the evaluation of the bursty nature of a data flow.

Hurst parameter can be used as a data stream control and description parameter. It could be used in intermediate nodes and in end-nodes to evaluate the characteristics of the current flow of data and to make decisions about, for example, admission or congestion control. The predominant way to quantify LRD is through the Hurst exponent, which is a scalar, but calculating this exponent is not straightforward. First, it can not be calculated definitively, only estimated. Second, although there

are several different methods to estimate the Hurst exponent, they often produce conflicting results, and it is not clear which provides the most accurate estimation [22].

There are different methods for estimating the H value. R/S analysis [7], [21] variance-time analysis [23], periodogram analysis [24], Whittle, and wavelet-based [18], [25] estimators are among these. These approaches are described and compared in [26], [13], [22] and tabulated in Appendix A. Wavelet-based estimator is considered to be unbiased and robust with respect to presence of deterministic trends in the analyzed process [25], [27].

In this thesis Hurst parameter estimator which was downloaded from [28] was used. This code is based on Abry-Veitch approach of using wavelets in estimating the Hurst parameter and is written in MATLAB.

According to [26] this approach does not perform well in the presence of noise and tends to over estimate the Hurst parameter, but it is a quick and well established solution which served our purposes. Also Hurst parameter was calculated for the Starwars movie in [5] using different approaches. These calculations produced results ranging from 0.78 to 0.83. Our calculation of the Hurst parameter for the same movie produced 0.800 which is comparable to the previously obtained results.

2.5.1 Discrete Wavelet Transform

In [18] it is stated that the discrete wavelet transform (DWT) represents a signal $X(t)$ as a weighted sum of basis functions called wavelets:

$$X(t) = \sum_{j=0}^{\infty} \sum_{k=-\infty}^{\infty} d(j,k) \psi_{j,k}(t) \quad (\text{Equation 6})$$

where $d(j, k)$ is the wavelet coefficient at octave j and time k and

$$\psi_{j,k}(t) = 2^{-j/2} \psi(2^{-j}t - k) \quad (\text{Equation 7})$$

is the wavelet obtained from an adequately chosen mother wavelet ψ . The wavelet $\psi_{j,k}$ is a scaled (by a factor of 2^j) and shifted (by k time units) version of the mother wavelet.

The DWT captures a signal at various time scales (levels of aggregation). Due to the scale invariance of the basis functions, it is suitable for analyzing properties that are present across a range of time scales, such as LRD. The DWT may be implemented by a filter-bank-based pyramidal algorithm. Its low computational cost makes the DWT a popular tool for signal analysis.

2.5.2 Wavelet-based Hurst Parameter Estimator

The wavelet-based Hurst parameter estimator is based on the shape of the PSD function (equation 4) of the LRD signal $X(n)$. It has been shown [18] that when the PSD has a power-law behavior, the relationship between the variance of the wavelet coefficients on a given octave and the octave j is

$$E\{d(j,k)^2\} = 2^{j\alpha} c_f C \quad (\text{Equation 8})$$

where $d(j,k)$ is the wavelet coefficient at octave j and time k , the average is calculated for various k and C is a constant that depends on the choice of the mother wavelet. When a suitable mother wavelet is chosen [18], calculation of equation 8 becomes a simple time average or sample mean for all k 's:

$$E\{d(j,k)^2\} = \frac{1}{n_j} \sum_{k=1}^{n_j} d(j,k)^2 \quad (\text{Equation 9})$$

where n_j is the number of wavelet coefficients available at octave j . Linear relationship with a slope α ($0 < \alpha < 1$) between $\log_2 E\{d(j,k)^2\}$ and j for a range of

octaves, including the coarsest, indicates presence of LRD. Therefore, α is obtained by performing linear regression of $\log_2 E \{d(j, k)^2\}$ over j in a range of octaves. H value is calculated by using equation 5. This estimator is called monofractal wavelet estimator. In the same reference [18] it is stated that an extension to the basic monofractal wavelet estimator is the multifractal estimator. In addition to the second moments (variances) of the wavelet coefficients, it also takes into account moments of higher order:

$$S_q(j) = \frac{1}{n_j} \sum_{k=1}^{n_j} d(j,k)^q \quad (\text{Equation 10})$$

It estimates the slope α_q by performing linear regression of $\log_2 S_q(j)$ for a range of j 's. H value is calculated using an expression analogous to equation 5, by taking into account the order of the moment:

$$H = 0.5 + \alpha_q/q \quad (\text{Equation 11})$$

Both monofractal and multifractal estimators are used to produce diagrams of $\log_2 E \{d(j, k)^2\}$ or $\log_2 S_q(j)$ versus j , with the corresponding confidence intervals. They are called logscale diagrams. The estimator used is a multifractal estimator which takes into account moments of higher order given as equation 10. Publicly available MATLAB code [28] is employed to compute the estimates of H from the slope of the linearship between $y_j = \log_2 E\{d(j,k)^q\}$ and j .

A graph obtained from the MATLAB code showing this linear relationship and the estimation of H value from this is shown in Figure 2. The Hurst parameter is represented together with its confidence interval.

Logscale Diagram, N=3 [(j₁, j₂)= (8,13), α-est = 0.861, Q= 0.865], D-init

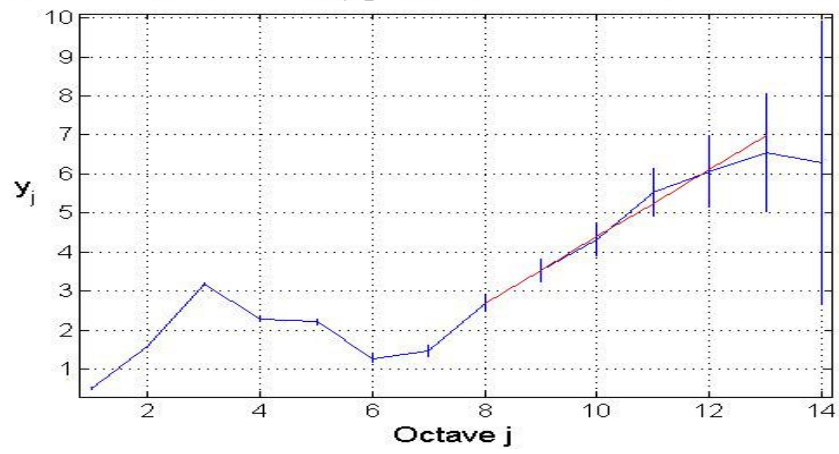


Figure 2 - Logscale Diagram of $y_j = \log_2 E \{d(j,k)q\}$ and j

CHAPTER 3

ON/OFF SOURCES

3.1 Video Traffic

VBR traffic is commonly used in many applications such as IPTv, VoD. Video trace files and synthetic traces are usually used to simulate VBR video traffic in network simulations. The trace file of MPEG-1 coded “Starwars” movie which is available online in ns-2 format [1] coded by Mark Garrett [5] and commonly used in self-similarity studies has been used in most of the simulations here.

In Starwars ns-2 format, each record in the original trace contains the number of bits in a frame and the frame rate for the encoding is 24 frames per second. Each frame is divided into 200 byte packets. These packets are transmitted evenly spaced over approximately 20 milliseconds. The source then remains idle for the remainder of the $1/24$ second frame time.

3.2 ON/OFF Sources

Recent evidence suggests that some characteristics of computer and telecommunications systems may be well described using heavy tailed distributions whose tail declines like a power law, which means that the probability of extremely

large observations is non-negligible. Such distributions for example have been found to describe the lengths of bursts in network traffic and the sizes of files in some systems.

As a result, system designers are increasingly interested in employing heavy-tailed distributions in simulation workloads. Unfortunately, these distributions have properties considerably different from the kinds of distributions more commonly used in simulations; these properties make simulation stability hard to achieve [29].

Heavy tailed distributions behave quite differently from the distributions more commonly used to describe characteristics of computing systems, such as the Normal distribution and the exponential distribution, which have tails that decline exponentially (or faster). In contrast, because their tails decline relatively slowly, the probability of very large observations occurring when sampling random variables that follow heavy tailed distributions is non-negligible.

By taking the ON/OFF times from a heavy-tailed distribution with an infinite variance (such as the Pareto distribution), it is shown in [7] (and proven in [24]) that it is theoretically possible to generate self-similar traffic by aggregating multiple sources. VBR traffic can be created using the ON/OFF sources which takes their ON and OFF times from exponential and Pareto distributions.

To understand the concept of this aggregated traffic stream, it is useful to follow the description as laid out in [24].

3.2.1 Pareto ON/OFF Sources

In [24] it is stated that a number of recent empirical studies of traffic measurements from a variety of working packet networks have convincingly demonstrated that actual network traffic is self-similar or long-range dependent in nature (i.e., bursty over a wide range of time scales).

In the same reference it is shown that superposition of many strictly alternating independent and identically distributed ON/OFF sources (also known as packet trains), each of which exhibits a phenomenon called the Noah Effect, results in self-similar aggregate traffic.

Intuitively, the Noah Effect for an individual ON/OFF source model results in ON and OFF periods (i.e., train lengths and inter train distances) that can be very large with non-negligible probability. The Noah Effect guarantees that each ON/OFF source individually exhibits characteristics that cover a wide range of time scales. There is in depth statistical analysis of large amounts of wide-area and Ethernet LAN traffic measurements in [24].

The result of the study indicates that the self-similar behavior has been observed in the Ethernet LAN traffic data and WAN traces. The Noah Effect is synonymous with the infinite variance syndrome the empirical observation that many naturally occurring phenomena can be well described using distributions with infinite variance.

Mathematically, the heavy-tailed distributions with infinite variance (i.e., Pareto or truncated stable distribution) are used to account for the Noah Effect. The parameter α , describing the "heaviness" of the tail of such a distribution gives a measure of the intensity of the Noah Effect.

Heavy-tailed distributions have been observed in many natural phenomena including both physical and sociological events. In [11] the use of heavy-tailed distributions to model real-world fractal phenomena, e.g. stock markets, earthquakes and the weather is established.

Pareto distribution (also referred to as power law distribution, double-exponential distribution and the hyperbolic distribution) as being the simplest heavy-tailed distribution, is used in this thesis to generate self-similar traffic.

In [12] a distribution is heavy-tailed if it asymptotically follows a power law. That is,

$$P[X > x] \sim x^{-\alpha} \text{ as } x \rightarrow \infty \quad (\text{Equation 12})$$

where $0 < \alpha < 2$.

Pareto distribution is one of the simplest heavy-tailed distributions and probability density function of Pareto distribution is given by

$$p(x) = \alpha k^\alpha x^{-(\alpha+1)}, \quad x \geq k \quad (\text{Equation 13})$$

where α is a shape parameter and the location parameter $k > 0$.

The distribution function has the form:

$$F(x) = P[X \leq x] = 1 - (k/x)^\alpha \quad (\text{Equation 14})$$

If $\alpha \leq 2$, the distribution has infinite variance, and if $\alpha \leq 1$, the distribution has also infinite mean. Thus, as α decreases, a large portion of the probability mass resides in the tail of the distribution. In the same reference it is indicated the relation between shape parameter and H is given by

$$H = (3 - \alpha) / 2 \quad (\text{Equation 15})$$

The relation (equation 15) shows the values of H that would be predicted by the shape parameter of Pareto ON/OFF source.

3.2.1.1 Pareto ON/OFF Traffic Generator

In [30] it is described how Pareto ON/OFF traffic is generated by using ns-2 simulator. The Pareto ON/OFF Traffic Generator (POO_Traffic) is a traffic generator (an application) embedded in the OTcl class Application/Traffic/Pareto. POO_Traffic generates traffic according to a Pareto ON/OFF distribution.

Packets are sent at a fixed rate during on periods, and no packets are sent during off periods. Both on and off periods are taken from a Pareto distribution with constant

size packets. These sources can be used to generate aggregate traffic that exhibits long range dependence.

A new Pareto ON/OFF traffic generator can be created using ns-2 script as follows:

```
set p [new Application/Traffic/Pareto]
$p set burst_time_ 500ms
$p set idle_time_ 500ms
$p set rate_ 200k
$p set packetSize_ 210
$p set shape_ 1.5
```

I. Input parameters:

burst_time_: Mean On (burst) time
idle_time_ : Mean Off (idle) time
rate_ : Send rate during burst
packetSize_: Packet size (fixed application frame size)
shape_ : Pareto shape parameter

II. Initial computation:

interval = packetSize_ * 8 / rate_
burstlen = burst_time_ / interval (in packets of given packetSize_)

III. In each On/Off round, the following two (independent) Pareto random variables are computed:

next_burstlen : # of packets to be transmitted in the next burst period
next_idle_time: next idle period length in seconds

IV. Pareto Traffic Generator algorithm:

1. Compute next_burstlen given the mean burstlen and the Pareto shape_ parameter.

2. Send all next_burstlen packets (each packet transmission interval is interval seconds).
3. Compute the next_idle_time using the mean idle_time_ and the Pareto shape_ parameter.
4. Go to sleep for next_idle_time and go back to step 1.

V. How Pareto distribution is used in the Pareto Traffic Generator:

The Pareto shape_ parameter is denoted as a in the following equations.

$$\begin{aligned} \text{burstlen} &= E(X) = b1 * a / (a - 1) \\ \text{idle_time_} &= E(Y) = b2 * a / (a - 1) \end{aligned}$$

Therefore:

$$\begin{aligned} b1 &= \text{burstlen} * (a - 1) / a \\ b2 &= \text{idle_time_} * (a - 1) / a \end{aligned}$$

ns-2 has a Pareto random number generator that takes the scale and shape parameter:

```
double pareto(double scale, double shape)
```

When the Pareto traffic generator needs to compute next_burstlen, it does:

```
int next_burstlen = int(pareto(b1, a) + 0.5);
/* next_burstlen should be at least 1 packet */
if(next_burstlen == 0) next_burstlen = 1;
```

When the Pareto traffic generator needs to compute next_idle_time, it does:

```
double next_idle_time = pareto(b2, a);
```

3.2.2 Exponential ON/OFF Sources

The exponential distribution, also known as the waiting-time distribution, describes the amount of time or distance between the occurrences of random events. If X has an exponential distribution with parameter $\lambda > 0$, its probability density function is given by:

$$f(x) = \lambda e^{-\lambda x}, \quad x \geq 0$$

where λ is mean time of process, x is time elapsed and $e=2.718\dots$

If $X \sim \text{exponential}(\lambda)$, then its mean and variance are given by:

$$E(X) = 1/\lambda \text{ and } V(X) = 1/\lambda^2$$

3.2.2.1 Exponential ON/OFF Traffic Generator

In [31] it is described how Exponential ON/OFF traffic is generated by using ns-2 simulator. Exponential ON/OFF object is embedded in the OTcl class Application/Traffic/Exponential. The member variables that parameterize this object are:

packetSize_ the constant size of the packets generated

burst_time_ the average “on” time for the generator

idle_time_ the average “off” time for the generator

rate_ the sending rate during “on” times

Hence a new Exponential ON/OFF traffic generator can be created and parameterized as follows:

```
set e [new Application/Traffic/Exponential]
```

```
$e set packetSize_ 210
```

```
$e set burst_time_ 500ms
```

```
$e set idle_time_ 500ms
```

```
$e set rate_ 100k
```

CHAPTER 4

NETWORK SIMULATIONS

4.1 Purpose and Scope

In this thesis the delay, jitter and packet loss performance of access networks under VBR video traffic was tested. ns-2 simulator was used to perform the simulations and actual as well as synthetically generated ON/OFF sources with ON and OFF times taken from exponential or Pareto distributions were used as inputs to the simulated networks such as those shown in Figures 3 and 4. It was assumed that the applied sources were the only traffic in the network.

