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Analysing the power consumption behaviour of Ethernet switch using Design of Experiment

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Abstract

At present, one of the main concerns of green network is to minimize the power consumption of network infrastructure. Surveys show that, the highest amount of power is consumed by the network devices during its runtime. However to control this power consumption it is important to know which factors has highest impact on this matter. This paper is focused on the measurement and modeling the power consumption of an Ethernet switch during its runtime considering various types of input parameters with all possible combinations. For the experiment, three input parameters are chosen. They are bandwidth, link load and number of connections. The output to be measured is the power consumption of the Ethernet switch. Due to the uncertain power consuming pattern of the Ethernet switch a fully-comprehensive experimental evaluation would require an unfeasible and cumbersome experimental phase. Because of that, design of experiment (DoE) method has been applied to obtain adequate information on the effects of each input parameters on the power consumption. The whole work consists of three parts. In the first part a test bed is planned with input parameters and the power consumption of the switch is measured. The second part is about generating a mathematical model with the help of design of experiment tools. This model can be used for measuring precise power consumption in different scenario and also pinpoint the parameters with higher influence in power consumption. And in the last part, the mathematical model is evaluated by comparing with the experimental values.

Keywords: Green Networking, Power consumption, Design of Experiment

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LIST OF SYMBOLS AND ABBREVIATIONS

ACK – Acknowledgement

ALR - Adaptive Link Rate

ASIC - Application-Specific Integrated Circuit

CRT - Cathode Ray Tube

DOE - Design-of-Experiments

EEE - Energy Efficient Ethernet

FDMA - Frequency Division Multiple Access

GHG - Green-House Gases

ICT - Information and Communication Technology

IEA - International Energy Agency

LAN – Local Area Network

LCD - Liquid Crystal Display

LPI - Low Power Idle

NP-hard - Non-deterministic Polynomial-time hard

OFAT - One Factor at a Time

PDU – Protocol Data Unit

PHB - Per Hop Behavior

PHYs - Physical layer devices

PoE - Power over Ethernet

R-sq – R squared

QoE - Quality of Experience

QoS - Quality of Service

TCP - Transmission Control Protocol

TDMA- Time Division Multiple Access

UPS - Uninterruptible Power Supply

1. INTRODUCTION

We are now living in an era of cutting edge technology. Everything is now in the reach of human, which were beyond imagination, even few decades ago. However this awe-inspiring enhancement in the field of technology has a huge impact on the environment. In coming years, in front of us we have the greatest challenge which is tackling the climate change. Power consumption is now become one of the top-most concern of world industries and the reduction of power consumption has become a primal goal for any industries, because of environmental, economical and ethical reasons. This concern has a strong influence over the field of information and communication technology (ICT).ICT plays major role in pointing out many environmental problem such as environment pollution, waste management, power and supply management. However, Rondeau et al. (2015) explained that the use of ICT can also have some impact on the environment in terms of ICT footprints such as carbon emission and electronic waste. To minimize the ICT footprint in the environment, there is a need to implement new requirements in order to design a sustainable green network. The number of ICT devices is increasing in exponential manner. Research shows that, by 2020, almost a third of the global population will own a PC. Whereas currently only one in fifty people owns a personal computer. 50% of the whole world population will own a mobile phone and one in twenty households will have a broadband connection. Moreover by 2020, when a large fraction of developing countries' populations will be able to afford ICT devices and will have caught up with developed countries' ownership levels, they will account for more than 60% of ICT's carbon emissions driven largely by growth in mobile networks and PCs. Moreover, data centers will grow faster than any other ICT technology, driven by the need for storage, computing and other information technology services. These advancements put lots of concern over the field of the information and communication technology sector, electronics equipment manufacturer and designer and more specifically on the networking field. In recent years, persistent efforts have been made to reducing unnecessary power consumption, which is usually known as a greening of the networking technologies and protocols. As power-related studies in networks are very specific and due to millions of innovation and improvement make it even harder. This work only focuses only one of the most important devices of wired network which is Ethernet switch. Every device has lifelong ICT usage. This starts from manufacturing till dismantling. But here the concern was only during the usage period of the Ethernet switch. The goal is to observe the behavior of switch with different variation of few selected variables. And by analyzing this variation propose a model which defines the relationship between few main parameters related to Ethernet switch and the power consumption. Two models are proposed for measuring the power. One is using full factorial method another is using linear regression. First model is based on full factorial which provides model with less number of experiments and for more elaborate experimental model linear regression model is used. For this work only those parameters are chosen which can be controlled on switch end. That means the plan was to choose only those parameters that network architecture may control during network design. Later on, rounds of experiments are done in hibernation mode to see the power consumption pattern and comparative discussion is done between always on and hibernation mode and energy efficient Ethernet mode. The idea is to get an overall idea about how these parameters affect on the power consumption and then provide a full planning of how to save the maximum amount of power consumption. Even though this work is a small part regarding reducing the power consumption of ICT field, however this work is directly related to reduce the power consumption and hence working towards improving the sustainability of the world.

The work is structured in following way. Section-2 describes the motivations behind the energy-awareness in the ICT division. Section-3 describes the background of the green networking and the design of experiment. Section-4 consists of related works done on this field. In the section-5 and section-6 describes the methodology of the design of experiments that has been used and research method behind doing the experiment respectively. Section-7 is describing all the results and analysis of this work. Section-8 consists of an elaborate discussion of the findings and provides some solutions to save power consumption. Lastly section-9 includes the conclusion of the whole study.

2. MOTIVATION

There are many topics that are motivated to do this work. Among them the main motivation is environmental concern. Efficient use of energy and economical feasibility also act as a great motivator. In this part few main motivators behind this work is briefly described.

2.1 Environment in jeopardy

Global warming and green house effect is not a new term anymore. According to climate studies published by University of California (2007) and University of East Angelia (2003) the last two decades of 20th century were the warmest in the history of last 400 years of global temperature. And it cannot be a coincidence that this last two decades are also the time when the technological advancement had started. Environmental problems that are tied to Green-House Gases (GHG) have increased during the recent years. All over the world, several studies are done in order to highlight the distressing effects of immense GHG emissions and their consequences on the climate change. According to a report published by the European Union in the year 2007, The GHG emission is needed to decrease in volume of at least 15%-30% to keep the overall global temperature increase by 2°C. Even though it seems less but this small amount of rise on the temperature can cause polar ice melts, sea level rise, intensified tropical storms and even disappearance of islands into the oceans. Smart2020 report (2008) explains a statistics report on ICT sectors, this report showed that ICT sector alone was responsible for 2% of global carbon emissions. And the trend of this curve is upwards. Everyday new advancement in the field of information and communication technology is being made. People are now becoming more connected. Technology is now reaching around the world. It is now not kept for one group of people. World is becoming smaller day by day due to progress in ICT. People are becoming more and more dependent to the technology and by following the trend it could be easily said that the involvement and use of ICT will even increase more than ever in the upcoming days. However at the same time these progresses come with a baggage of carbon footprint and environment pollution that cannot be ignored.

2.2 Under Utilized Energy efficiency

Energy efficiency refers to products or systems that are using less energy but doing the same job than conventional products or systems. In a way they are better than the conventional products. In today's world, there are many efficient products for homes, buildings, computer equipment and so on. Unfortunately, energy efficiency is not used as frequently as they are supposed to be. People at home or in business are not taking the energy efficient choice for several reasons. One of the main reasons is to unwillingness towards change. Secondly they are not well aware of the situation of current scarcity of the power resources. They are also not aware that how much money they can actually save by switching to energy efficient system. However one of the most important reasons that go with the context of this work, is people are uninformed about a power management plan for the tools that can reduce power consumption in significant amount just by doing some small modifications in the system.

2.3 Power Greedy Network Devices

Following the trend of rapid growth of Internet access, there is also huge demand for edge network devices, data centers and other network infrastructure and it is imaginable. And it is safe to assume that ICT energy demand is also growing at a quick pace in developing and emerging countries. Now there rises an important question is which device is most power greedy in the context of ICT structure. There are several candidates to choose from and several assumptions can be made. However according to the report of Datacenter Dynamics (2012), within a period of one year (2011 to 2012) global data center power consumption demand has increased to 63%. It is one of the most abrupt changes in the power consumption in last decade or so. As cost feasibility is a key business consideration, therefore most of the data center operators are trying to improve energy efficiency. It is possible to see the direct effect of datacenter as they are collective in nature; however there are more graving problem is growing power consumption demand of billions of edge devices and user end network equipment, scattered in offices and homes around the world. Even though the individual power consumption of these devices may not look high but when they all are considered together it consumes a huge amount of power. Figure-1 shows a graph based on the study of International

Energy Agency (2013) on the global energy footprint of information and communication technologies in 2013. It clearly shows that the edge devices causing the maximum amount of carbon footprint which is 42% of the total ICT. However datacenter is creating only 21% which is exactly the half of what these end devices are made.