The topology shown in Figure 3 is a residential video distribution network where Node 0 is the server; Node 1 is the router or Digital Subscriber Line Access Multiplexer (DSLAM) and the other nodes represent customer premises equipments (CPE). The network shown in Figure 4 on the other hand was assumed to be a cable TV distribution network delivering Internet traffic. The topology can be considered as Local area network (LAN) having 100 Mbps speed. Cable networks can be modeled as LAN [32], [33] because cable networks are based on modified LAN technologies and the Hybrid Fiber Coax (HFC) network, which accounts for the backbone of most modern cable systems. The one major drawback to this strategy is that these networks are all based on media sharing.

Synthetic sources were applied to the network and the results were compared with the case when data obtained from actual video sources. Hurst parameter was used as a metric and it was calculated for different ON/OFF sources using a wavelet based estimator which was downloaded from [28].

The effects of distribution type, ON/OFF times, simulation duration, numbers of nodes used in the simulations on the long range dependence of the synthetically generated signals were investigated and they are presented in section 4.3, 4.4, 4.5, and 4.6.

4.2 ns-2 Simulator

There is a range of simulation platforms used in network research, for a range of purposes; ns-2 simulator, which is an on-going collaborative effort that has provided a shared simulation resource for the networking research community. The commercial simulators OPNET and SSFNET are some other popular network simulators. ns-2 stands for Network Simulator version 2.

It is discrete event simulator where the advance of time depends on the timing of events which are maintained by a scheduler. It has a capability of simulating wired and wireless network and provides substantial support to simulate bunch of protocols like TCP, UDP, FTP, HTTP. ns-2 simulator is based on two languages: an object oriented simulator, written in C++ , and a OTcl (an object oriented extension of Tcl) interpreter, used to execute user's command scripts. It uses TCL as its scripting language and is primarily UNIX based.

ns-2 also incorporates libraries of network topology and traffic generators, the network animator NAM, an emulation interface to allow the ns-2 simulator to interact with real-world traffic, and a wide range of contributed code from the user community.

The simulator has been used by a wide range of researchers to share research and simulation results, and to build on each other's work. The detailed information and setup files to install can be reached from [34].

4.3 Simulation Setup 1

These simulations were made to measure effects of ON/OFF times, simulation duration and the number of nodes on the long range dependence of the artificially generated sources. It is possible to emulate VBR video using exponential or Pareto traffic generation agents of ns-2. In ns-2, an application object may be of two types, a traffic generator or a simulated application.

There are different parameters associated with these and the ON and OFF periods of the sources can be set to different values when defining these agents. To show the variation of the Hurst parameter with the traffic characteristics in the network, one to many networks were simulated which were assumed to be a video server transmitting VBR video to different clients. The simulated network topology is presented in Figure 3.

It was assumed that the duplex link between Node 0 and Node 1 has a bandwidth of 1 Gbps, a delay of 0.1ms and has a DropTail queue. The other links were assigned speeds of either 256 kbps or 512 kbps randomly, a delay of 0.1ms and were assumed to have a DropTail queue.

In ns-2, queues are assigned to the links, hence in this part queue limits (ql) of 50 packets were assigned. Because the packet size is 200 bytes, 50 packets buffer means 10 KB memory. The rate parameter was set to 500 kbps for exponential and Pareto distributions.

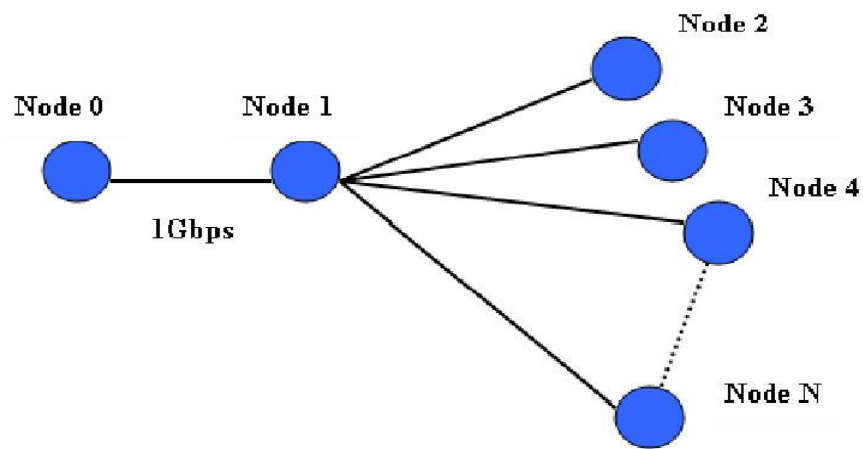


Figure 3 - Distribution network topology used in the simulations

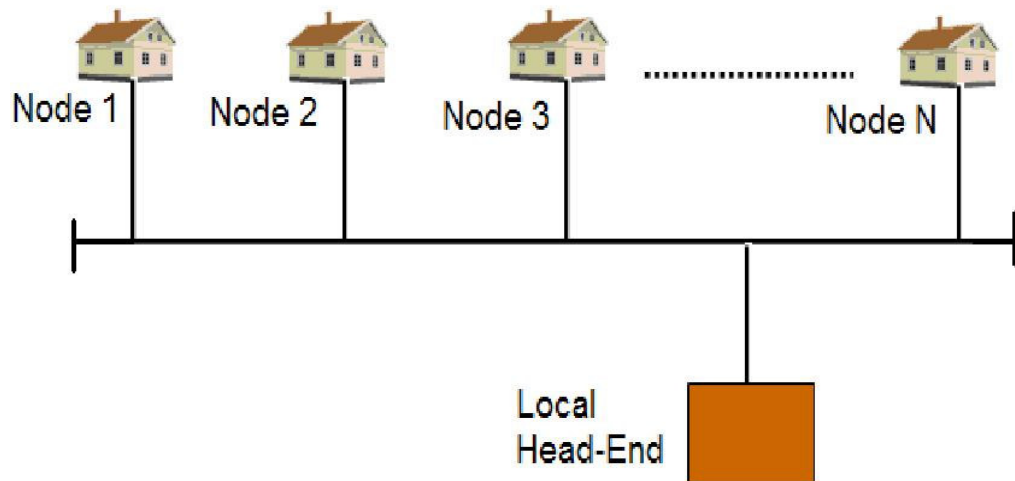
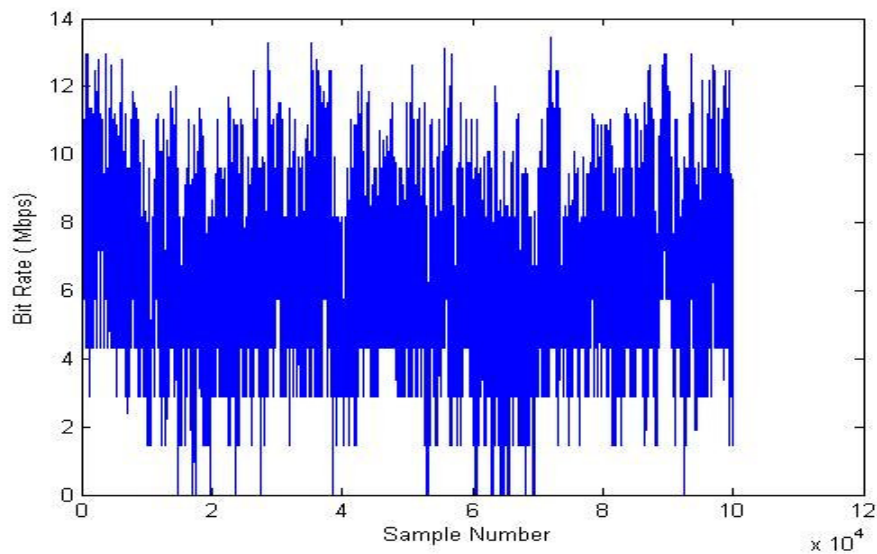


Figure 4 - Cable access network assumed in the simulations

For the network shown in Figure 3 exponential and Pareto traffic was generated from Node 0 to each of the nodes Node 2 to Node N passing through Node 1. The number of nodes was changed from 10 to 40 in steps of 5. The effects of different parameters such as ON/OFF periods, simulation time, packet sizes and bit rates on the estimated value of the Hurst parameter for the traffic from Node 0 to each of the client nodes were then tested. It was assumed that no other traffic was present in the links. Based on the ON/OFF periods, this approach produces a time series like signal which could then be used in the network to simulate VBR video input. The aggregated traffic from Node 0 to each of the nodes Node 2 to Node 40 and passing through Node 1 was analyzed. The outputs of the aggregated traffic generated by the Pareto and exponential distributions when running the simulation for 1000 seconds are shown in Figures 5 and 6 respectively. These were generated by sampling the traffic once every 0.01 seconds at Node 1 hence there were a total of 100 000 samples for each.



**Figure 5 - VBR Simulation using Pareto distribution for aggregated traffic at Node 1
(Simulation Duration=1000 seconds)**

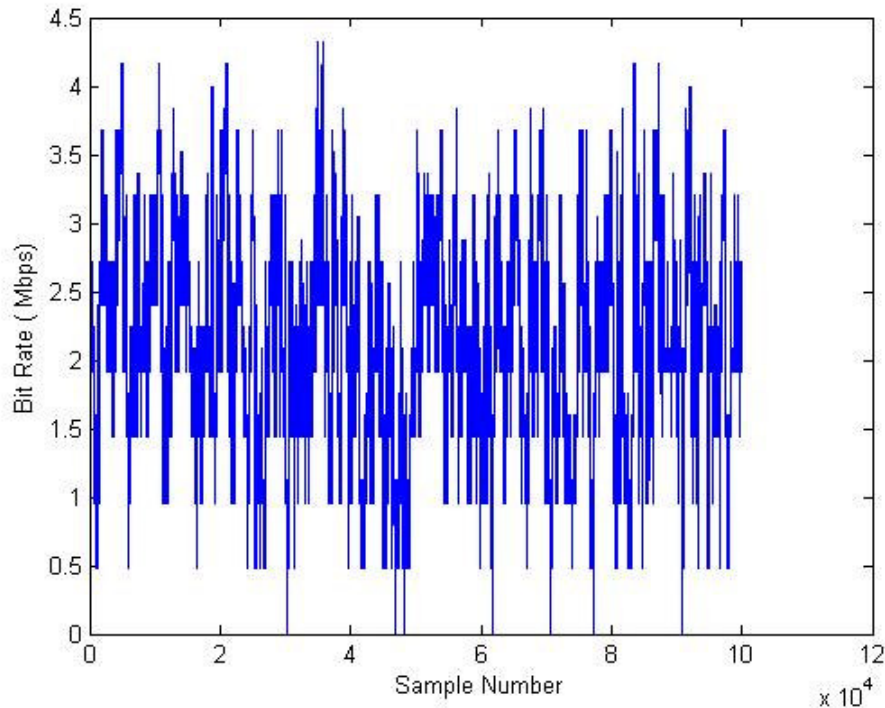


Figure 6 - VBR like signal generated using exponential distribution for aggregated traffic at Node 1 (Simulation Duration =1000 seconds)

The ON/OFF periods of Pareto distribution was used as 1 second whereas this value was taken as 5 seconds for the case of exponential distribution as these figures produced the acceptable Hurst parameters as explained later. These values are visible in the figures where the data produced for the Pareto distribution appears to be much more condensed.

Traffic was created using Pareto distribution from single source to one destination to test the LRD behavior. Two nodes (Node 0 and Node 1) were used in the simulation. Node 0 was connected to Node 1 with 512 kbps link. Node 0 was sending the traffic generated according to Pareto distribution to Node 1. 500 kbps bit rates were used and simulation was performed for 100 seconds simulations. The Hurst parameter was measured as 0.846 with confidence interval [0.739, 0.953]. The output of the traffic received by Node 1 is shown in Figure 7. These were

generated by sampling once every 0.5 seconds at Node 1 for 100 seconds. Hence there were a total of 200 samples for each.