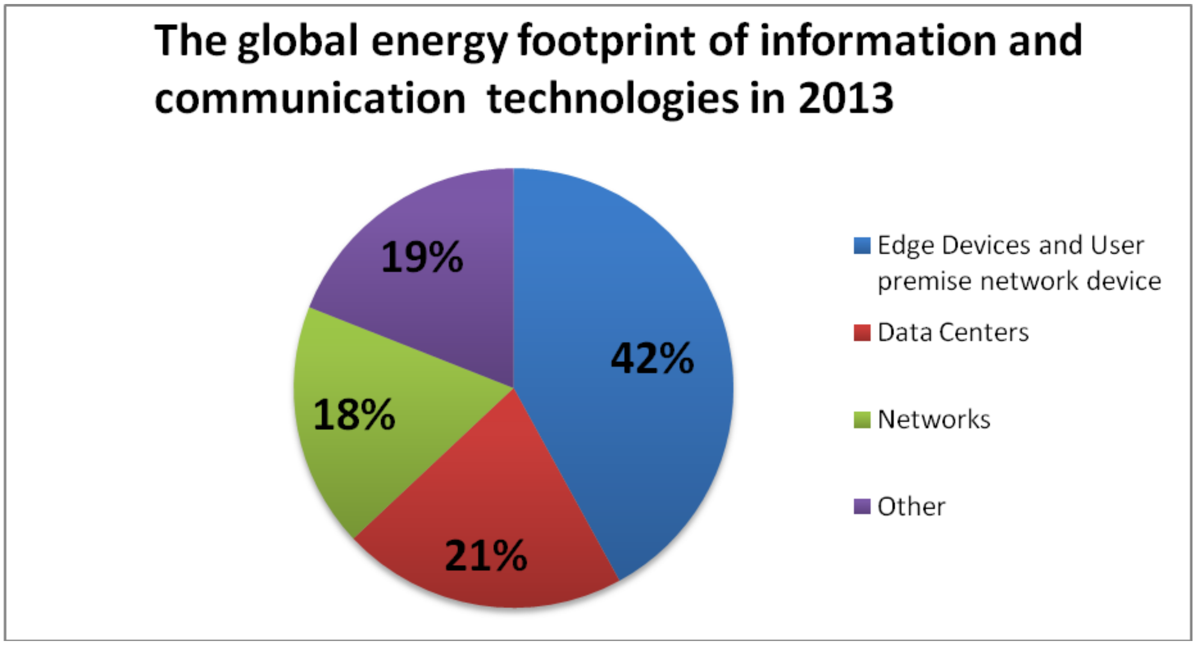

Figure 1: Global energy footprint of ICT (data based on International Energy Agency 2014)

2.4 Enable Greater Deployment

While many of us talking about wide spread ICT, It should be kept in mind that there are many parts of the world where electricity is a scant resource. According to the report of the International Energy Agency's (World Energy Outlook 2009), U.N. Development Program published their collection of data on energy access, mainly focusing on the developing world. According to the statistics an expected 79 percent of the people in the third world country have no access to electricity despite decades of international development work. If we consider the total number of individuals, who does not have electricity in their life then the number would be about 1.5 billion. That is one fourth of the whole world's population. This population is concentrated mostly in Africa and southern Asia. And there are also several countries with not so strong electricity producing infrastructure which results frequent black-outs. Therefore for these places electricity is one of the barriers to widespread Internet deployment. So saving power is a moral obligation. Moreover networking equipment in a disaster-hit area will rely on external or backup source of power for example UPS. If all the networking equipment are designed to consume less power, then they can last longer. Thus hospitals, police, and other non-profit agencies in the affected area will be able to access, retrieve and transmit data for longer.

2.5 Towards Stable Economy

The influence of energy efficiency and green ICT is not only environmental. They have strong influence on global economy. In small context, energy efficiency and reducing of power consumption can decrease the electricity bill by significant amount for any company or industry. However on a higher note Bianzino (et. al) (2010) explained that one third reduction of the GHG emissions may produce an economical profit that is higher than the amount of investment required reaching this target. Moreover according to the analysis of International Energy Agency (IEA) (2010) energy efficiency has the potential to improve economic growth while reducing energy demand. But due to under evaluation of this situation they assessed that two third of the economically viable energy efficiency potential will remain unnoticed. In their new study, "Capturing the Multiple Benefits of Energy Efficiency" (2014), they called the energy efficiency techniques as "hidden fuel". They explained how it is possible to shift beyond qualitative assessments. They have provided examples of how to measure and even monetize the value of energy efficiency to the economy and society.

3. BACKGROUND

This chapter presents an overview of the green networking, describing its trends. It also describes green networking strategies and promising research fields for example virtualization, resource consolidation, green TCP, hibernation, energy efficient Ethernet, adaptive link rate and clustering. It also describes about design of experiments and general terms and ideas of it.

3.1 Green Networking

Green networking is a term that is used to define more efficient use of networking. This term is broad. It only does not mean efficient use of networking rather it extends to cover several approaches that reduce energy consumption, cost of networking and most importantly build a more environmental friendly networking system. Green networking is fairly a new term. According to Penttinen(2012) the first effort towards green networking is done by Gupta and Singh in the year 2003. Since then researchers are working on it to make the network system more efficient. As we know ICT is also one of the reasons behind environment pollution and emission of GHG, so it should be one of the main concerns for every personnel related to technical advancement. Green networking is the trend of creating computer networks in such a way that it will conserve power, lower environmental pollution, reduce resource use, and enhance utilization. By doing this it is not only make the current computer network more efficient it can also expand networking radius and cover those areas of developing countries where internet is still unknown. However, according to Ayguade and Torres (2014) green networking field has receiving importance more than ever nowadays. They have pinpoint two main reasons behind this. The first one is an ongoing global political movement that strongly recommending all the big companies in general to do more sustainable practices. And the second one is, all the renowned company themselves are interested to minimize the resource use and increase utilization in order to reduce their operating costs.

3.2 Green Networking Strategies

The common and the most popular way for designing the computer network system conflicts with the idea of green networking. The traditional way of networking system is designed according to some principles which directly oppose the idea of green networking. For example over provisioning and redundancy are two principles that are very common for successful network designing however both of these conflicts with the green networking terms. Over provisioning means design the network according to its highest usage. It is a very common practice while designing the network. During over provisioning network designing, network is designed according to its maximum peak hour traffic. This is done due to provide better QoS support and to reduce the number of failure. However it results unnecessary power consumption during low traffic period. This kind of design provides better user experience but it is not green at all. The second principle that is also very common in traditional network is redundancy. To provide better customer support, resiliency and fault tolerance, network is also designed in a redundant way. To reduce the adverse effect of device failure more devices are added to the infrastructure. More than one copy of backups is made which requires more data space hence more datacenters. All of these in the end are causing more power consumption. Due to this sort of ideology which completely conflicts with the environment ones, green networking become a technically challenging research field.A completely new set of strategies are needed to be introduced in order to save more power consumption. These strategies are needed to be environment friendly and at the same it should maintain the quality of service and network reliability.

There are several green networking practices that have been invented and introduced in last decade or so. According to Beckmann et al. (2014), based on which level the change can be taken place, techniques can be divided into two parts. One is software level methods. And another one is hardware level methods. Software level methods include the techniques like virtualization, recourse consolidation and green TCP. On the other hand hardware level method includes adaptive link rate, hibernation, energy efficiency Ethernet.

3.2.1 Software level Methods

I. Virtualization

Virtualization is one of the most common and easy to implement method that can be considered as green networking strategies. This is done by dividing up the resources for example operating system, server network connections that give the illusion to the network applications. These applications get the impression that they are independent working version of the divided resource. In the case of network virtualization bandwidths are spit into channels. All these channels can work independently. Different applications can be assigned in different channels. There are mainly two type of methods that are used to split bandwidth. One is Time division multiple access (TDMA). In TDMA each channel gets complete bandwidth for fraction of time. And the second method is frequency division multiple access (FDMA). In FDMA every applications is assigned to a certain fraction of the total bandwidth. Virtualization is done in order to get higher utilization of the network infrastructure. And at the same time it reduces the number of active link which reduces power consumption to a certain extent. For example it is always better to use one network link by 5 applications rather than 5 network links where most of the time links are idle. That is why network virtualization is a green networking strategy.

II. Resource consolidation

Resource consolidation is another software level method towards green networking. Usually it is nothing but the effective and efficient use of computer server resources. It reduces the total number of required machines by increasing the utilization of all the servers. It is usually common to see that, companies are having multiple low utilized servers. This cause significant amount power consumption and emits an awful amount of green house gases. Therefore, most current day companies apply server consolidation in the system infrastructure. However, even though consolidation can bring efficiency and increase utilization, it makes the data complicated in nature that is difficult to understandable for the general users. Therefore it is common practice to use consolidation combined with virtualization. It keeps the applications isolated from each other resulting an abstraction between the applications and underlying complexity of the system.