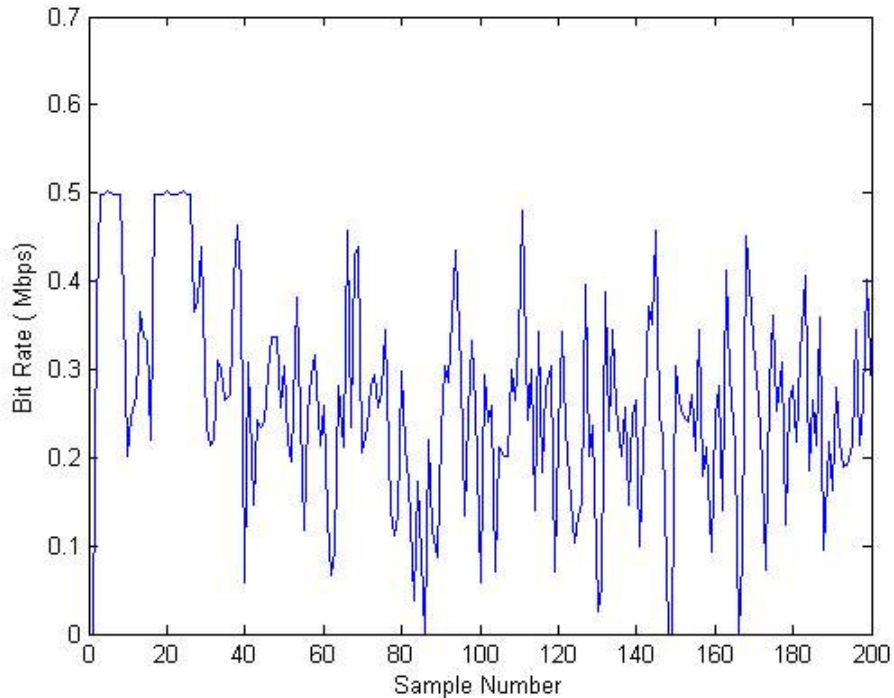
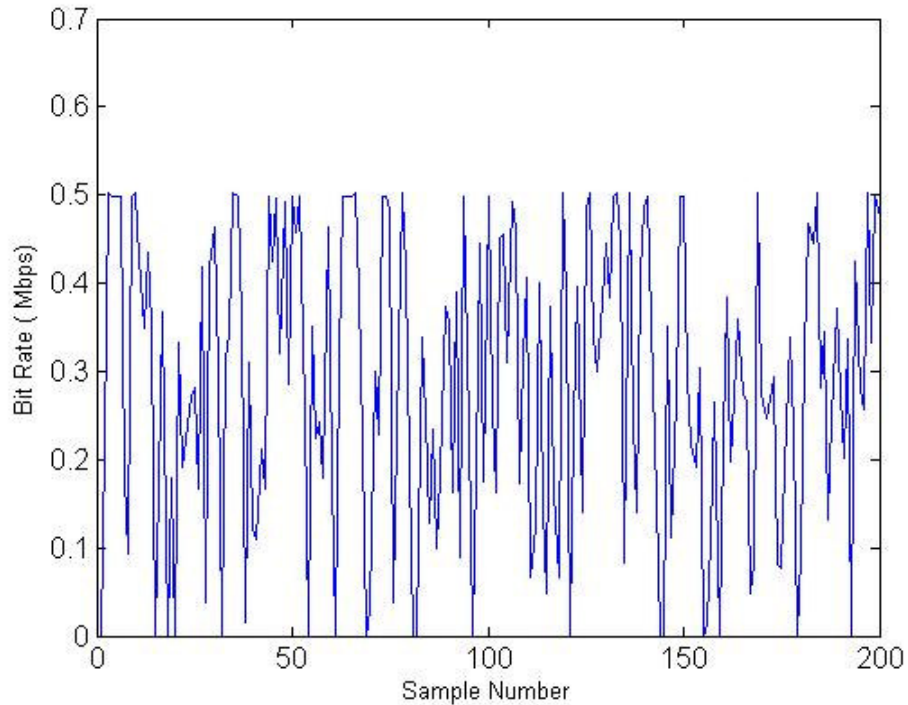


Figure 7- VBR Simulation using Pareto distribution for single traffic at Node 1 (Simulation Duration=100 seconds)

The maximum bit rate was 0.5 Mbps kbps shown in Figure 7 when the bit rate was set to 500 kbps.

The same calculations were repeated for the exponential distribution. Traffic was created using exponential distribution from single source to destination. Two nodes (Node 0 and Node 1) were used in the simulation. Node 0 was connected to Node 1 with 512 kbps link. Node 0 was sending the traffic generated according to exponential distribution to Node 1. 500 kbps bit rates were used and simulation was performed for 100 seconds. The Hurst parameter was measured as 0.867 with confidence interval [0.760, 0.974]. The output of the traffic received by Node 1 is shown in Figure 8. There were a total of 200 samples for each.

Simulations were also performed for different time durations and the Hurst parameters obtained for the different processes under different conditions are presented in the next section.



**Figure 8- VBR Simulation using exponential distribution for single traffic at Node 1
(Simulation Duration=100 seconds)**

4.3.1 Results of simulation setup 1

The data generated during the simulations are stored in a trace file and analyzed later to calculate the Hurst parameters of the random inputs. For the purpose of comparison the Hurst parameter for the Starwars trace was also calculated using the estimator adopted in the study. The Hurst parameter for this data when the simulation was performed for 4 seconds for a network with 10 nodes was estimated to be 0.800 with a confidence interval of [0.638,0.961]. Later the values of Hurst parameter of Starwars trace obtained for longer simulation periods and larger network shall also be presented. The aggregated traffic including packets

which were sent from Node 0 to each of the nodes Node 2 to Node N was also examined. The Hurst parameter was calculated for aggregated traffic at Node 1.

The estimated Hurst parameters are shown in Table 1 and Table 2 for exponential and Pareto distributions respectively. It can be observed from the tables that for exponential distribution, ON/OFF periods of 15 ms give reasonable values for the Hurst parameter. For Pareto distribution, on the other hand, ON/OFF times of 50 ms with the shape factor between 1.2 and 2 produced acceptable results.

**Table 1- H for exponential distribution with different ON/OFF times
(Simulation Duration = 4 seconds and Number of Nodes=10)**

ON time (ms)	OFF time (ms)	H	Confidence Interval
15	15	0.803	0.641-0.965
20	20	0.975	0.813-1.137
25	25	1.018	0.856-1.180
50	50	1.239	1.077-1.400
75	75	1.272	1.122-1.442
100	100	1.274	1.134-1.461
125	125	1.304	1.151-1.498
150	150	1.287	1.142-1.470
200	200	1.327	1.212-1.514
250	250	1.408	1.246-1.569
300	300	1.456	1.289-1.612

**Table 2- H for Pareto distribution with different ON/OFF times and shape factors.
(Simulation Duration=4 seconds and Number of Nodes=10)**

ON time (ms)	OFF time (ms)	Shaping Factor	H	Confidence Interval
15	15	1	1.221	1.06-1.383
15	15	1.2	1.069	0.907-1.231
15	15	1.5	0.839	0.677-1.001
20	20	1	1.221	1.06-1.383
20	20	1.2	1.035	0.873-1.196
20	20	1.5	0.966	0.804-1.128
25	25	1	1.221	1.06-1.383
25	25	1.2	1.081	0.920-1.243
25	25	1.5	0.729	0.567-0.890
50	50	1	1.221	1.060-1.383
50	50	1.2	0.941	0.780-1.103
50	50	1.5	0.683	0.522-0.845
50	50	2	0.750	0.588-0.911
50	50	2.5	0.954	0.742-1.116
100	100	1	1.221	1.06-1.383
100	100	1.2	1.061	0.900-1.223
100	100	1.5	1.328	1.167-1.490
200	200	1	1.221	1.06-1.383
200	200	1.2	1.385	1.223-1.543
200	200	1.5	1.610	1.448-1.771
300	300	1	1.221	1.060-1.383
300	300	1.2	1.473	1.311-1.615
300	300	1.5	1.676	1.500-1.800

The calculations were repeated for different number of nodes in the network. Keeping the ON/OFF periods at 15 ms, the Hurst parameter for traffic generated using input signals produced according to exponential distribution was estimated. The results are shown in Table 3. The same calculations were repeated for Pareto distribution with ON/OFF times fixed at 50 ms. These results are shown in Table 4. These simulations were performed for a period of 4 seconds.

**Table 3- H for exponential distribution for different numbers of nodes
(Simulation Duration = 4 seconds and ON/OFF times=15ms)**

Number of Nodes	H	Confidence Interval
10	0.803	0.641-0.965
15	0.833	0.672-0.995
20	0.778	0.617-0.940
25	0.806	0.644-0.968
30	0.699	0.537-0.861
35	0.627	0.465-0.788
40	0.632	0.470-0.793

**Table 4- H for Pareto distribution for different numbers of nodes
(Simulation Duration =4 seconds, ON/OFF times=50ms, Shaping factor=1.5)**

Number of Nodes	H	Confidence Interval
10	0.683	0.522-0.845
15	0.797	0.635-0.958
20	0.797	0.635-0.959
25	0.687	0.526-0.849
30	0.767	0.606-0.929
35	0.749	0.587-0.911
40	0.806	0.645-0.968

It can be observed from the tables that the number of nodes affects the traffic hence the LRD properties of the signals generated. This is expected because as the number of nodes increases, the transmitted as well as the dropped packets due to the congestion in the network increases hence the aggregated data flowing in the links undergo changes.

The Hurst parameter of the signals obtained as a result of running the simulation for 1000 seconds was also calculated. These results are shown in Table 5 for exponential distribution and Table 6 for Pareto distribution. A network with 10 nodes was used for these calculations because the trace files generated were already very large even for this size network. The shape parameter of the Pareto distribution was taken as 1.5.

**Table 5- H for exponential distribution with different ON/OFF times
(Simulation Duration =1000 seconds and Number of Nodes=10)**

ON time	OFF time	H	Confidence Interval
15 ms	15 ms	0.467	0.361-0.574
20 ms	20 ms	0.506	0.399-0.613
25 ms	25 ms	0.527	0.420-0.634
50 ms	50 ms	0.544	0.360-0.729
300 ms	300 ms	0.544	0.360-0.729
1 s	1 s	0.531	0.425-0.638
5 s	5 s	0.907	0.722-1.091
10 s	10 s	1.063	0.879-1.248
15 s	15 s	1.156	0.912-1.282
20 s	20 s	1.279	1.096-1.464
30 s	30 s	1.321	1.146-1.501
50 s	50 s	1.440	1.333-1.547

**Table 6- H for Pareto distribution with different ON/OFF times
(Simulation Duration =1000 seconds, Shaping Factor=1.5 and Number of Nodes=10)**

ON time	OFF time	H	Confidence Interval
50 ms	50 ms	0.744	0.637-0.851
1s	1s	0.961	0.854-1.068
10 s	10 s	0.823	0.716-0.930
20 s	20 s	0.855	0.670-1.039

The changes in Hurst parameter were also investigated changing the simulation period between 1000 and 10 000 seconds. The results are shown in Table 7 for the case where exponential distribution was employed for the ON/OFF times which were set to 5 seconds. A network with 10 nodes was used in this simulation.

For longer simulation times the H value decreased meaning the self similarity of the generated data is becoming lower. This is in agreement with the expectation that ON/OFF sources generated according to exponential distribution should have short range dependence. Changing the ON/OFF periods to 10 seconds improved the H value considerably especially for simulations which are 4000 seconds and longer shown in Table 8.

**Table 7- H for exponential distribution with different simulation durations
(ON/OFF times=5 seconds and Number of Nodes=10)**

Simulation Duration	H	Confidence Interval
1000	1.013	0.907-1.120
2000	0.965	0.894-1.036
4000	0.565	0.458-0.672
6000	0.740	0.656-0.824
8000	0.574	0.503-0.646
10000	0.596	0.533-0.659

**Table 8- H for exponential distribution with different simulation durations
(ON/OFF times=10 seconds and Number of Nodes=10)**

Simulation Duration	H	Confidence Interval
1000	1.063	0.879-1.248
2000	1.017	0.911-1.124
4000	0.927	0.861-0.994
6000	0.909	0.857-0.962
8000	0.902	0.857-0.946
10000	0.916	0.877-0.956

Table 9 shows the Hurst parameters obtained for simulation ran for different periods of time for ON/OFF sources generated using Pareto distribution. The shape parameter was set to 1.5 and a network with 10 nodes was used. In this case H value showed small variations for all the time periods and was within the acceptable limits. The ON/OFF periods were set to 1 second.

**Table 9- H for Pareto distribution with different simulation durations
(ON/OFF times=1 second and Number of Nodes =10)**

Simulation Duration	H	Confidence Interval
1000	0.961	0.854-1.068
2000	0.955	0.913-0.998
4000	0.868	0.839-0.896
6000	0.869	0.846-0.892
8000	0.876	0.856-0.895
10000	0.876	0.858-0.893

The effect of packet size on H value was also investigated using both exponential and Pareto distributions for the ON/OFF times. The packet size was changed from 50 to 1500 bytes for exponential distribution while keeping the number of nodes at 10 and simulation period 1000 seconds. No significant changes were observed in H

value for the different packet sizes and the results are shown in Table 10. The ON/OFF periods were fixed at 5 seconds. For the case of the Pareto distribution, the simulation was performed for 1000 seconds, the ON/OFF periods were set to 1 second and the shape factor was taken as 1.5. Again a network with 10 nodes was used and the results are shown in Table 11. Significant changes were not observed in H value for the different packet sizes for exponential and Pareto distributions. Figure 9 shows the comparison between Pareto and exponential distribution according to their H values under the changing packet sizes from 50 bytes to 1500 bytes. This is expected because as the sizes of packets change, the aggregated data does not change.

Table 10- H for exponential distribution with different packet sizes
 (Simulation Duration =1000 seconds, ON/OFF times=5 seconds and Number of Nodes=10)

Packet Size (byte)	H	Confidence Interval
50	0.907	0.722-1.091
100	0.907	0.722-1.091
200	0.907	0.722-1.091
400	0.908	0.723-1.092
1000	0.908	0.723-1.092
1500	0.908	0.723-1.092

Table 11- H for Pareto distribution with different packet sizes
 (Simulation Duration =1000 seconds, ON/OFF times=1 second, Shaping Factor =1.5,
 Number of Nodes=10)

Packet Size (byte)	H	Confidence Interval
50	0.918	0.852-0.984
100	0.918	0.852-0.984
200	0.919	0.852-0.985
400	0.917	0.851-0.983
1000	0.920	0.854-0.986
1500	0.920	0.853-0.986

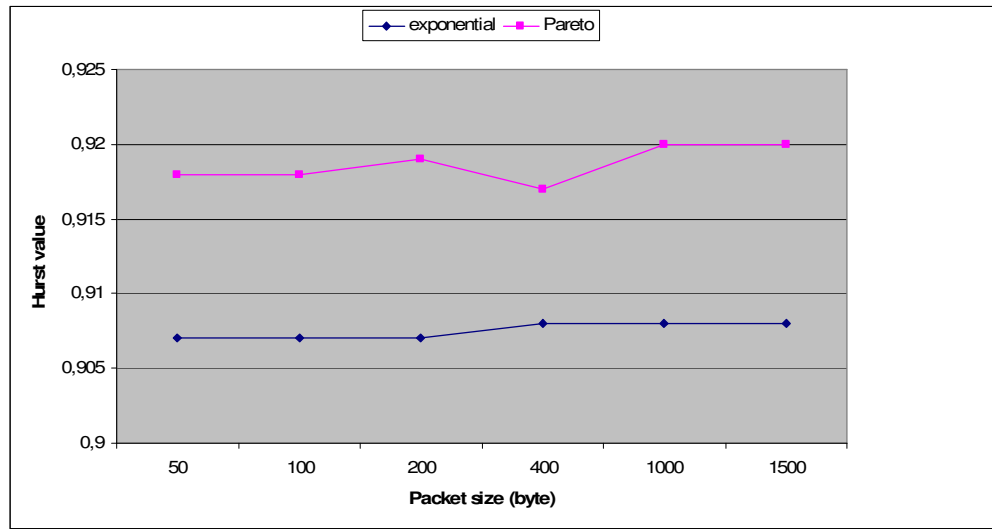


Figure 9- Hurst parameter when synthetic ON/OFF sources are applied to Figure 3 with different packet sizes. The Hurst parameter does not change significantly

The effect of bit rates on H value was also investigated using both exponential and Pareto distributions for the ON/OFF times. The bit rates were changed from 100 kbps to 1000 kbps for exponential distribution while keeping the number of nodes at 10 and simulation period 1000 seconds, no significant changes were observed in H value for the different bit rates and the results are shown in Table 12.

For the case of the Pareto distribution, the simulations were performed for 1000 seconds, and the ON/OFF periods were kept at 1 second and the shape factor was taken as 1.5. Again a network with 10 nodes was used and the results are shown in Table 13. Figure 10 shows the comparison between Pareto and exponential distribution according to their H values under the changing bit rates from 100 kbps to 1000 kbps.

This is also expected because as the bit rates change, the numbers of packets transmitted in 1 second increase but the aggregated data does not change.

Table 12- H for exponential distribution with different bit rates
 (Simulation Duration = 1000 seconds, ON/OFF times=5 seconds and Number of Nodes=10)

Bit Rates(kbps)	H	Confidence Interval
100	0.908	0.723-1.092
250	0.908	0.723-1.092
500	0.907	0.722-1.091
750	0.907	0.722-1.091
1000	0.907	0.722-1.091

Table 13- H for Pareto distribution with different bit rates
 (Simulation Duration =1000 seconds, ON/OFF =1 second, Shaping Factor =1.5 and Number of Nodes =10)

Bit Rates(kbps)	H	Confidence Interval
100	0.957	0.850-1.064
250	0.961	0.854-1.068
500	0.961	0.854-1.068
750	0.961	0.854-1.068
1000	0.961	0.854-1.068

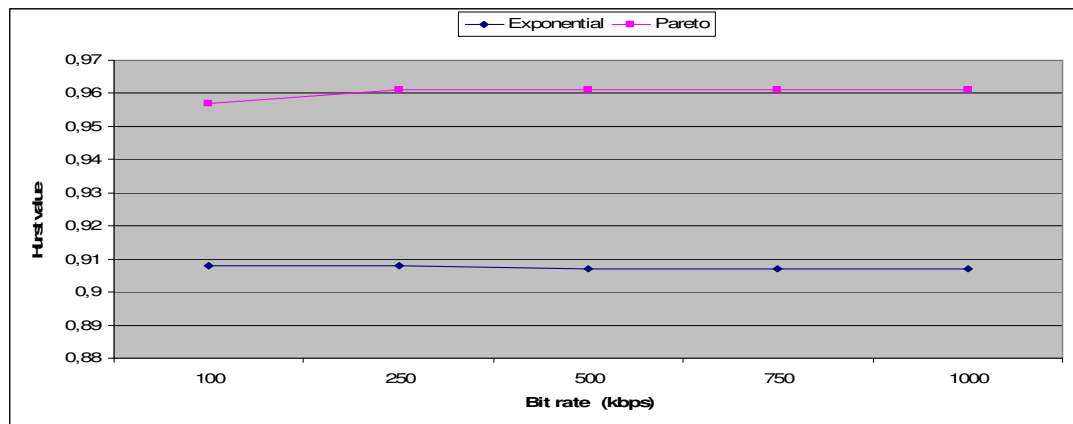


Figure 10- Hurst parameter when synthetic ON/OFF sources are applied to Figure 3 with different bit rates. The Hurst parameter does not change significantly.

Similar calculations were performed for the Starwars movie trace, the results are shown in Table 14. For a network with 10 nodes applying Starwars trace as an input to each of the nodes from Node 0 produced traffic with a Hurst parameter of 0.800 in the 4 seconds simulation as stated before. This figure was 0.925 when the simulation for a 10 node network was performed for 1000 seconds. The results of Starwars trace, Pareto and exponential distributions were compared in terms of Hurst parameter under the different simulation times, and Figure 11 shows the results.

Table 14- H for Starwars trace with different simulation durations (Number of Nodes =10)

Simulation Duration	H	Confidence Interval
1000	0.925	0.860-0.990
2000	0.943	0.901-0.986
4000	1.018	0.989-1.047
6000	0.918	0.896-0.941
8000	1.029	1.009-1.048
10000	1.234	1.194-1.273

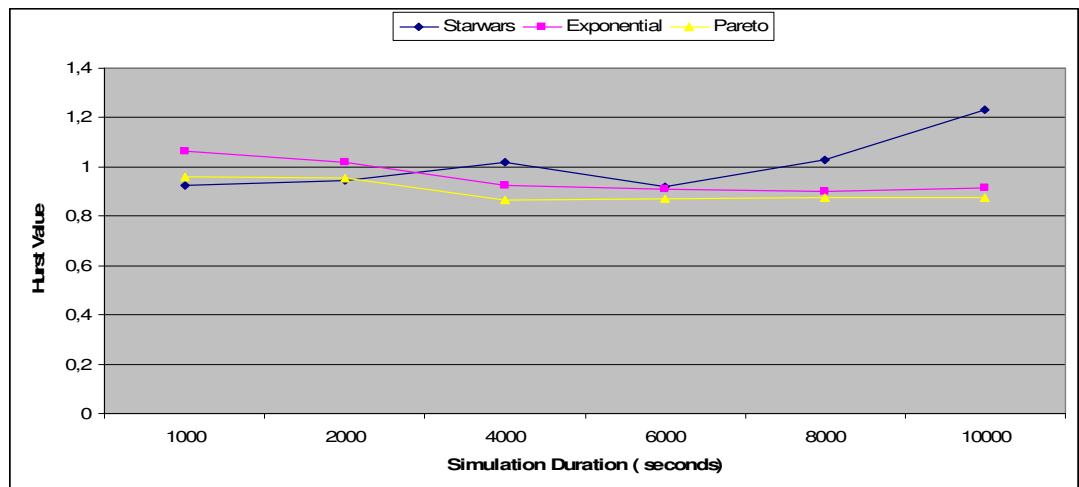


Figure 11- Hurst parameter when synthetic sources and Starwars trace are applied to Figure 3 with different simulation periods. (ON/OFF times=10 seconds for exponential distribution and 1second for Pareto distribution)

4.4 Simulation Setup 2

The simulations were also performed using the topology shown in Figure 3 to investigate the effects of access speed on the Hurst parameter. The same topology assumed in simulation setup 1 was used. The difference between simulation setup 1 and setup 2 is access speeds. It was assumed that the duplex link between Node 0 and Node 1 has a bandwidth of 1 Gbps, a delay of 0.1ms and has a DropTail queue. The other links were assigned speeds of either 1 Mbps or 2 Mbps randomly, a delay of 0.1ms and were assumed to have a DropTail queue. Queue limits of 50 packets were used. The rate parameter was set to 1500 kbps for exponential and Pareto distributions.

4.4.1 Results of simulation setup 2

The Hurst parameter for Starwars data when the simulation was performed for 4 seconds for a network with 10 nodes was estimated to be 0.775 with a confidence interval of [0.614, 0.937]. It was measured to be 0.800 with a confidence interval of [0.638, 0.961] in simulation setup 1.

The simulation for the synthetic traces were run in 4 seconds for a network with 10 nodes and the results of the estimated Hurst parameters are shown in Tables 15 and 16 for exponential and Pareto distributions respectively. It can be observed from the tables that for exponential distribution ON/OFF periods of 15 ms give reasonable values for the Hurst parameter.

For Pareto distribution, on the other hand, ON/OFF times of 50 ms with the shape factor between 1.2 and 2 produced acceptable results. The results are very similar to those observed for simulation setup 1.

**Table 15- H for exponential distribution with different ON/OFF times
(Simulation Duration =4 seconds, Number of Nodes=10)**

ON time (ms)	OFF time (ms)	H	Confidence Interval
10	10	0.671	0.509–0.832
15	15	0.773	0.611–0.935
20	20	0.943	0.782–1.105
25	25	1.019	0.858–1.181
30	30	1.041	0.879–1.203
50	50	1.237	1.075–1.399
300	300	1.446	1.284–1.608

**Table 16- H for Pareto distribution with different ON/OFF times and shape factors.
(Simulation Duration =4 seconds and Number of Nodes =10)**

ON time (ms)	OFF time (ms)	Shaping Factor	H	Confidence Interval
15	15	1	1.254	1.092–1.415
15	15	1.2	1.075	0.913–1.236
15	15	1.5	0.891	0.730–1.053
50	50	1	1.254	1.092–1.415
50	50	1.2	0.910	0.749–1.072
50	50	1.5	0.720	0.559–0.882
50	50	2	0.737	0.575–0.898
50	50	2.5	0.967	0.805–1.128
100	100	1	1.254	1.092–1.415
100	100	1.2	1.060	0.898–1.222
100	100	1.5	1.378	1.216–1.540
300	300	1	1.254	1.092–1.415
300	300	1.2	1.511	1.350–1.673
300	300	1.5	1.597	1.435–1.759

Similar calculations were repeated for different number of nodes in the network while keeping the ON/OFF periods at 15 ms. The Hurst parameter was estimated for traffic generated using input signals produced according to exponential distribution. The results are tabulated in Table 17. The same calculations were repeated for Pareto ON/OFF times with these periods fixed at 50 ms. These results are shown in Table 18. These simulations were performed for a period of 4 seconds. The results are very similar to those observed for simulation setup 1.

**Table 17- H for exponential distribution for different numbers of nodes
(Number of Nodes =4seconds and ON/OFF=15ms)**

Number of Nodes	H	Confidence Interval
10	0.773	0.611-0.935
15	0.812	0.650-0.974
20	0.879	0.717-1.041
25	0.755	0.593-0.917
30	0.806	0.644-0.968
35	0.625	0.463-0.787
40	0.703	0.541-0.865

**Table 18- H for Pareto distribution for different numbers of nodes
(Simulation Duration =4 seconds, ON/OFF =50ms, Shaping Factor=1.5)**

Number of Nodes	H	Confidence Interval
10	0.720	0.559-0.882
15	0.796	0.634-0.958
20	0.780	0.618-0.942
25	0.724	0.562-0.886
30	0.779	0.618-0.941
35	0.758	0.596-0.920
40	0.818	0.656-0.980

The Hurst parameter of the signals obtained as a result of running the simulation for 1000 seconds was also calculated. These results are shown in Table 19 for exponential distribution and Table 20 for Pareto distribution. A network with 10 nodes was used for these calculations because the trace files generated were already very large even for this size network. The shape parameter of the Pareto distribution was taken as 1.5. It can be observed from the results of 1000 seconds simulation that for exponential distribution ON/OFF periods of 5 seconds give reasonably values for the Hurst parameter. For Pareto distribution, on the other hand, ON/OFF times of 1 second with the shape factor 1.5 produced acceptable results.

Table 19- H for exponential distribution with different ON/OFF times.
(Simulation Duration =1000 seconds and Number of Nodes =10)

ON time	OFF time	H	Confidence Interval
15 ms	15 ms	0.516	0.409-0.623
20 ms	20 ms	0.553	0.446-0.660
25 ms	25 ms	0.509	0.402-0.616
50 ms	50 ms	0.505	0.398-0.612
300 ms	300 ms	0.480	0.373-0.586
1 s	1 s	0.532	0.425-0.638
5 s	5 s	0.907	0.722-1.091
10 s	10 s	1.063	0.879-1.248
20 s	20 s	1.279	1.095-1.464

Table 20- H for Pareto distribution with different ON/OFF times
(Simulation Duration =1000 seconds, Shaping Factor =1.5 and Number of Nodes =10)

ON time	OFF time	H	Confidence Interval
50 ms	50 ms	0.739	0.632-0.846
1s	1s	0.961	0.854-1.068
10 s	10 s	0.824	0.717-0.930
20 s	20 s	0.797	0.613-0.982

The effect of bit rates on H value was also investigated using both exponential and Pareto distributions for the ON/OFF times. Changing the bit rates from 100 kbps to 1500 kbps for exponential distribution while keeping the number of nodes at 10 and simulation period 1000 seconds, no significant changes were observed in H value for the different bit rates, the results are shown in Table 21. The ON/OFF periods were fixed at 5 seconds.

For the case of the Pareto distribution, the simulations were performed for 1000 seconds, the ON/OFF periods were 1 second and the shape factor was taken as 1.5. Again a network with 10 nodes was used and the results are shown in Table 22. No significant changes were observed in H value for the different bit rates for exponential and Pareto distributions.

Table 21- H for exponential distribution with different bit rates
 (Simulation Duration =1000s, ON/OFF times=5 seconds and Number of Nodes =10)

Bit Rates(kbps)	H	Confidence Interval
100	0.908	0.723-1.092
500	0.907	0.722-1.091
1000	0.907	0.722-1.091
1500	0.907	0.722-1.091

Table 22- H for Pareto distribution with different bit rates
 (Simulation Duration =1000 seconds, ON/OFF =1 second, Shaping Factor =1.5
 and Number of Nodes =10)

Bit Rates(kbps)	H	Confidence Interval
100	0.957	0.850-1.064
500	0.961	0.854-1.068
1000	0.961	0.854-1.068
1500	0.961	0.854-1.068

According to the results of simulation setup 2, the changes on the links are not effect the Hurst parameter significantly. So, the result of simulation setup 1 and 2 are very similar to each other.

4.5 Simulation Setup 3

In this case again the same topology shown in Figure 3 was assumed as in simulation setups 1 and 2. A network with 100 nodes was simulated in this part while 40 nodes were used in simulation setups 1 and 2. The access speeds were changed between 512 kbps, 1 Mbps and 2 Mbps according to topology shown in Figure 3. The simulations were run for 100 seconds because the trace files generated were already very large even for this size network. 512 kbps, 1 Mbps and 2 Mbps access speeds were assigned randomly and %10 of the nodes were running at 512 kbps speeds, %45 at 1 Mbps speeds and %45 at 2 Mbps.

4.5.1 Results of simulation setup 3

To calculate the Hurst parameter, the simulations were run for the Starwars trace for 100 seconds for a network with 100 nodes. Queue limits of 50, 100 and 150 packets were used. The results are shown in Table 23.