III. Green TCP

Green TCP is an energy-aware application approach. The application that can detect and predict the idle periods by analyzing its own behavior is known as energy-aware applications. It can predict the upcoming long idle period and act accordingly. During these idle periods they can go to sleep mode or low power state that will reduce the power consumption by a certain level. Transmission control protocol (TCP) is a connection oriented protocol. That means it requires acknowledgement (ACK) for every transmitted data. If for a certain period of time there is no acknowledgement then re transmission is made. And after a set retransmission the connection will be lost. Because of that there should be always some sort ACK is required in order to keep the connection alive. Modern machines save their running work in ram and go to sleep mode during idle period. However they cannot keep the connection alive as their network hardware does not work during sleep mode. This causes connection lost and bring problem to the client applications. For example server will clean up all the files that were opened by the client application before it went to sleep. It may causes information loss. Moreover reconnecting causes overhead in time, that reduces the quality of experience (QoE) of the user. One way is to use some extra hardware to keep the network alive but it is a costly solution. Therefore Irish and Christensen (2008) propose a software solution called “green-TCP”. The idea behind green TCP is to add an extra control message that will allow client to go to sleep mode but connection will not be lost. For example, a ‘sleep’ message can be sent by the client to the server which will indicate that client is going to sleep mode and there will be a timestamp mentioning the duration of the sleep period. Server will not send any message to client during this period. And connection will be kept alive. Therefore there will be no chance of losing the connection. Client will send a ‘wake’ message when it is want to awake. And the connection will be reestablished and server will send the all the buffered message to the client. If the duration of the timestamp is passed and there is no wake up message only then the connection will be lost. Green-TCP is implemented entirely in software; both the client and server applications are needed to be updated in order to use and accept the additional requests.

3.2.2 Hardware Level Methods

I. Adaptive Link Rate

As discussed earlier most of the networks are designed over provisioning which gives ample opportunity to reduce power consumption to certain extent. Networks are designed to tackle the maximum request therefore all the network link is fixed to its maximum capacity even during the idle or low traffic period. Adaptive link rate (ALR) is downgrading or adjusting the link capacity according to the incoming traffic. Usually link capacity ranges from 10mbps to 1gbps. Therefore link rate can be reduced when there is less traffic resulting less power consumption. According to Nevedschi et al (2008), when a negotiation process is done during the link setup, the maximum capacity link is usually chosen even if a lower capacity link can fulfill the requirement. Therefore adaptive link rate mechanism offers an algorithm which automatically adjusts the link speed according to the traffic. That means when there is a high level of traffic it will main its maximum capacity. However for a certain duration if there is no significant traffic is passing through the network then network will auto negotiate to a lower level of link capacity. The level of link speed is chosen according to the traffic pattern. It will again increase its speed when traffic increases. However this auto negotiation process takes hundreds of milliseconds to complete. During this time communication is interrupted as the link is down. Many important data can be lost due to this and ultimately does not provide better QoS or QoE. For reducing this downtime Blanquicet(2008) proposed a method to select the physical layer devices (PHYs) more quickly. In this method a frame exchange is used for renegotiating the change of the speed that withholds the need of restarting the auto negotiation process. This method makes the transformation of the speed faster but still it is not fast enough. The adjustments of equalizers, echo cancellers and timing circuits are needed which takes time. Researchers are working in this field in order to make the change even quicker. Nevertheless there is great advantage in switching to the lower data rates whenever its possible. There is always a tradeoff between lowering the power consumption and provide better user experience. The main difficulty of implementing ALR is choosing the speed. It is always hard to know that when and how much the speed is needed to be lowered. Nevedschi (2008) showed that choosing the ideal rate for ALR is NP-hard (Non-deterministic Polynomial-time hard).

II. Hibernation

Hibernation means shutting down the power of the system while maintaining its state. Hibernation is a common phenomenon for computers. However networking device like switch and routers it is fairly new. Only few new models have the capability of hibernation. Hibernation can reduce the power consumption to a certain level. However it is not completely shutdown. All the settings are stored in the hard disk during its hibernate period. Hibernate mode saves more power than sleep mode. In this work hibernation feature of the switch is discovered and its behavior is observed for different cases. Therefore more detail discussion is available in the later chapters.

III. Energy Efficient Ethernet

Energy Efficient Ethernet (EEE) is another way to reduce power consumption used by Ethernet devices. EEE is applied during the periods of low link utilization. That means when the traffic is not high. Energy efficient Ethernet is specified in IEEE 802.3az-2010. The energy efficiency of EEE is a function of the link utilization, packet transmission time, and the distributions of packet inter arrival times. The primary concept behind EEE is that the links that are used for communication will only consume power when there is traffic. Generally a link is not always busy. During a certain period of the day the traffic load becomes completely close to null. So the idea is to save power consumption during these times when there is no data is transmitted. EEE has its own signaling protocol that indicates that there is a gap in the data and link can go to idle mode. The same signaling protocol is also used to indicate that the link is needed to wake up after a previously defined delay period. The EEE protocol use the normal idle signal that is usually transmitted between data packets with a modification. This signal is known as low power idle (LPI). The transmitter sends this LPI signal instead of idle signal so that the link can go to sleep. After sending LPI for a period of time, transmitter stops sending any sort of signals so that the link can go inactive. However transmitter periodically, sends some sort of pulse signals so that the link does not remain active for long period without a refresh. And when the transmitter wants to wake the link up again and to be ready to transmitting data it sends normal idle signal. It is work as a wakeup call. And after a predefined period of time link becomes ready to send and receive data.

This ends the discussion about different types of strategies that is used or can be used more frequently in order to build a green and sustainable network. However before applying any of these methods it is better to pin point the factors or variables of the network that have highest impact on power consumption so that a proper strategy or set of strategies can be used to save power consumption. Several methods can be applied in order to find out the different factors that are responsible for power consumption. In this work a statistical approach named as design of experiment has been used to find out the parameter which has highest impact. The following part provides a brief summary of design of experiment.

3.3 Design of experiment

Design-of-experiments (DoE) is a combined name of all sort of data collection techniques based on observation of a response from any sort of event. At the beginning of DoE's long history, the word "experiment" referred to classical (e.g., physical, chemical) experiments, whereas nowadays running a computer code of a simulation is also considered as a "computer experiment". The experiment is controlled by a set of input variables (or factors in DoE terms) and a set of output (or response) variables (or functions) can be observed. The set of all possible input combinations is known as experimental domain. For a single combination of input an execution of the experiment is done which is called an experimental run or trial. This experiment can be real experiment or computer simulated experiment. However there is a difference between these two. On one hand computer run experiment is fully deterministic. For a same value of all the inputs output will be always same. On the other hand real experiment is non deterministic. For same input value result could vary. That in the end helps to find some other hidden variable. Design of experiments is performed mainly to draw conclusions about the studied phenomenon. There could be several end result or final goal that can be set for design of experiment. For example to maximize, minimize, hidden pattern finding etc. can be set as final goal of design of experiment. To make the finding from the experiment more effective multiple runs of same experiments is done. However to get the appropriate result from these sets of runs, these runs should be executed according to an appropriate DoE method. Depending on what the term information means and on the sense the optimality is defined in, various DoE approaches are available. The Branches of DoE that has been applied in this work is briefly described in the Methodology section. Design of experiment is generally used for complex experiments. However there is no harm to use in for simple experiments. Design of experiments helps to understand the inner structure of the experiment and the relation between the input variables and response variables, whose are cannot exactly be defined by just by seeing the raw results. The unavailability of the knowledge of the inner relationships between the variables points to black box models. Black box model are those where there is ample information about input variable and output variable but the functionality inside the system is unknown. Design of experiments is a suitable choice for black box modeling.

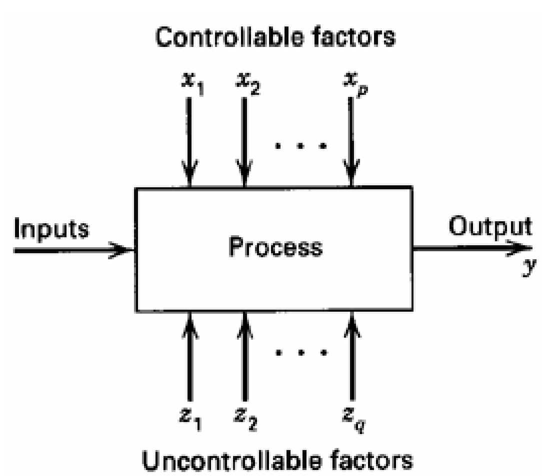

Figure 2: Design of Experiment general architecture

Figure 2 shows the general architecture of design of experiment. Where we have few fixed inputs, some controllable factors that will be controlled during experiment, few uncontrollable factors for example noise and an output or response variable. However this structure can vary depending on the type of experiment that is run.

A well planned and executed experiment can offer a new perspective about the response variable. The behavior of the response variable can be depended on one or several factorials. That is why OFAT approach is put into place in design of experiment. OFAT means one factor at a time. Therefore experiments are done by holding certain factors constant and altering the levels of another variable. However this approach is not so effective if all the factors level were changed simultaneously.

According to many researchers, design of experiment is originated from the work of R. A. Fisher in the early stage of the 20th century. He showed to the world that if a experiment is well designed before its execution and all the possible outcome is thought thoroughly before running the experiment then it can avoid frequent failure problem during analysis period. Even though the work looks time consuming, but in the end the total cumulative time is always less.

According to Keith M. Bower, a well–performed experiment may provide answers to questions such as:

- *What are the key factors in a process?*
    - Many times it is possible that all the input variable does not has as effect on output variable as we might think. After the analysis we can see which variable is the key factor for the response variable. And we can also discard the variable which has negligible effect.
- *At what settings would the process deliver acceptable performance?*
    - As different variable has different level of input so design of experiment can pin point the exact configuration of the input variables when it is possible to get the wanted result from the response variable.
- *What are the interaction effects in the process?*

- Sometimes it is possible that some input variable does not have that much impact on the response variable. However it does not mean that we can discard this variable. There is always a possibility that this variable can have some effect when it is combined with some other variable. So it is important to know the interaction effect of the variables. And with design of experiment it is also possible to know that.

There are few concepts which are very common in the field of design of experiments. They are randomization, blocking and replication.

Randomization: Randomization is the order in which the different runs of experiment are done. It is mainly done to avoid the effects of uncontrolled variables. If all the experiments has some sorts of pattern or all the input variables level is changed in the same order then this order or can has some unwanted effect on the result.

Blocking: Blocking is done when randomizing a factor is impossible or too costly. Sometimes frequent changes in the levels of variable could be difficult or costly then blocking is used. Blocking is actually carrying out all of the trials with one setting of the factor. And then all the trials with the other settings are done serially.

Replication: Replication means doing the same experiments more than once including the setup. Replication is done mainly to avoid the errors made by the person who is running the experiments. It reduces the error term to certain extent if there is any error in the first place.

4. RELATED WORK

Several works has been done in both for wired and wireless network in order to find the power consumption pattern on the network device. However design of experiment in the field of networking is comparatively atypical.

4.1 Related Work in Power Consumption

One of the difficult things for running this experiment was to decide the parameter. There is a whole bunch of things that is needed to consider. Though this works goal is to choose only those parameters that can be controlled. Gupta, Grover and Singh (2004) are one of the pioneers of thinking about power consumption of the networking devices though their main target was feasibility rather than environment. They did a feasibility study on power management of Ethernet switches. They had examined the feasibility of introducing power management schemes in network devices in the LAN. They had mainly focused on the sleep mode. They were looking for finding some chance to put several components or the whole switch in a sleep during low traffic activity. They had experimented the LAN switches and found out that for significant amount of time the switch is remain inactive. So they had used an abstract sleep model which was designed for Ethernet switches and tested for finding the possibilities of saving of power in different times of the day. They also found that for different interfaces for example interfaces connecting to hosts to switches, or interfaces connecting switches, or interfaces connecting switches and routers has different sort of possibilities for saving power consumption. They developed an algorithm based on the periodic protocol and traffic estimation on different times of the day. Their result showed that sleeping mode is feasible for LAN for some cases. However there are some tradeoffs between power-saving and sleep related losses that needed to be considered. Overall, they provide a fair guideline for running an experiment on switches.

Christensen, Nordman and Brown (2004) explained that how network device can have impact on environment pollution. They focused on few of the main aspects of power management in the network devices. They point out some acute practices of the human which is causing more power consumption then it actually needed. The first one is induced consumption. Computers and other devices are left on all the time even they are not in use. For the sake of resource sharing and auto backing up of the files everything is left on although the utilization is very low. The second reason is increasing network link data rates. Because high link rate is available it does not mean it is required all the time. High link rate consumes more power. And during the idle period it should reduce link rate in order to reduce consumption. The third cause they point out is display proliferation. The monitor becomes much easier to fit in a place when it took a leap from CRT to LCD. However this causes users to use multiple displays in commercial and also in home which actually results a lot of power consumption. Their whole work was focusing on the places that can be utilized to save power consumption.

Mahadevan and Shah (2010) mainly worked on the energy management strategies for network switches. They performed experiments in order to evaluate some energy management strategies. Though their work based on network switches, they mainly focused on the network switches used in datacenters. They started their experiment by performing a lifecycle assessment of all the running switches of a datacenter. That actually considered as the use phase of the network switches. Then they examined various energy management techniques to reduce this operational footprint. For example they proposed to reduce the operational energy use of network switches by powering off unused components. All the components of the switch are not in used so they can be switched off when there is no work. Another more efficient way of saving energy is that they described is to forward traffic, when there is less traffic. That means when there is less amount of traffic is going on use a particular set of switches to transfer all the packets and can shut off rest of the switches which will provide a viable alternative to reducing the total energy footprint of networking within data centers.Then theystep by step examined a variety of energy management methods to reduce this operational footprint, and find that for an Ethernet switch lifecycle, during the use phase the maximum amount of power is consumed. Lastly they concluded by discussing how these results may persuade network design in the future. Foll(2008) did similar kind of experiment to find out the power consumption within orange telecom company.And he also came up with similar kind of results.

According to Mayo and Ranganathan(2004)and Rivoire and Shah (2007) from device manufacturers point of view one of the challenge is to make sure that networking devices such as switches and routers are power proportional, that means they will consume power proportional to their load and usage like computers and laptops. Mayo and Ranganthan made two main contributions. At first they provided a model for energy scale-down. They provide some ideas about how to scale down the energy. One of their approaches to design scale down is to use individual purpose devices as examples of power competent design points, and then structure the model efficiently by using insights from these design points. To recognize the scale of the potential benefits, they had presented an energy comparison of a wide spectrum of mobile devices. These comparisons of the devices showed the opportunities for scale down. On the basis of this knowledge they then proposed and evaluate three important requirements such as display scale down, wireless scale down and processor scale down for overall energy scaling down. By following their model they concluded that it is possible to reduce energy consumption by factors of two to ten which is important for future designs.

4.2 Related Work Based on DoE used in network context

Zhan and Goulart (2009) used design of experiment for analyzing the broadband wireless link for rural areas where cellular coverage is limited. Their main focus on this paper was to introducing design of experiment. Design of experiment helped them to analyze the interactions between different variables. 3G is one of the most common ways to internet deployment in the rural areas. However for several applications quality of services is important. Therefore they had experimented these connections based on certain parameters for example packet size, location buffer size and wireless provider. They used design of experiment in order to get a better understanding of the effect of the factors and their interactions. That will ultimately help the end user to select the best option which will improve the quality of service of the 3G connection.

Toreto and Perkins (2005) and Gendy and Bose(2003) used full factorial method for analyzing the mobile ad-hoc network and per hopQoS respectively. According to Toreto and Perkins performance of the ad-hoc network depends on several different factors. Their primary goal was to see the performance behavior of the ad-hoc network according to these parameter changes. They have considered factors including protocol design at every layer, retransmission limits and timers. They also considered few system factors such as network size and traffic load and also one environmental factors- channel fading. The whole experiment is done based on design of experiment. They used DoE tools to analyze the network performance and which ultimately led them to more precise conclusions. They used 2^k factorial for quantifying the main and interactive effects of the factors such as network density, node mobility, traffic load, network size and channel fading on two response metrics such as packet delivery ratio and end to end delay. Using the achieved results then they have developed two first order linear regression models that explain the relationship between the influential factors and the response variables. On the other hand Gendy and Bose (2003) use different input traffic scenario and per hop behavior on routers. They also used statistical approach based on design of experiment. They used a real network as a test bed to characterize the per-hop quality of service of a given per hop behavior (PHB). They have implemented a full factorial design of experiment to analyze the influence of different PHB configurations and input traffic scenarios on per hop quality of service. They used analysis of variance to spot the most influential input and PHB configuration parameters that have highest impact on per-hop quality of service. Then they have applied multiple regression analysis to model the behavior of per hop QoS depending on these parameters. They conclude that this is one of the most effective ways to model the behavior. It is capable of characterizing any given per hop behavior within the ranges of the experiments. It also provides a functional relationship for the PHB output characters. These experiments provide a fair idea about how to prepare the test-bed.

Mahadevan and Sharma (2009) benchmarked the switch behavior for different parameters. They have first explained the difficulties in network power management and then present a power measurement studies over various network devices like network switches, hub, core switches routers and wireless access points in commercial buildings and datacenter. They did not use any design of experiment method though. They propose a benchmark for users for power consumption which will help them to measure and reduce the power consumption. They have used several parameters such as base chassis power, number of line cards, number of active ports, port capacity and port utilization, ternary content addressable memory, firmware and traffic load. Their experiment was vast and they tried to cover several things together. And they didn't focus on interaction of the parameters but rather they measure for predefined scenarios. They also proposed a network energy proportionality index which is a measurable metric. This can be used to compare power consumption behaviors of multiple devices. In their work they explained that switch consumes power proportionately to the load and usage. It differentiates between parameters which have impacts and which does not have impacts. It helps our work to select the parameter for the experiment.

5. METHODOLOGY

This section describes the design of experiment (DOE) methods that have been used to model the power consuming pattern of the Ethernet switch. Here statistical analysis methods have been applied to identify the most influential parameters affecting the power consumption of the Ethernet switch within the range and domain of these experiments. Two methods have been used to model the equation. One is full factorial method and another is linear regression analysis.

5.1 Full Factorial

A Full Factorial Design of Experiment provides responsive information about factor main effects and factor interactions. It also provides the process model's coefficients for all the factors and interaction. A full factorial DOE is a planned set of tests on the response variable or variables with one or more inputs factors with all possible combinations of levels. If we have n factors, with the i-th factor having k_i levels, and if each experiment is repeated for r times, then the total number of experiments: $\prod_{i=1}^{n} k_i * r$.