Table 23- H for Starwars trace for different queue sizes.
(Simulation Duration =100 seconds and Number of Nodes =100)

Queue Size (packets)	H	Confidence Interval
50	0.743	0.636-0.850
100	0.743	0.636-0.850
150	0.743	0.636-0.851

To calculate the Hurst parameter, the simulation was run for exponential distribution with ON/OFF periods at 300 ms for a network with 100 nodes for 100 seconds simulation period. Queue limits of 50,100 and 150 packets were used and the packet rates were assigned between 500 kbps and 2000 kbps. The results are shown in Table 24. The same calculations were repeated for Pareto distribution with ON/OFF periods kept at 50ms and the results are shown in Table 25. The shape parameter of the Pareto distribution was taken as 1.5. It was observed that the queue limit on the links does not effect the Hurst parameter seriously according to the results shown in Tables 23, 24 and 25.

4.6 Simulation Setup 4

In this setup the topology shown in Figure 4 was used. Nodes 1 to N represent CPE (Customer-premises equipment). In this case the local head-end offered speeds of 1 Gbps and the LAN had an aggregate speed of 100 Mbps. 100 nodes were assumed in the network. The buffer was located at the head-end and it was assumed to be 50 packets (10 KB memory) long. The simulation duration was 100 second in the simulations. It was assumed that no other traffic was present in the links.

4.6.1 Results of simulation setup 4

The Hurst parameter was calculated for the Starwars trace using the estimator. The result was 0.743 with [0.636-0.850] confidence interval this result was similar to the value obtained in simulation setup 3 for the movie. The Hurst parameter was calculated for exponential distribution with ON/OFF periods kept at 300 ms during 100 seconds simulation period. 100 nodes were used in the network and the bit rates were changed between 500 kbps and 2000 kbps.

The same calculations were repeated for Pareto distribution with ON/OFF periods taken as 50 ms. The shape parameter of the Pareto distribution was taken as 1.5. The results are shown in Table 26. The results were very similar to those obtained in simulation setup 3.

**Table 24- H for exponential distribution for different queue size and different bit rates.
(ON/OFF times=300 ms, Simulation Duration =100 seconds and Number of Nodes =100)**

Queue Size (packets)	Bit Rate (kbps)	H	Confidence Interval
50	2000	0.718	0.611-0.825
	1750	0.719	0.612-0.826
	1500	0.718	0.611-0.825
	1250	0.719	0.611-0.826
	1000	0.718	0.611-0.825
	750	0.717	0.610-0.824
	500	0.718	0.611-0.825
100	2000	0.718	0.611-0.825
	1750	0.718	0.611-0.825
	1500	0.718	0.611-0.825
	1250	0.717	0.610-0.824
	1000	0.717	0.610-0.824
	750	0.717	0.610-0.824
	500	0.718	0.611-0.825
150	2000	0.718	0.611-0.825
	1750	0.718	0.611-0.825
	1500	0.718	0.611-0.825
	1250	0.718	0.611-0.825
	1000	0.718	0.611-0.825
	750	0.718	0.611-0.825
	500	0.718	0.611-0.827

**Table 25- H for Pareto distribution for different queue size and different bit rates.
(ON/OFF times = 50 ms, Simulation Duration =100 seconds and Number of Nodes =100)**

Queue size	Bit Rate(kbps)	H	Confidence Interval
50	2000	0.808	0.701-0.915
	1750	0.808	0.701-0.914
	1500	0.807	0.700-0.914
	1250	0.807	0.700-0.915
	1000	0.807	0.700-0.915
	750	0.808	0.702-0.915
	500	0.810	0.703-0.917
100	2000	0.808	0.701-0.915
	1750	0.808	0.701-0.914
	1500	0.809	0.701-0.915
	1250	0.809	0.702-0.915
	1000	0.807	0.700-0.914
	750	0.810	0.703-0.917
	500	0.810	0.703-0.917
150	2000	0.808	0.701-0.915
	1750	0.808	0.701-0.914
	1500	0.808	0.701-0.914
	1250	0.809	0.702-0.915
	1000	0.807	0.700-0.914
	750	0.810	0.702-0.915
	500	0.810	0.702-0.915

**Table 26- H for Pareto and exponential distribution for different bit rates.
(Simulation Duration =100 seconds and Number of Nodes =100)**

Bit Rate(kbps)	Hurst Parameter	
	Pareto	Exponential
500	0.807	0.718
750	0.807	0.718
1000	0.807	0.718
1250	0.807	0.718
1500	0.807	0.718
1750	0.807	0.718
2000	0.807	0.718

4.7 Network Performance

The packet loss and delay were measured for simulation setup 1 for different number of receiving nodes. The link between Node 0 and Node 1 was assigned 1 Gbps bandwidth, and the other links were assigned either 256 kbps or 512 kbps randomly for the topology shown in Figure 3 as mentioned in simulation setup 1. In these simulations synthetic sources which were generated with ON/OFF values set to produce acceptable Hurst parameters were used. Figures 12 and 13 show packet loss and delay in the network under Starwars trace and synthetically generated ON/OFF sources were applied as input. The packet loss and delay were measured for aggregated traffic at Node 1 for each of the links from Node 0 to Node 2 up to Node N.

The ON/OFF times were set to 50 ms for Pareto and 20 ms for exponential distributions. The rates of the sources were set to 700 kbps and 900 kbps for Pareto and exponential distributions respectively. Queue limits of 50 packets were used.

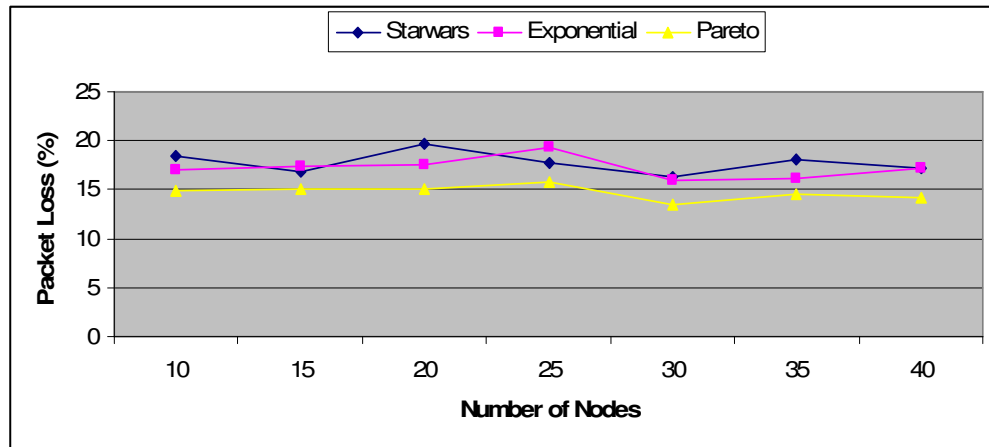


Figure 12- Packet loss when synthetic ON/OFF sources and Starwars trace were applied to the network of Figure 3 with different number of nodes. The synthetic sources were produced using ON /OFF times of 50 ms for Pareto and 20 ms for exponential distributions respectively. Simulations were carried out for 100 seconds using simulation setup 1.

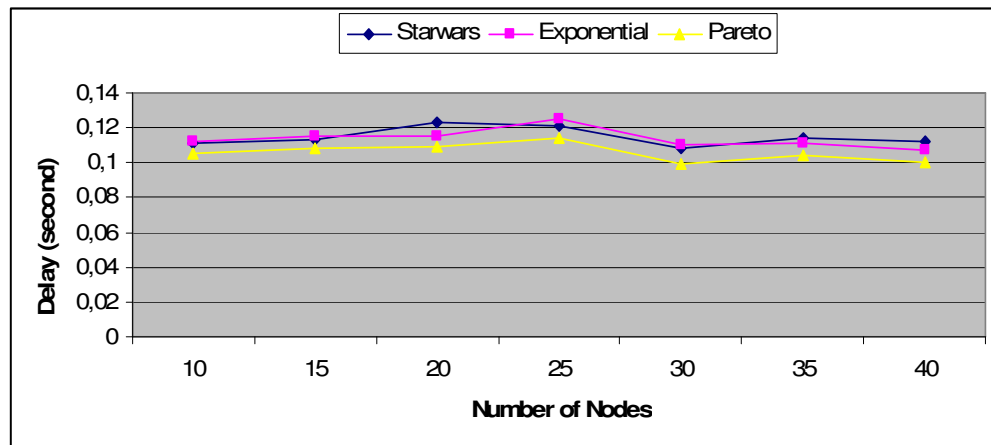


Figure 13- Delay when synthetic ON/OFF sources and Starwars trace were applied to the network of Figure 3 with different number of nodes. The synthetic sources were produced using ON /OFF times of 50 ms for Pareto and 20 ms for exponential distributions respectively. Simulations were carried out for 100 seconds using simulation setup 1.

Figures 12 and 13 show that the loss and delay when a synthetic ON/OFF source was applied as input produces similar results as the Starwars trace for these set of parameters. It was also observed in the previous section (simulation setup 1) that the rate had little effect on the Hurst parameter hence this value was chosen freely for different sources.

The packet loss and delay were measured for simulation setup 2 for different bit rates. The number of nodes was set to 100. The link between Node 0 and 1 was assigned a bandwidth of 1 Gbps and the other links were assigned 1Mbps and 2 Mbps randomly for the topology shown in Figure 3 as mentioned in simulation setup 2. The ON/OFF time was selected as 50 ms for Pareto distribution because the ON/OFF time produced acceptable Hurst parameters (H was 0.823 for Pareto). Figure 14 shows the packet loss as a function of bit rate.

The packet loss was measured to be zero until 1 Mbps rates was reached. Figure 15 show the delay as a function of bit rate.

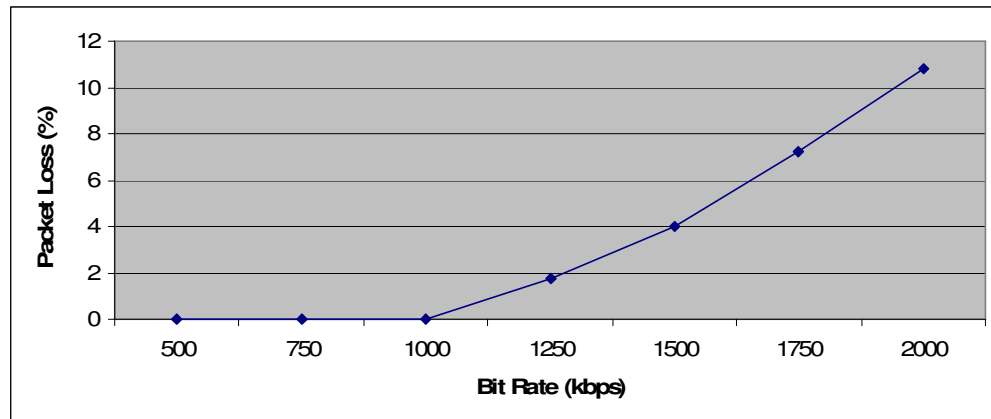


Figure 14- Packet Loss vs. bit rate for ON/OFF sources generated using Pareto distribution. 100 nodes were used and simulations were performed for 100 seconds with ON/OFF times set to 50 ms using simulation setup 2.

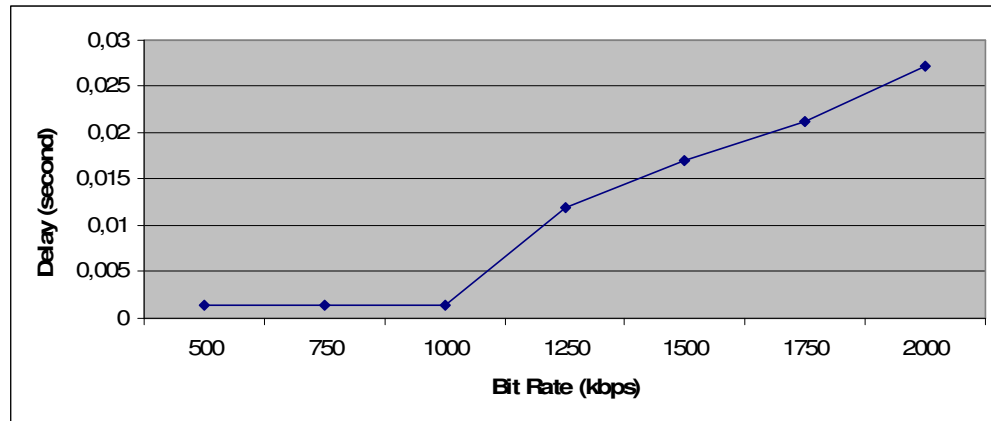


Figure 15- Delay vs. bit rate for ON/OFF sources generated using Pareto distribution. 100 nodes were used and simulations were performed for 100 seconds with ON/OFF times set to 50 ms using simulation setup 2.

The packet loss, delay and jitter were measured for simulation setup 3 for different bit rates applying ON/OFF sources as input and changing their rate to observe the performance of the network under different loads. The link between Node 0 and Node 1 was assigned 1 Gbps bandwidth, and the other links were assigned 512 kbps, 1 Mbps and 2 Mbps randomly for the topology shown in Figure 3 as mentioned in simulation setup 3. The number of nodes was set to 100. The ON/OFF time was selected as 300ms for exponential distribution and 50 ms for Pareto distribution because the ON/OFF times produced acceptable Hurst parameters (H was 0.809 for Pareto and 0.718 for exponential distribution) in the simulation setup 3 section. Figures 16 and 17 show the variation of packet loss with respect to bit rate for the two distributions used.

Packet loss reaches unacceptable levels as the bit rate increases above 1 Mbps. The buffer sizes also affect the packet loss as expected. The difference between Pareto and exponential distributions is also visible in the figures.

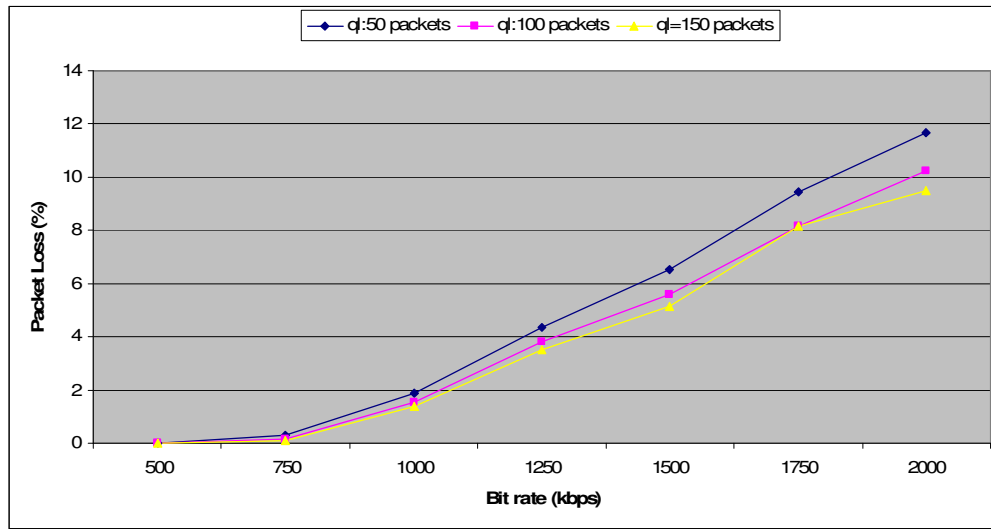


Figure 16- Packet Loss vs. bit rate for ON/OFF sources generated using Pareto distribution. 100 nodes were used and simulations were performed for 100 seconds with ON/OFF times set to 50 ms using simulation setup 3.

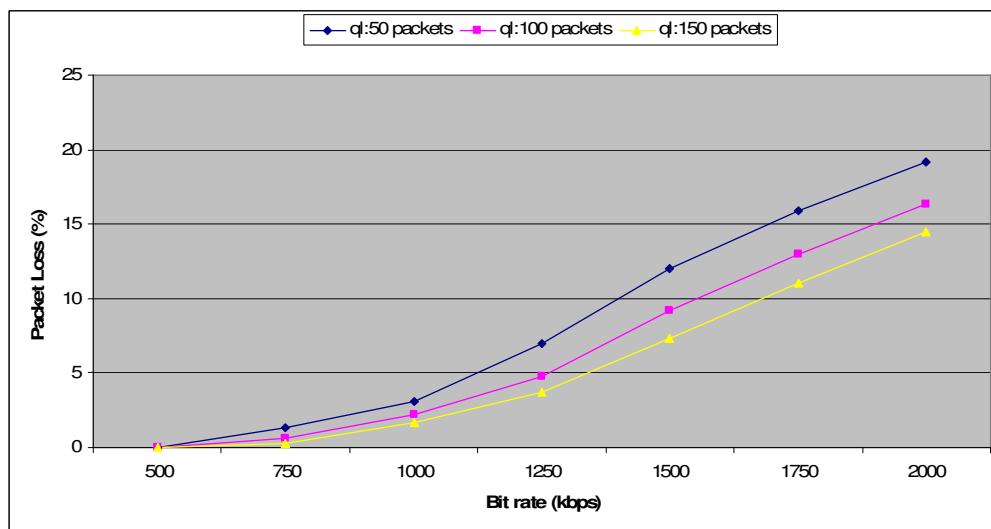


Figure 17- Packet Loss vs. rate for ON/OFF sources generated using exponential distribution. 100 nodes were used and simulations were performed for 100 seconds with ON/OFF times set to 300 ms using simulation setup 3.

Figures 18 and 19 show the delay as a function of bit rate. Maximum delay was in the range of 70 ms for both distributions. As the buffer (queue) size increases delay also increases as expected.

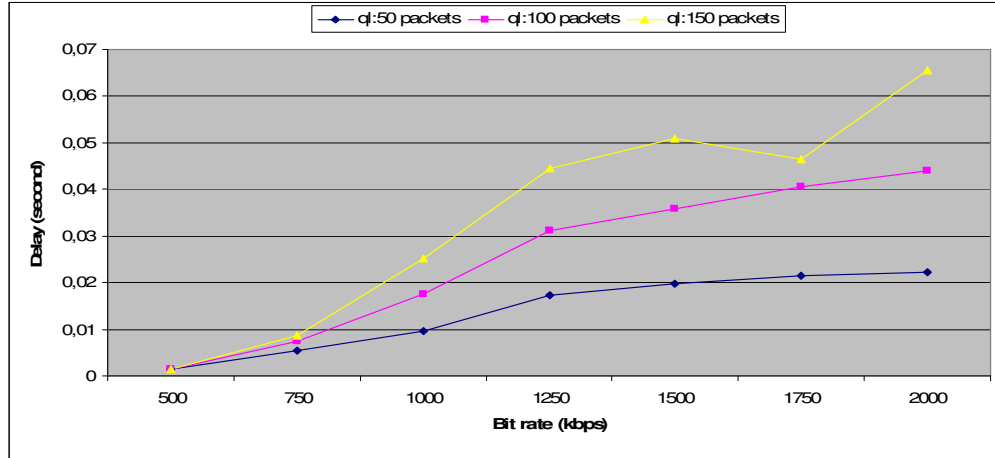


Figure 18- Delay vs. bit rate for ON/OFF sources generated using Pareto dist. 100 nodes were used and simulations were performed for 100 seconds with ON/OFF times set to 50 ms using simulation setup 3.

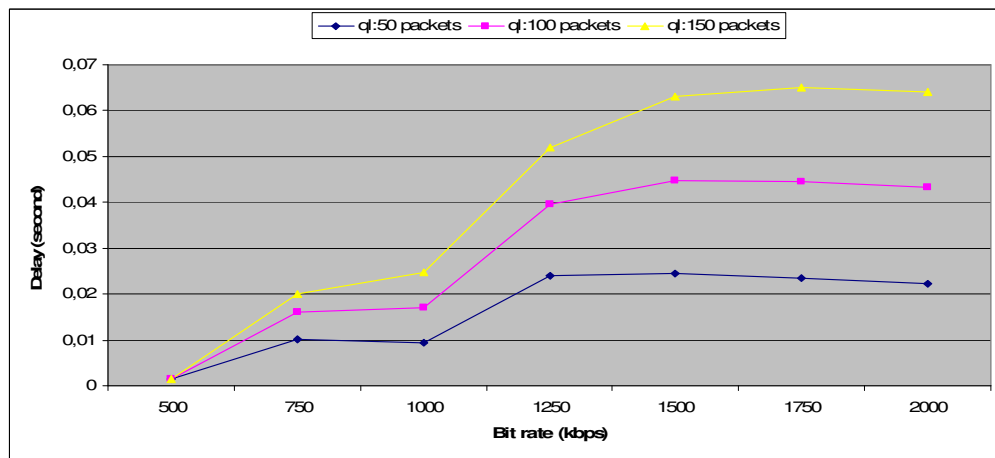


Figure 19- Delay vs. bit rate for ON/OFF sources generated using exponential distribution 100 nodes were used and simulations were performed for 100 seconds with ON/OFF times set to 300 ms using simulation setup 3.

Figures 20 and 21 show the jitter as a function of bit rate. As the buffer (queue) size increases jitter also increases [35].

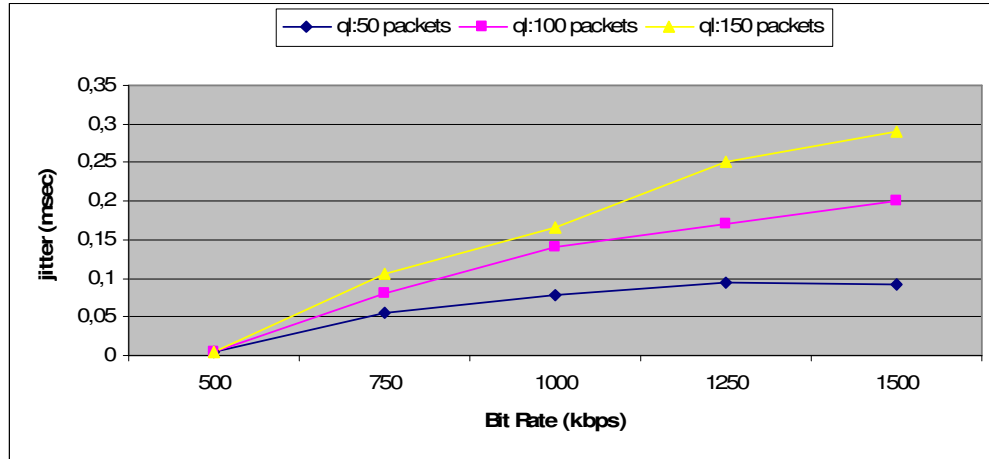


Figure 20 - Jitter vs. bit rate for ON/OFF sources generated using Pareto distribution. 100 nodes were used and simulations were performed for 100 seconds with ON/OFF times set to 50 ms using simulation setup 3.

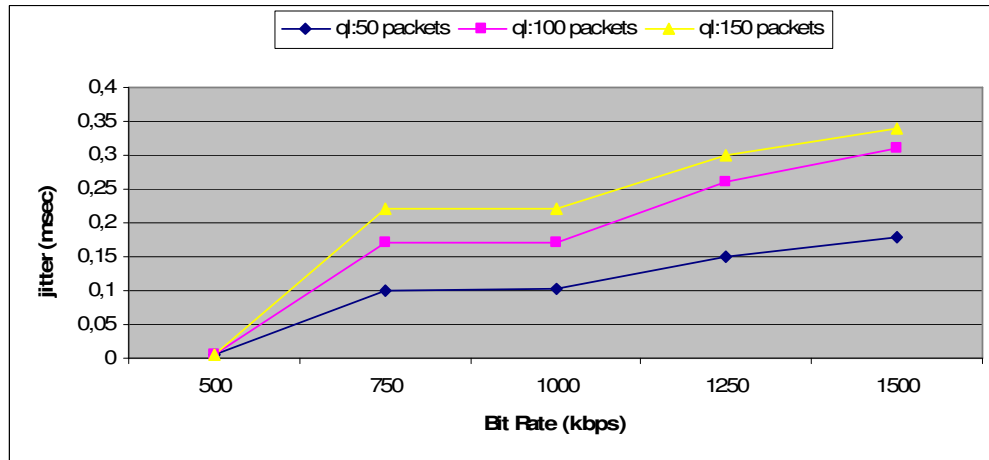


Figure 21 - Jitter vs. bit rate for ON/OFF sources generated using exponential distribution. 100 nodes were used and simulations were performed for 100 seconds with ON/OFF times set to 300 ms using simulation setup 3.

The packet loss, delay and jitter were measured for simulation setup 4 for different bit rates. The local head-end offered speeds of 1 Gbps and the LAN had an aggregate speed of 100 Mbps for the cable type network of Figure 4 as mentioned in simulation setup 4. 100 nodes were assumed in the network. The results are shown in Figures 22, 23 and 24 for packet loss, delay and jitter respectively.

Higher delay values compared to the network topology shown in Figure 3 (simulation setup 3) were measured in the simulations of this network. The packet loss values were again quite high for bit rates above 1.5 Mbps but it was measured to be zero until these rates are reached.

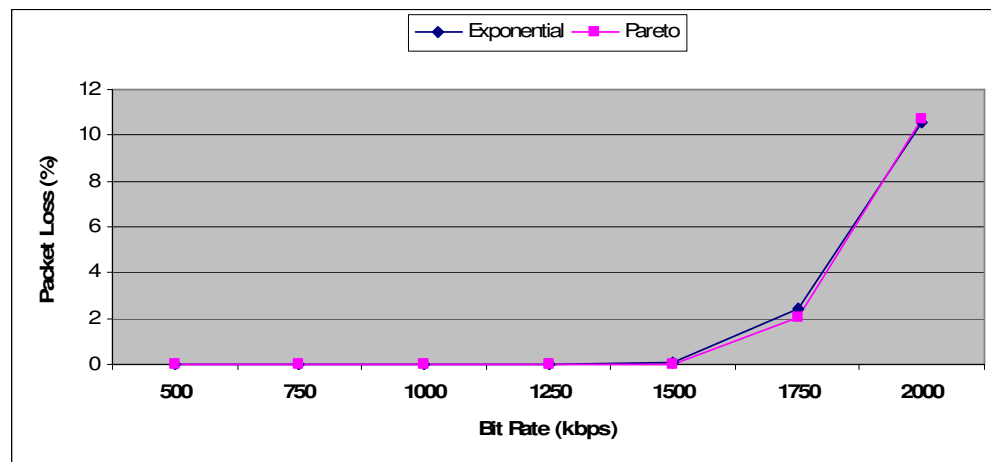


Figure 22- Packet Loss vs. bit rate for ON/OFF sources generated using Pareto and exponential distributions. The network was a cable distribution network. 100 nodes were used and simulations were performed for 100 seconds using simulation setup 4.

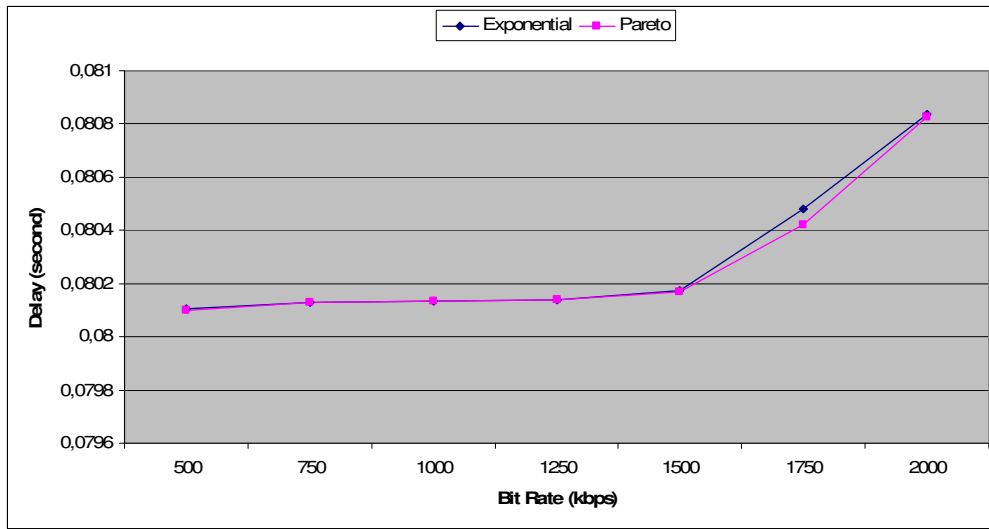


Figure 23- Delay vs. bit rate for ON/OFF sources generated using Pareto and exponential distributions. The network was a cable distribution network. 100 nodes were used and simulations were performed for 100 seconds using simulation setup 4.