One of the most important parts of full factorial method is to design the experiment. Because to get an effective result, it is important to have the appropriate model. Key steps in designing an experiment include:

1) ***Identify factors of interest and a response variable:*** Before starting the experiment it is important to have the list of variables that will be varied and also the response variable or variables that will be measured. In other words these factors of interests are the key to run the experiment. By varying the values of these factors we will get different values of response variable. That will ultimately help us to analysis the behavior of the system.

2) ***Determine appropriate levels for each explanatory variable:*** The second step is to find out the appropriate level for the varying factors. If a factor is continuous then it is important to define some fixed level for the experiment. One factor can have several levels. Minimum

number of level is two. For example: it could be high and low. However this leveling is entirely depends on the designer of the experiment and the factors.

3) ***Determine a design structure***: Next key step of the experiment is to decide the structure of the design. As discussed earlier each varying factors can have several levels. And depending on the design the total number of experiment run is determined. Therefore if the number of variable is a big number and if every variable has several levels then the number of experiments might not be feasible. To keep the feasibility in mind, the design should be effective and at the same time within the limit.

4) ***Randomize the order:*** Randomization is another important feature of the full factorial experiment that should be kept in mind. There should not be any sort of pattern while varying the factors. Any pattern can have some hidden effect on the experiment that is unwanted.

5) ***Organize the results:*** The last step of the experiment is organize the results in order to draw appropriate conclusions. From a full factorial analysis several outcome can be achieved. The target is to find the right result that is required.

Full factorial experiments provide two types of conclusion. One is main effects another one is interaction effects. Main effects often mean the impact of the changing factors level. Main effect usually shows a single factors effect on the overall response variable. Main effect is calculated by finding out the difference between factor average and grand mean. Whereas grand mean is the overall average of the result. Main effects plots are a quick and efficient way to visualize effect size. In addition to determining the main effects for each factor, it is often significant to identify how multiple factors interact in effecting the results. An interaction occurs when one factor affects the results in a different way depending on a second factor. Interaction plots are used to conclude the effect size of interactions.

The main objective of full factorial method is to learning the most from as few numbers of experiments as possible. It identifies the factors affect mean and variation which usually helps to identify if the parameter is necessary for the model or not. And then lastly it produces prediction equations which can be used for validation.

5.2 Linear Regression Analysis

Regression analysis is the method of fitting straight lines to set of data. As discussed by Robert(2014) in a linear regression model, the variable of interest in this case is power consumption which is predicted from k other variables using a linear equation. If Y denotes the dependent variable or the response, and $X_1, \ldots, X_k$, are the independent variables, then linear regression analysis would be look like:

$$Y = c_0 + c_1 X_1 + c_2 X_2 + \ldots + c_k X_k$$

Where, c_0, c_1, c_2, c_k are constant, independent and identically distributed. C_0 is the so-called catch of the model. In other words, the expected value of Y when all the X's are zero or has no value to mention. And c_i is the coefficient (multiplier) of the variable X_i. All the c's and X's together is the overall model. Each X has its own coefficient and these coefficients are non-related with others. This is about one of the simplest possible model for predicting one variable or response from a group of other variables. The model is built on few strong assumptions.

1. The value of Y which is the response variable, is a linear function of the X variables. This means:

a. When there is a change in the value of X_i by an amount of ΔXi, considering this change could be both positive and negative and holding all the other variables fixed, then the projected value of Y changes by a proportional amount $c_i \Delta X_i$. This c_i is a constant value that could be both positive and negative number.

b. The value of c_i is always the same, regardless of values of the other X's.

c. If we calculate the separate effects of the X's on the response value Y, and sum these effects then it would be the same of the total effect of the X's on the response value of Y.

2. There could be some unexplained variations of Y which are independent random variables. The equation for Y is modeled based on the provided relationship with Y and X's.

3. They are normally distributed.

Nevertheless these assumptions will never be exactly justified in the real world experiment. The values from real world experiment are not ideal so there will be variation. The regression model constructs very well-built assumptions about the way in which Y depends on the X's. It can be said that the causal or predictive effects of the X's with respect to Y are linear and additive and non-interactive and that any variations in Y that are not explained by the X's are statistically independent of each other and identically normally distributed under all conditions.

However, here linear regression analysis with two way interactions has been used. It considers all the possible interactions between all the parameters. Stepwise regression method has been deployed which is used in the probing stages of model building to find out a useful subset of factors. The process step by step adds the most significant variable or the combination of the variables and removes the least significant variable or the combination of the variables.

6. RESEARCH METHOD

In this section, the few vital parts of research method, for example parameter and response selection and every tiny detail of the experiment are described. This part summaries the whole experiment part, from planning to the very end of this work.

6.1 Parameter and Response Selection

Parameter selection is one of the important issues before starting anything. This work entirely focuses on Ethernet switch behavior and goal was to include those parameters that can have major effect. Rondeau and Lepage did similar experiments with switch and mention few parameters [23]. In [7], it is explained that there is no impact of packet size on the power consumption. Because of that packet size is not considered as parameter. As discussed earlier for conducting the experiment we have initially considered three parameters, bandwidth or link capacity, number of PC connected to the switch and link load on the switch. For full factorial model, however, only two factors bandwidth and number of connected pc have been considered. Link load has not been considered because initial experiment shows that link load has rather less impact on power consumption compare to other two variables. For a fixed value of bandwidth and number of pc connected regardless the load of the link power consumption does not vary much. Therefore, link load is neglected for reducing the complexity of the model. On the other hand for linear regression analysis all three variables are used. IEEE introduced IEEE802.3az energy efficiency Ethernet protocol. In [3] Christensen et. al. discusses about power management protocols and it considered traffic in their protocol. Therefore in our model link load is introduced. Basically link load is nothing but traffic load in each port. This is introduced considering the future aspects which are controlling the power consumption of switch and also check the effect of idle mode. The target was to review Ethernet switch as a black box and observe its behavior in different scenario. Because of that we have only considered those parameters which are directly in relation with Ethernet switch. Now for bandwidth three different values have been used 10Mbps, 100Mbps and 1000Mbps.

As Ethernet switch has 24 link ports. Therefore number of active connections are varied from 2,4,6,8,10,12,14,16,18,20,22,and 24 connections to cover the whole range.

Link load can be expressed by following equation:

Link load = Total incoming traffic/ (Active link* link capacity) %

Different link load value is used by varying traffic. The goal of this work is to provide a power consumption model of an Ethernet switch so it can be used to recognize the pattern of consuming power and control the power consumption later on.

For the experiment only one response is measured which is power consumption in watt. Power consumption is measured for different combination of bandwidth and number of pc and link load.

6.2 Experiment Detail

The experiment was done using the architecture of figure.3. A CISCO Ethernet Switch 2960x is used for the experiment. Architecture was designed in a way as every two PC is acted as a pair. One PC of the pair is sending data and another one receiving data. In this experiment, Powerspy2 sensor is used to measure the power consumption of the monitored switch. Powerspy2 is an energy analyzer (reference: powerspy2 user manual). The data of power consumption is sent in real-time via Bluetooth (see the appendix 1). The necessary information such minimum, maximum, standard deviation, and average value of power consumption can be obtained by powerspy2.It provides a precision of three digits after decimal. All the links used same configuration for link capacity (Bandwidth). That means there for every experiment there was only one kind of link capacity. JPerf is used for traffic generator (see the appendix 2). Jperf is a network tool that is built to monitor the performance of the network. Different variation of traffic is generated which provides us various link load to observe the Ethernet switch behavior. Variation of traffic is done by changing maximum segment size and window size. Maximum segment size varies between 256,512 and 1518 bytes. And window size varies from 1 to 123 kilobytes. Each experiment is run for 10 minutes in order to observe a stable and steady value.

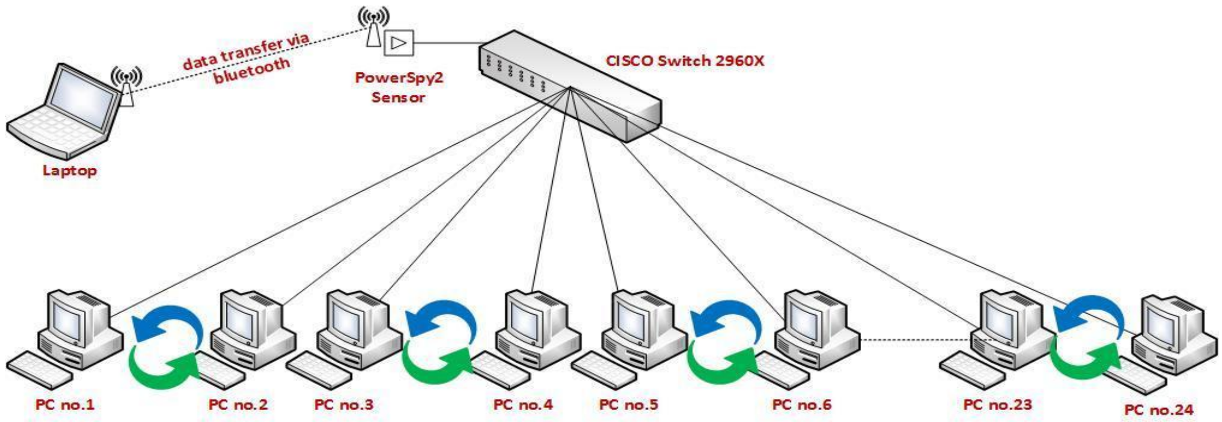

Figure 3: Network Architecture

The 0 connection-scenario is omitted because it is practically impossible for a network to have no connections. At least, the network should consist of at least 2 PCs to communicate each other. Therefore the scenario starts with 2 PCs and then increase up to 24 PCs to occupy all the Ethernet switch ports. The experiment is conducted considering the most common TCP protocol.TCP is the basic communication protocol for the both internet and intranet.

The experiment has two parts. One is done for normal mode and another is done for hibernation mode. This CISCO Ethernet Switch 2960x is designed with hibernation mode. In hibernation mode, the switch powers off the CPU cores, application-specific integrated circuit (ASIC), and connected Power over Ethernet (PoE) devices. Therefore it saves power by switching off most of the hardware components in the data path. Therefore when the switch is powered on again, the whole switch is reloaded. This switch can be put in to hibernation mode in two ways. One is by scheduling and another one is by using the command line interface at the switch. However for powering on the switch power on button is needed to be pressed if there is no scheduling is done. It is known that in hibernation mode there will be no traffic that means link load will be null. Therefore the idea was to find out if there any pattern of power consumption during hibernation mode without traffic. In hibernation mode two control variables is considered. One is number of connected pc and another one is the bandwidth. In hibernation mode the power goes to a low rate than the switched on mode. However the goal was to see if there is any effect of these variables on the power consumption during hibernation mode.

7. RESULT AND ANALYSIS

In this section, at first initial insight from the raw data has been discussed. The data pattern is discussed without any model has been applied. Then a discussion of the results of our statistical design of experiment, along with an analysis of these results has been made. Visual illustration regarding the impact of the factors on the power consumption is provided.

7.1 Initial result

As discussed earlier two rounds of experiments has been conducted. Figure.4 shows the power consumption pattern of the Ethernet switch when there is three variables are involved. To show the combined effect of link load, bandwidth and number of connected pc, link load has been used in the x-axis. For a fixed number of pc and bandwidth, link load is increased by increasing traffic. In the graph, we can see there are three chunks of data in the plot plane. These three chucks represent the variability of the link load. Three colors denote three different bandwidths. As it is seen that, without using any analyzing tool, it can be said that 1000mbps bandwidth has larger impact on compare to other two bandwidths in concern of power consumption. Whereas 10mbps and 100mbps has more or less similar effect on the power consumption. One more thing is clearly visible is that changing the link load has clearly very little impact on the power consumption as all three chunks looks almost the same despite of different traffic load.

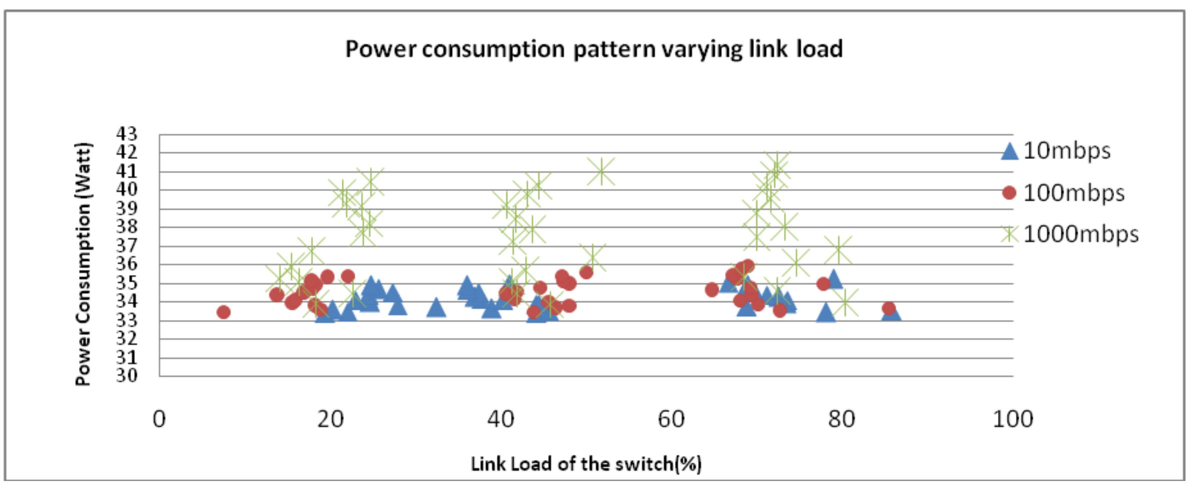

Figure 4: Power consumption pattern varying link load

Figure 5 shows a more detail and comparative result between three levels of bandwidths. In the x-axis there is number of connected PC and in the y-axis there is power consumption. For same number of connected pc three different bandwidths is shown. This graph denotes two important information. Firstly it can be said that for every bandwidth whenever there is an increase in the number of connected PC, the power consumption is also increased. And secondly in context of power consumption 1000mbps is more responsible for consuming power than 10mbps and 100mbps.

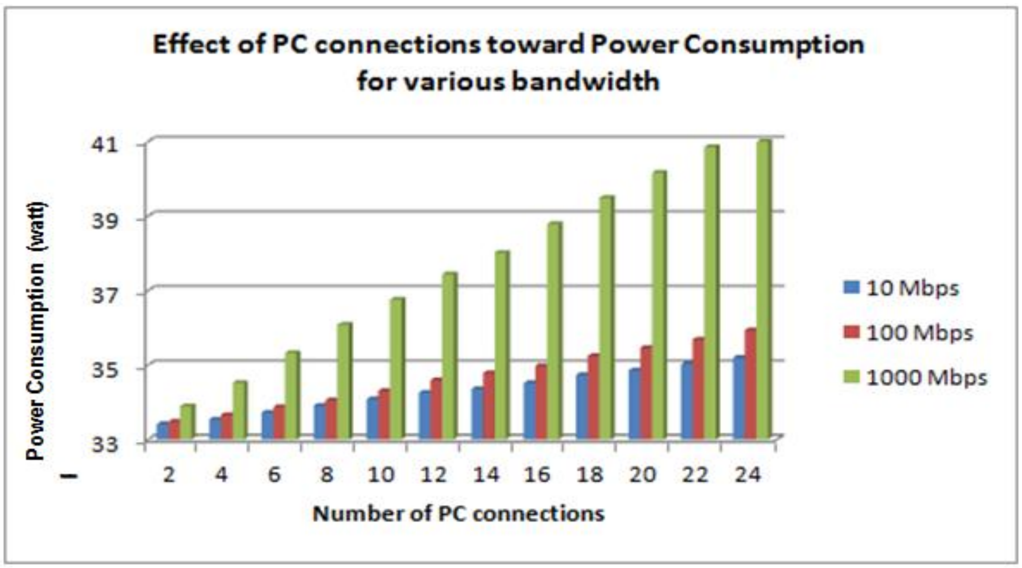

Figure 5: Effects of Number of Connected PC for various bandwidths on power consumption

Figure-6 shows the effect of link load on power consumption for different bandwidth. For this graph a fixed number of connected PC is chosen that is 14. Now for these 14 PCs different bandwidths are used. And for different bandwidths different rate of link load is provided in order to observe the change in the power consumption. This graph provides a clear idea about how much effect does actually have in power consumption. As it can be seen that for a fixed bandwidth even if the link load is changed in three different levels the power consumption does not change much.

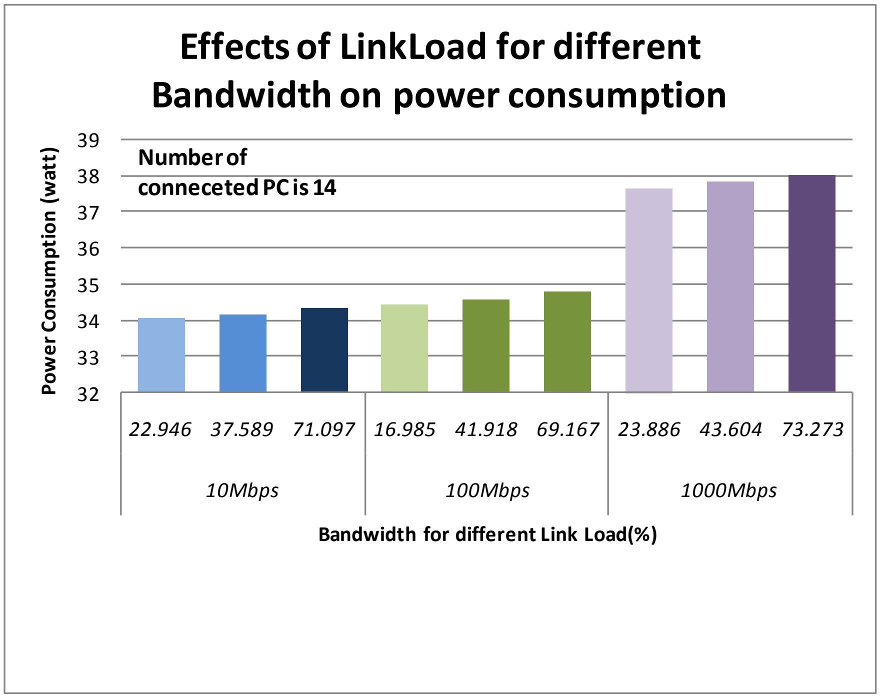

Figure 6: Effects of link load for Different Bandwidth on power consumption

The second part of the experiment is to see the effect of hibernation. For different number of connected pc we have the power consumption values. Therefore in figure-3 combines two parts of the experiment and shows together the result. Three different colors is for three different bandwidth. Number of connected pc is from 0 to 24 which is the total capacity of the switch. Here it is seen that there is an astonishing difference between on mode and hibernation when comes to the power consumption. During hibernation the power consumes right in the range of 19 to 21 watt regardless of the bandwidth. However when the switch is on, power consumption goes up high.