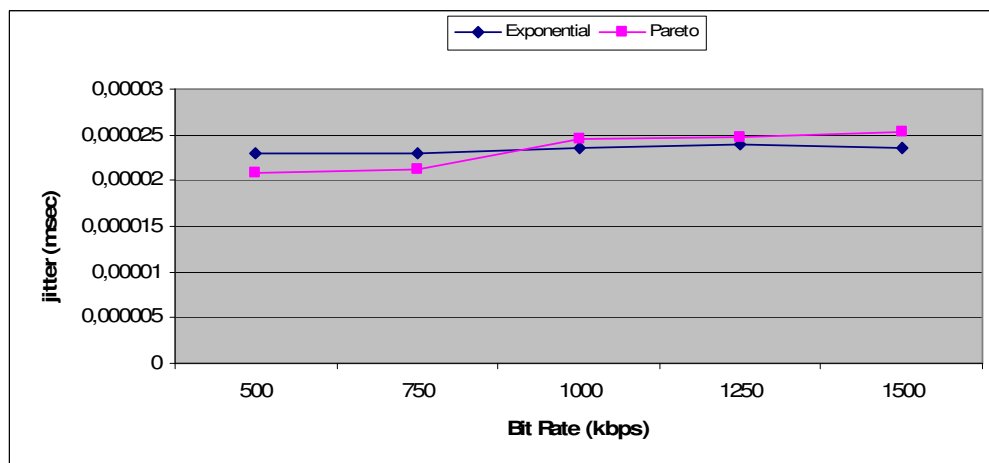


Figure 24 - Jitter vs. bit rate for ON/OFF sources generated using Pareto and exponential distributions. The network was a cable distribution network. 100 nodes were used and simulations were performed for 100 seconds using simulation setup 4.

CHAPTER 5

SIMULATION VERIFICATION

To verify the simulations, the packet loss rate was calculated at the router for the Starwars movie in ns-2 by using the topology shown in Figure 25 and the simulation results were compared with the results of reference [3]. 100 sources were used that generate Starwars video traffic and feeding a common router R connected to traffic destination D. FIFO buffer with DropTail queue management policy was used at the router. Each of source was connected to R with 10 Mbps speed. The buffer size was changed from 128 packets to 1024 packets in steps of 128 packets. Since the packet size was set to 200 bytes, hence 128 packets of buffers size means that 25.6 KB memory.

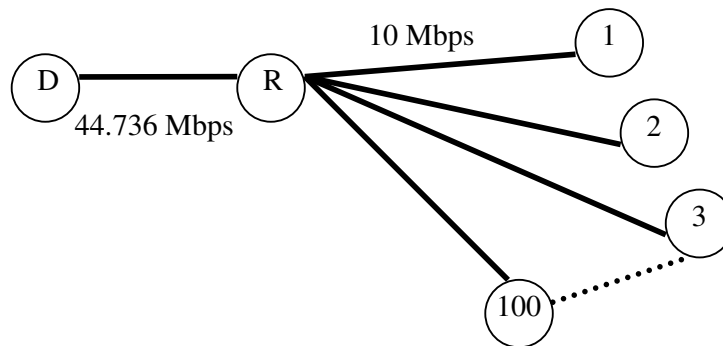


Figure 25 – Simulated topology to verify the simulations.

The comparison of the simulation results with the results of reference [3] for the same simulation scenario in the observation interval [$t_{\text{start}}=60$ seconds, $t_{\text{end}}=1200$ seconds] is shown in Table 27.

Table 27 – The loss rate comparison.

Buffer sizes (KB)	Loss rate (%) of reference [3]	Loss rate (%) of our simulations
25.6	16.4	17.34
51.2	11.9	12.63
76.8	7.73	8.69
102.4	4.12	4.92
128	2.10	3.04
153.6	0.98	1.44
179.2	0.29	0.39
204.8	0.049	0.073

Results of the simulations are closer to the results of reference [3] according to the results shown in Table 27.

The results of scripts measuring packet loss and delay were compared with the results of Trace graph tool to test the accuracy of scripts. The free version of Trace graph was downloaded from [36]. Free version of Trace graph tool can not calculate packet loss or delay if the trace file exceeds 15 MB. This tool is used to analyze packet loss and delay for the ns-2 trace file obtained from the trials. The size of trace file produced by the simulations reaches 800 MB when the simulations performed for 100 seconds or higher, so Trace graph tool was not used since it has scalability problem. Awk scripts were used [Appendix B] in all simulations to calculate delay, packet loss, jitter instead of using Trace graph tool.

To compare the results of Trace graph with the results of the scripts, the topology shown in Figure 3 was used with 15 nodes. The link between Node 0 and Node 1

was assigned a speed of 1 Gbps and the other links were assigned speeds of either 512 kbps or 1 Mbps randomly, a delay of 0.1ms and they were assumed to have a DropTail queues. The simulation was performed for 4 seconds and it produced a 5.14 MB size of trace file. The aggregated Pareto traffic including packets which were sent from Node 0 to each of the nodes Node 2 to Node 13 and passing through Node 1 was analyzed. The packet loss and delay were measured at Node 1. The results of Trace graph tool are shown in Figure 26.

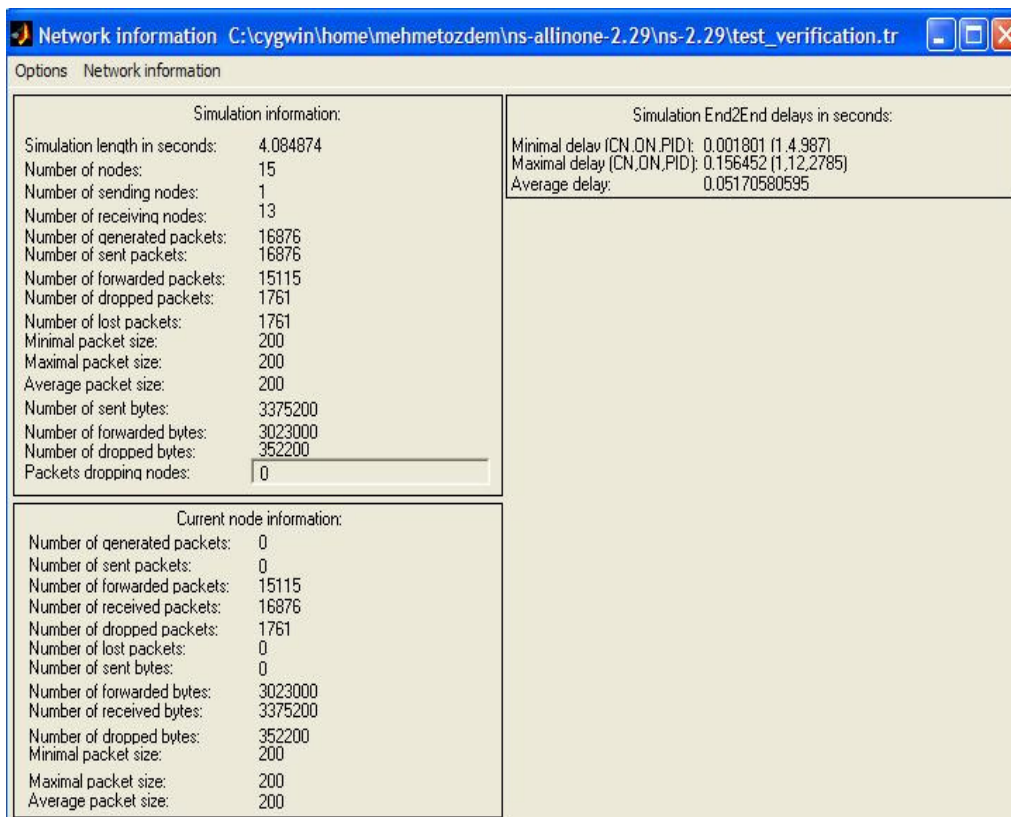
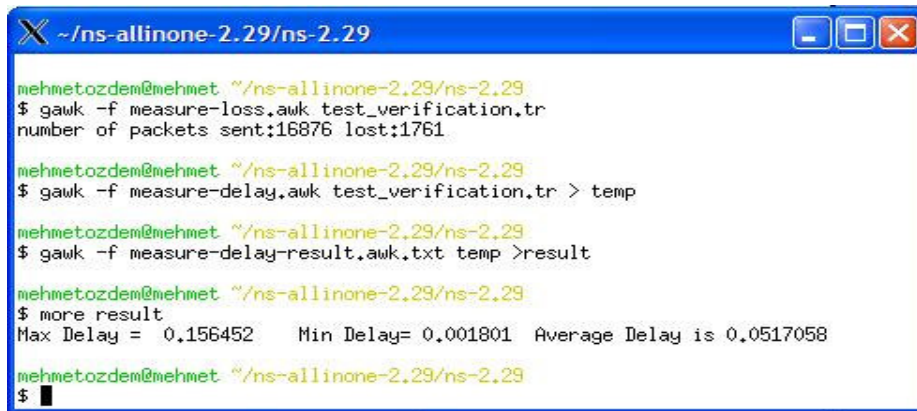


Figure 26- Packet loss and delay measurement using Trace graph tool.

There are three fields including simulation information, current node information and simulation end2end delay shown in Figure 26. Node 1 was selected as current node. The result shows that 16876 packets were generated by Node 0 and 1761 packets were dropped at Node 1. The maximum delay was measured as 0.156452

seconds, minimum delay was measured as 0.001801 seconds and average delay was measured as 0.0517058 seconds.

Figure 27 shows the results of the scripts used to calculate the packet loss and delay. It can be observed that the result of the scripts and the results of Trace graph tool produced the same result for the packet loss and delay.



```
~/ns-allinone-2.29/ns-2.29
mehmetozdem@mehmet ~/ns-allinone-2.29/ns-2.29
$ gawk -f measure-loss.awk test_verification.tr
number of packets sent:15876 lost:1761

mehmetozdem@mehmet ~/ns-allinone-2.29/ns-2.29
$ gawk -f measure-delay.awk test_verification.tr > temp

mehmetozdem@mehmet ~/ns-allinone-2.29/ns-2.29
$ gawk -f measure-delay-result.awk.txt temp >result

mehmetozdem@mehmet ~/ns-allinone-2.29/ns-2.29
$ more result
Max Delay = 0,156452   Min Delay= 0,001801   Average Delay is 0,0517058

mehmetozdem@mehmet ~/ns-allinone-2.29/ns-2.29
$
```

Figure 27- Packet loss and delay measurement using awk scripts.

CHAPTER 6

CONCLUSIONS

Packet loss, average delay and average jitter performance of access networks under VBR video traffic was investigated in this study. Synthetically generated signals as well as actual video traces were used to simulate VBR video in the simulations. ns-2 network simulator and its built in capabilities to generate the traces were used. The Hurst parameter was used as a metric to test the conformance of the artificial signals to actual video sources.

It was observed that Pareto distribution was produced acceptable traces for most ON/OFF values and for simulations performed for long periods of time. The exponential distribution, on the other hand, was performed fine for generating traces to be used in short simulations. Network size also affected the Hurst parameter hence the LRD properties of the time series produced artificially. The H value, however, did not deviate significantly with the changing bit rate or changing packet size.

The performance of distribution networks was measured using simulations with synthetically generated signals as well as actual traces of VBR video applied as inputs. The performance results of distribution networks show that the rate of video signals should be kept under 1 Mbps for access networks if a mixture of 1 Mbps and 2 Mbps speeds are used and the rate of video signals should be kept under 512

kbps for access networks if a mixture of 512 kbps, 1 Mbps and 2 Mbps speeds are used.

For a TV quality video over IP service, the access link speeds should be 1 Mbps or higher. The results conform to the study conducted in [3] as similar loss rates are measured and to [2] since similar speed requirements are deduced. For cable type shared network, rates less than 1.5 Mbps may support 100 channels over a 100 Mbps Ethernet. Our contribution has been the use of artificially generated ON/OFF sources and the flexibility of being able to make additional measurements because of this approach [37].

6.1 Future Work

The simulation results will be compared with the IPTv infrastructure of Turk Telekom.

REFERENCES

- [1] *Starwars trace*. (n.d). Retrieved July 8, 2006, from <http://www.att.com>.
- [2] Hastings, K. & Nechita, N. (2000, November). Challenges and opportunities of delivering IP-based residential television services. *IEEE Communications magazine*, Vol.7, pp. 86-92.
- [3] Markovski, V., Xue, F. & Trajković, L. (2001). Simulation and Analysis of Packet Loss in User Datagram Protocol Transfers. *The Journal of Supercomputing*, Vol.20, no. 2, pp. 175-196.
- [4] Beran, J., Sherman, R., & Willinger, W. (1995, February/March/April). Long Range Dependence in VBR Video Traffic. *IEEE Transactions on Communications*, Vol.43, no. 2/3/4.
- [5] Mark, W., Garrett, M.W. & Willinger, W. (1994). Analysis, modeling and generation of self-similar VBR video traffic. *SIGCOMM .94: Proceedings of the conference on Communications architectures, protocols and applications*, pp. 269-280, London, UK.
- [6] Bohnert, T. & Monterio, E. (2005, October 24-27). A comment on Simulating LRD Traffic with Pareto ON/OFF sources. *CoNEXT. 2005*, pp. 228-229, Toulouse, France.
- [7] Leland, W., Willing, M. & Wilson, D. (1994, February). On the self similar nature of Ethernet traffic. *IEEE/ACM Transaction on Networking*, Vol. 2, pp.1-15.
- [8] Reisslein, M., Lassetter, J., Ratnam, S., Lotfallah, O., & Panchanathan, S. (2002, December). *Traffic and quality characterization of scalable encoded video: a large- scale trace-based study, Part 1: Overview and definitions*

(Tech. Rep. No.2). USA, Arizona State University Telecommunications Research Center.

- [9] Reisslein, M., Lassetter, J., Ratnam, S., Lotfallah, O., Fitzek, P. & Panchanathan, S. (2003, January). *Traffic and quality characterization of scalable encoded video: large-scale trace-based study, Part 2: Statistical analysis of single-layer encoded video* (Tech. Rep. No.5). USA, Arizona State University Telecommunications Research Center.
- [10] Rose, O. (1995, February). *Statistical properties of MPEG video traffic and their impact on traffic modeling in ATM systems* (Tech. Rep. No.101). Germany, University of Wurzburg, Institute of computing Science.
- [11] *LRD*. (n.d). Retrieved July 4, 2006, from <http://www.answers.com/topic/lrd>
- [12] Paxson, V. & Floyd, S. (1995, June). Wide area traffic: the failure of Poisson modeling. *IEEE/ACM Transactions on Networking*, Vol. 3, Issue 3, pp. 226 – 244.
- [13] Sahinoglu, Z. & Tekinay, S. (1999, January). On Multimedia Networks: Self-Similar Traffic and Network Performance. *IEEE Communication Magazine*, Vol. 37, Issue: 1, pp. 48-52.
- [14] Yilmaz, H. & Sankur, B. (2003, July 2-5). Internet over digital video broadcast: performance issues. *Video/Image Processing and Multimedia Communications 4th. EURASIP* , Vol. 2, pp. 823- 828.
- [15] Mandelbrot, B. (1982). *The fractal geometry of nature*, New York, NY: W.H. Freeman.
- [16] Crovella, M. & Bestavros, A. (1996, May). Self Similarity in World Wide Web Traffic: Evidence and Possible Causes. *Proceedings, ACM Sigmetrics conference on Measurement and Modelling of Computer System*.
- [17] Zelimir, L. (2002, April). *Wavelet Based Estimators Of Long-Range Dependence In Traffic Traces*. Unpublished master thesis. Simon Fraser University, Vancouver.

- [18] Bogdanov, M., Cackov, N., Lucic, Z. & Trajkovic, L. (2005, May 23-26). Wavelet-based estimation of long-range dependence in MPEG video traces. *IEEE International Symposium on Circuits and Systems 2005*. Vol. 3, pp. 2068 - 2071.
- [19] Park, K. & Willinger, W. (2000). *Self Similar Network Traffic and Performance Evaluation*. New York, NY: Belkey.
- [20] Si Jun Huang. (2000, July). *Principle, Benefits and Applications of VBR Coding For Digital Video Broadcasting, With Statistical Multiplexing Extension*. Retrieved December 12, 2006, from Scientific-Atlanta, Research Department. Web site: <http://www.sciatl.com>
- [21] Cano, J.C. & Manzoni, P. (2000, September 5-7). On the use and calculation of the Hurst parameter with MPEG videos data traffic. *Proceedings of the 26th Euromicro Conference*, Vol. 1, pp. 448 - 455.
- [22] Karagiannis, T., Molle, M. & Faloutsos, M. (2004, September). Long-Range Dependence. *IEEE Internet Computing Magazine*, Vol. 8, pp. 57 - 64.
- [23] Beran, J. (1994). *Statistics for Long-Memory Processes*. Newyork, NY: Chapman & Hall.
- [24] Willinger, W., Taqqu, M. S., Sherman, R. & Wilson, D. V. (1997). Self-Similarity Through High-Variability: Statistical Analysis of Ethernet LAN Traffic at the Source Level. *IEEE/ACM Transactions on Networking*, Vol. 5, no. 1, pp. 71-86.
- [25] Veitch, D. & Abry, P. (1999, April). A wavelet-based joint estimator of the parameters of long-range dependence. *IEEE Transactions on Information Theory*, Vol. 45, no.3, pp. 878-897.
- [26] Faloutsos, M., Karagiannis, T. & Riedi, R. (2002, November). Long-Range Dependence now you see it now you don't. *IEEE Global Telecommunication Conference*, Vol. 3, pp. 2165-2169.
- [27] Roughan, M. & Veitch, D. (1999, March). Measuring long-range dependence under changing traffic conditions. *IEEE INFOCOM 1999*, Vol. 3, pp. 1513-1521.

- [28] *Code for estimation of scaling exponents*. (n.d). Retrieved July 8, 2006, from <http://www.cubinlab.ee.mu.oz.au/~darryl/>
- [29] Crovella, M. & Lipsky, L. (1997, December 7-10). Long-lasting Transient Conditions In Simulations With Heavy-tailed Workloads. *Simulation Conference Proceedings*, pp. 1005-1012.
- [30] *Pareto ON/OFF traffic generator*. (n.d.). Retrieved July 27, 2006, from http://nile.wpi.edu/NS/Howto/app_pareto_on_off.html.
- [31] *ns-2 manual*. (n.d.). Retrieved July 2, 2006, from <http://www.isi.edu/nsnam>.
- [32] Saleem Bhatti (1997, May). Issues in Residential Broadband Internet Service Provision. *8th. Joint European Networking Conference*, Edinburgh, UK.
- [33] Paul Sabatino. (1999). *Digital Subscriber Lines and Cable Modems*. Retrieved January 26, 2007, from Ohio State University, Computer Science Dept. Web site: <http://www.cs.wust.edu/~jain/cis788-97/rbb/index.htm>
- [34] *Network simulator*. (n.d.). Retrieved July 14, 2006, from <http://www.isi.edu>
- [35] Dhamdhere, A., Jiang, H. & Dovrolis, C. (2005, 13-17 March). Buffer sizing for congested Internet links. *24th Annual Joint Conference of the IEEE Computer and Communications Societies. Vol. 2*, pp.1072-1083.
- [36] *Trace graph tool*. (n.d). Retrieved July 14, 2006, from www.tracegraph.com
- [37] Mehmet Özdem, Y. Murat Erten (2007, March). *Performance of distribution networks under VBR video traffic*. Paper will be presented at IEEE SoutheastCon 2007, Richmond, VA, USA

APPENDICES

APPENDIX A: OTHER HURST PARAMETER ESTIMATION APPROACHES

The wavelet-based method was used in the study to estimate Hurst parameter. There are different approaches for estimating the Hurst parameter as mentioned section 2.5. R/S, variance-time and periodogram estimators were described in this part.

R/S Analysis

Given n observations ($X_k: k=1,2,\dots,n$) with sample mean $\bar{X}(n)$ and sample variance $S^2(n)$, the re-scaled adjusted range (R/S) is given by [21]:

$$\frac{R(n)}{S(n)} = \frac{1}{S(n)} [\max(0, W_1, W_2, \dots, W_n) - \min(0, W_1, W_2, \dots, W_n)]$$

where $W_k = ((X_1 + X_2 + \dots + X_n) - k \bar{X}(n))$, $k > 0$. In [7] it is defined that self-similar processes are well represented by the equation

$$E \left[\frac{R(n)}{S(n)} \right] \approx an^h \quad \text{as } n \rightarrow \infty, \text{ where } 0.5 < H < 1$$

H value is estimated by plotting $\log(E[R(n)/S(n)])$ versus $\log(n)$ and using a least-squares linear approximation technique.

Variance-Time Analysis

The relation between the variance of an aggregated process $X(m)$ and the block size m is given by [21],[23]:

$\text{Var}(X(m)) \sim a_1 m^{-\beta}$, $0 < \beta < 1$ as $m \rightarrow \infty$, or equivalently $r(m)(k) \rightarrow 0$, as $m \rightarrow \infty$ ($k=1,2,\dots$). This relation indicates that aggregated processes with long-range dependence have a non-degenerate correlation structure and that variance decreases linearly (for large m). This analysis consists in plotting $\log(\text{Var}(X(m)))$ against $\log(m)$, and dividing the original series into nonoverlapping blocks of size m for various values of m . To obtain an estimate of β , we use the slope of a simple least squares line for the obtained points. Again, using the well-known relation $H=1-\beta/2$, we can estimate H . To obtain a representative estimate, the initial block size m (transient period), and the number of groups (N/m) must be large enough.

Periodogram Analysis

In [21] the periodogram of time series $(X=X_1, X_2, \dots, X_N)$ is defined as

$$I(v) = \frac{1}{2\pi N} \left| \sum_{j=1}^n X(j) e^{ijv} \right|^2, i = 1, 2, \dots, q; q = \left(\frac{N-1}{2} \right)$$

Where v is the frequency and N is the length of the series. In the finite variance case $I(v)$ is an estimate of the series spectral density. Series with long-range dependence will have a spectral density proportional to $|v|^{-1-2H}$ for frequencies close to the origin, and so a log-log plot of the periodogram versus the frequency can be approximated by a straight line with a slope of $1-2H$. In practice, only the lowest 10% of the frequencies for the calculation is used.

APPENDIX B: SAMPLE SCRIPTS AND CODES USED IN SIMULATIONS

ns-2 simulator uses Tcl as a command and configuration interface. awk scripting language was used in the study to calculate packet loss, delay and jitter. Appendix B includes the sample scripts and Tcl codes.

1. Tcl Code used simulation setup-3, Table 25

```
#PARETO Distribution
#Links are randomly assigned 512 kbps, 1 mbps and 2 mbps
#Starting times are randomly assignedbetween 0-1s
#burst_time(ON)=50ms
#idle_time(OFF)=50ms
#packetsize =200byte
#Bit rate =1000K
#shape factor =1.5

set ns [new Simulator]
set f [ open 5a12iptvpar_50_100_1_5_50ms_r1000_100s.tr w]
$ns trace-all $f
proc finish {}
{
global ns f
$ns flush-trace
close $nf
exit 0
}

#limit=number of nodes
set limit 100
#queue size=50 packet=10KB
```

```

set ql 50#set random variables for starting time
set rng [new RNG]
$rng seed 1
set RVbr [new RandomVariable/Uniform]
$RVbr set min_ 0
$RVbr set max_ 1
$RVbr use-rng $rng
puts " bit rates  "
for {set i 2} {$i<$limit} {incr i}
{
set br($i) [expr [$RVbr value]]
puts " $i  $br($i)"
}
#set nodes
for {set i 0} {$i<$limit} {incr i}
{
set n($i) [$ns node]
}
#set links which are depend on random variables
for {set i 2} {$i<$limit} {incr i}
{
    if { $br($i) < .300 }
    {
$ns duplex-link $n(0) $n($i) 1Mb .10ms DropTail
    }
if { $br($i) > .300 && $br($i) < .400}
{
$ns duplex-link $n(0) $n($i) 0.512Mb .10ms DropTail
    }
if { $br($i) > .400 && $br($i) < 1}
{
$ns duplex-link $n(0) $n($i) 2Mb .10ms DropTail
    }
$ns queue-limit $n(0) $n($i) $ql
}
$ns duplex-link $n(1) $n(0) 1000.0Mb .10ms DropTail
#Set up UDP connections

```

```

for {set i 2} {$i<$limit} {incr i}
{
set udp($i) [ new Agent/UDP]
$ns attach-agent $n(1) $udp($i)
}
#Set sinks
for {set i 2} {$i<$limit} {incr i}
{
set null($i) [ new Agent/Null]
$ns attach-agent $n($i) $null($i)
}
#connect source to destination
for {set i 2} {$i<$limit} {incr i}
{
$ns connect $udp($i) $null($i)
}
#set flow ids
for {set i 2} {$i<$limit} {incr i}
{
$udp($i) set fid_ ($i)
}
#attach file to connections
for {set i 2} {$i<$limit} {incr i}
{
set cbr($i) [ new Application/Traffic/Pareto]
$cbr($i) attach-agent $udp($i)
$cbr($i) set packetSize_ 200
$cbr($i) set burst_time_ 50ms
$cbr($i) set idle_time_ 50ms
$cbr($i) set rate_ 1000k
$cbr($i) set shape_ 1.5
}
set RVstart [new RandomVariable/Uniform]
$RVstart set min_ 0
$RVstart set max_ 1
$RVstart use-rng $rng

```



```

puts " start times"
for {set i 2} {$i<$limit} {incr i}
{
set startT($i) [expr [$RVstart value]]
puts " $i $startT($i)"
}
# set the simulation start time
for {set i 2} {$i<$limit} {incr i}
{
$ns at $startT($i) "$cbr($i) start"
}
# set the simulation end time
set fin 100.0
for {set i 2} {$i<$limit} {incr i}
{
$ns at 100.0 "$cbr($i) stop"
}
$ns run

```

2. Sample awk scripts to calculate packet loss, delay and jitter.

measure-delay.awk which calculates delay (seconds)

```

BEGIN {
highest_packet_id = 0;
}
{
#$1,$2,...,$12 represent the related column of the trace file
action = $1;
time = $2;
from = $3;
to = $4;
type = $5;
pktsize = $6;
flow_id = $8;
src = $9;
dst = $10;
seq_no = $11;

```

```

packet_id = $12;
if ( packet_id > highest_packet_id )
    highest_packet_id = packet_id;
if ( start_time[packet_id] == 0 )
    start_time[packet_id] = time;
if ( flow_id == 2 && action != "d" ) {
    if ( action == "r" ) {
        end_time[packet_id] = time;
    }
} else {
    end_time[packet_id] = -1;
}
}

END {
    for ( packet_id = 0; packet_id <= highest_packet_id; packet_id++ ) {
        start = start_time[packet_id];
        end = end_time[packet_id];
        packet_duration = end - start;

        if ( start < end ) printf("%f %f\n", start, packet_duration);
    }
}

```

measure-delay-result.awk which prints maximum, minimum and average delay (seconds)

```

NR == 1 { m=$2 ; p=$2 }
$2 >= m { m = $2 }
$2 <= p { p = $2 }

{ s += $2 }
END { print "Max Delay = ", m, " Min Delay= " p, " Average Delay is", s/NR }

```

measure-packetloss.awk which calculates packet loss

```

BEGIN {
    # Initialization. Set two variables. fsDrops: packets drop. numFs: packets sent
    fsDrops = 0;

```

```

        numFs = 0;
    }
    {
        action = $1;
        time = $2;
        from = $3;
        to = $4;
        type = $5;
        pktsize = $6;
        flow_id = $8;
        src = $9;
        dst = $10;
        seq_no = $11;
        packet_id = $12;
        if (from==1 && to==0 && action == "+")
            numFs++;
        if (flow_id>=2 && action == "d")
            fsDrops++;
    }
    END {
        printf("number of packets sent:%d lost:%d\n", numFs, fsDrops);
    }

```

#measure-jitter.awk which calculates jitter

```

BEGIN {
    highest_packet_id = 0;
}
{
    action = $1;
    time = $2;
    flow_id = $8;
    seq_no = $11;
    packet_id = $12;
    if ( packet_id > highest_packet_id ) {
        highest_packet_id = packet_id;
    }
}

```

```

#Record the transmission time
if ( start_time[packet_id] == 0 ) {
    # Record the sequence number
    pkt_seqno[packet_id] = seq_no;
    start_time[packet_id] = time;
}
#Record the receiving time for
if ( action != "d" ) {
    if ( action == "r" ) {
        end_time[packet_id] = time;
    }
} else {
    end_time[packet_id] = -1;
}
}
END {
    last_seqno = 0;
    last_delay = 0;
    seqno_diff = 0;
for ( packet_id = 0; packet_id <= highest_packet_id; packet_id++ ) {
    start = start_time[packet_id];
    end = end_time[packet_id];
    packet_duration = end - start;
    if ( start < end ) {
        seqno_diff = pkt_seqno[packet_id] - last_seqno;
        delay_diff = packet_duration - last_delay;
        if ( seqno_diff == 0 ) {
            jitter = 0;
        } else {
            jitter = delay_diff/seqno_diff;
        }
        printf("%f %f\n", start, jitter);
        last_seqno = pkt_seqno[packet_id];
        last_delay = packet_duration;
    }
}
}

```