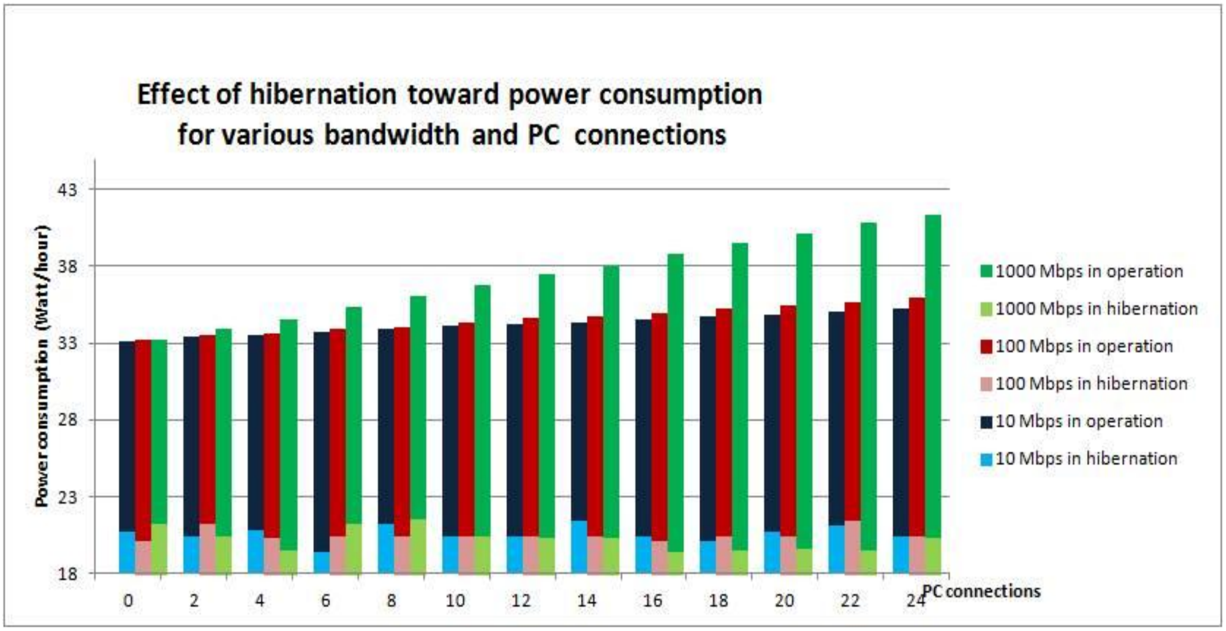

Figure 7: Effect of hibernation mode on power consumption

7.2 Analysis by Modeling

In this section result analysis are described. For two different methods data are analyzed and model for power consumption is proposed. At first the full factorial model is presented with explanation of f-value and p-value. Minitab has been used to do the modeling. Before going to further detail there are two terms that are needed to know. One is null hypothesis another is alternative hypothesis. The null hypothesis means that there will be no observed effect during the experiment. And alternative hypothesis will come to the act when null hypothesis is rejected. In our experiment null hypothesis is these factors do not have any effect on the response variable. If we can reject the null hypothesis then it will prove that these have some effects on the response variable. Hence it is possible to draw some equation based on these factors. F-value and P-value are used to reject the null hypothesis. F-value is a ratio of mean squares. The numerator is the mean square for the parameter. The denominator is chosen in a way that the expected value of the numerator mean square differs from the expected value of the denominator mean square. But this difference is caused only by the effect of variable. A high f-value most of the case is an indication of rejection of null hypothesis. That means there is a significant effect of that variable on that model. The p-value for each term tests the null hypothesis that the coefficient is equal to zero (no effect). A low p-value (< 0.05) indicates that it can reject the null hypothesis. In other words, a variable that has a low p-value is likely to be an important adding to the model because changes in the variables value are related to changes in the response variable. Conversely, a larger p-value suggests that that variable is insignificant for the model and changes in the variable values are not related with changes in the response. For all the equation confidence interval was 95% and significance level was .05. Residual plots also have been used in order to check the validity of the equation. A residual plot is a graph that is used to examine the goodness-of-fit in regression and analysis of variance. Examining residual plots helps you determine whether the ordinary least squares assumptions are being met. Two kind of residual plot has been used to justify the model for both full factorial and linear regression when switch is on operation mode. The first one is Normal probability plot of residuals. Normal plot of residuals is used to verify the assumption that the residuals are normally distributed. And the second graph is histogram of the residuals. This histogram is used to determine where the data is skewed or not. More the values are in 0.0 more it will emphasize the normality assumption. All the models are justified by its adjusted R-squared (R-sq) value. In a broader sense R-sq is the proportion of all the variation in the response variable that is being explained by the model. If the number of variables compare to total number of experiments is low then higher R-sq value means the model is well designed. However it is better to use adjusted R-sq value which is adjusted according to the number of used variable on the model.

7.2.1 Switch on Operation mode

Full Factorial

Full factorial method generates a model for power consumption of Ethernet switch based on number of pc connected and bandwidth or link capacity. Figure-8 is the normal probability plot of residual where response is power. This graph is used for checking the assumption of normality of error terms. In this case it can be seen that most of the points are clustered around red line except one or two. This is an indication that the error terms are approximately normal.

Figure-9 is the histogram of the residual. Maximum value is near to the 0.0 shows that it also follows the normality assumption. That means there is not any data that is unexplained.

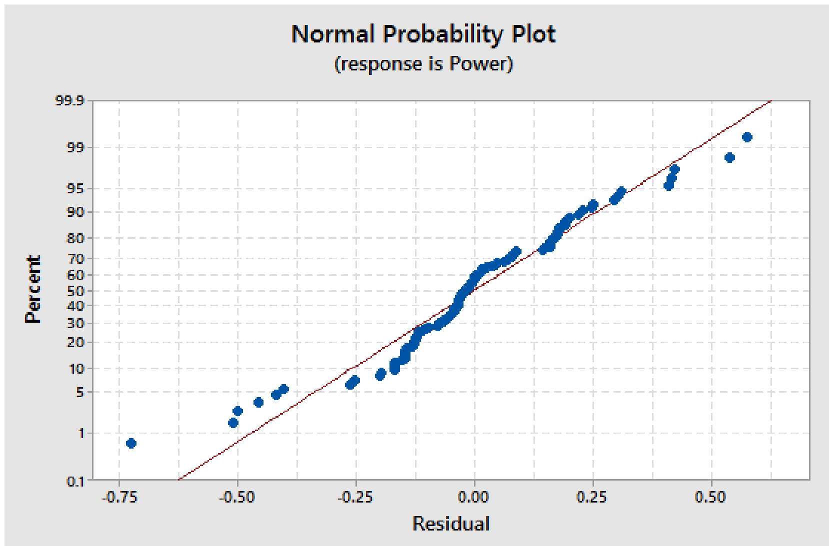

Figure 8: Normal Probability of residual (Full Factorial)

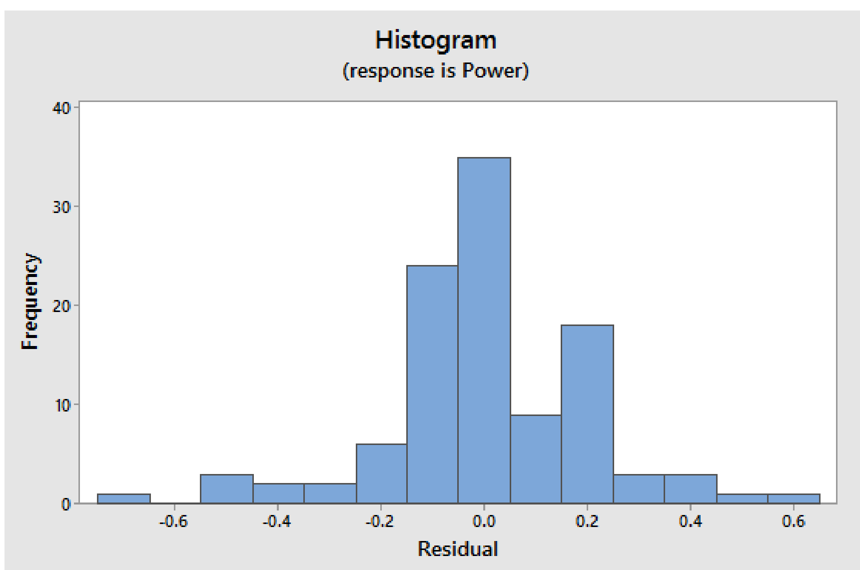

Figure 9: Histogram for Residual (Full Factorial)

Figure-10 shows the main factors effect on the power consumption. As it can be seen for bandwidth (link capacity) there is a really high impact when the bandwidth is 1000Mbps. However change of power consumption between 10 Mbps to 100Mbps is not so much. On the other hand number of PC shows a rather linear relation with the power consumption. As the number of connected pc's are increased the power consumption is also increased. We include 2-way interaction while modeling. It means all the variables combined effect is also are considered. In this case 2-way interaction would be bandwidth* pc. This model includes bandwidth* pc in order to get more precise result.

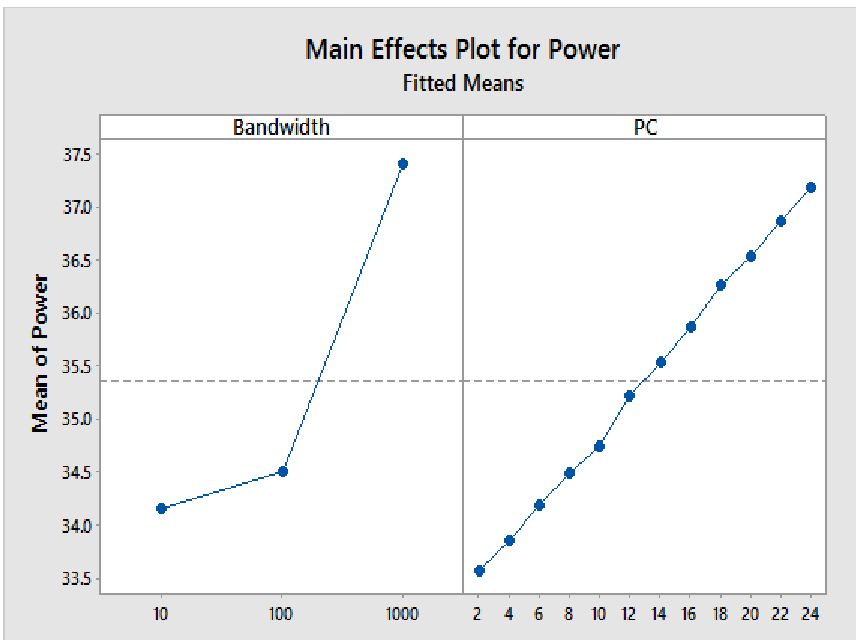

Figure 10: Main effect for power (Full factorial)

Figure-11 depicts the 2-way interaction of pc and bandwidth. From the graph it can be conclude that from the interaction variable bandwidth*pc is also work same way as main variable. When the band width is 10 mbps or even 100 mbps the power consumption is not as high as 1000mbps.

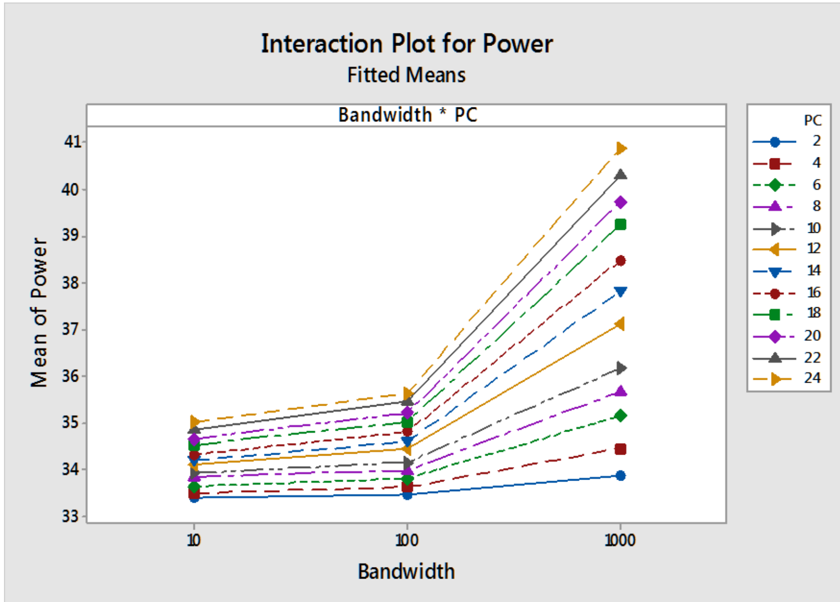

Figure 11: Interaction effect for power (Full Factorial)

Table.1. shows the f-value and p-value of the variables and which shows that bandwidth has highest significance. P-value shows that all variable is significant for calculating power consumption. The model has a R-sq adjusted value of 98.53%. It means 98.53% of the time the variation in response variable is caused by these factors.

Source	F-Value	P-Value
Bandwidth (Mbps)	1875.86	0.000
PC	215.39	0.000
Bandwidth (Mbps)*PC	50.15	0.000

Table 1: F-value and P-value of factors (Full factorial method)

The model provides a rather long equation which considers all the possible 2-way interaction. Considering {x1,x2,x3} are the different link capacities as {10Mbps, 100Mbps and 1000Mbps} and {y1,y2,y3…,y12} are the pairs of connected pc as {2,4,6,…,12} then the equation looks like this:

Power (watt) = 35.3642 - 1.2012 x1- 0.8470 x2+ 2.0482 x3- 1.7822 y1 - 1.5109 y2 - 1.1661 y3 - 0.8681 y4 - 0.6156 y5- 0.1439 y6 + 0.1726 y7 + 0.5044 y8 + 0.9022 y9+ 1.1731 y10 + 1.5119 y11+ 1.8226 y12+ 1.017 (x1*y1) + 0.839 (x1*y2)+ 0.638 (x1*y3) + 0.539 (x1*y4) + 0.371 (x1*y5)+ 0.085 (x1*y6) - 0.145 (x1*y7) - 0.347 (x1*y8)- 0.538 (x1*y9) - 0.674 (x1*y10) - 0.821 (x1*y11)- 0.964 (x1*y12) + 0.731 (x2*y1) + 0.615 (x2*y2)+ 0.459 (x2*y3) + 0.335 (x2*y4)+ 0.247 (x2*y5) + 0.061 (x2*y6) - 0.092 (x2*y7) - 0.218 (x2*y8)- 0.394 (x2*y9) - 0.477 (x2*y10) - 0.569 (x2*y11) - 0.698 (x2*y12) - 1.748 (x3*y1) - 1.453 (x3*y2) - 1.098 (x3*y3) - 0.874 (x3*y4)- 0.619 (x3*y5)- 0.146 (x3*y6) + 0.237 (x3*y7) + 0.566 (x3*y8)+ 0.931 (x3*y9) + 1.151 (x3*y10) + 1.390 (x3*y11) + 1.662 (x3*y12)

Here from the co-efficient value it can be said that all the terms as significant impact on calculating the power consumption. Here all the possible terms are shown. However on a given switch there cannot be different number of pc connected at the same time.

So a general formula can be deployed because for a given scenario only four terms from the equation will be used.

Power (watt) = 35.3642 + αX + βY + γ(X*Y)

Where X is bandwidth, Y is number of active PC connected and α, β, γ are the co-efficient of the variables although allocation of different bandwidth is possible for different ports. Then the number of variable will be increased.

Linear Regression Analysis:

After doing full factorial multiple linear regressions analysis is done. As discussed earlier here link load is also used as a variable. Figure -12 and Figure-13 shows the residual graph of the model. Both normal probability plot and the histogram show that the error terms are approximately normal. Thus our assumption of normality is valid. In other words it means that most of the value can be explained through our model.

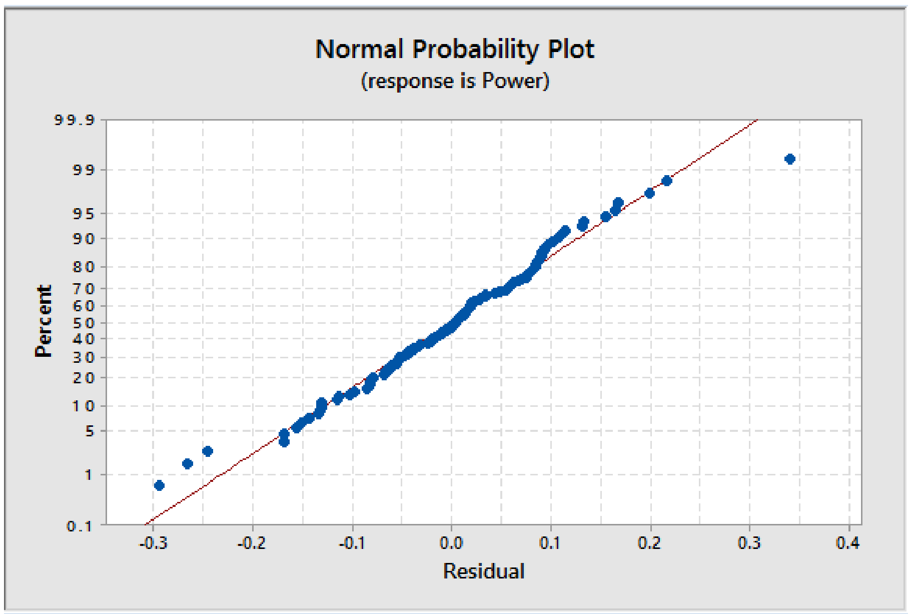

Figure 12: Normal probability of residual (Linear regression)

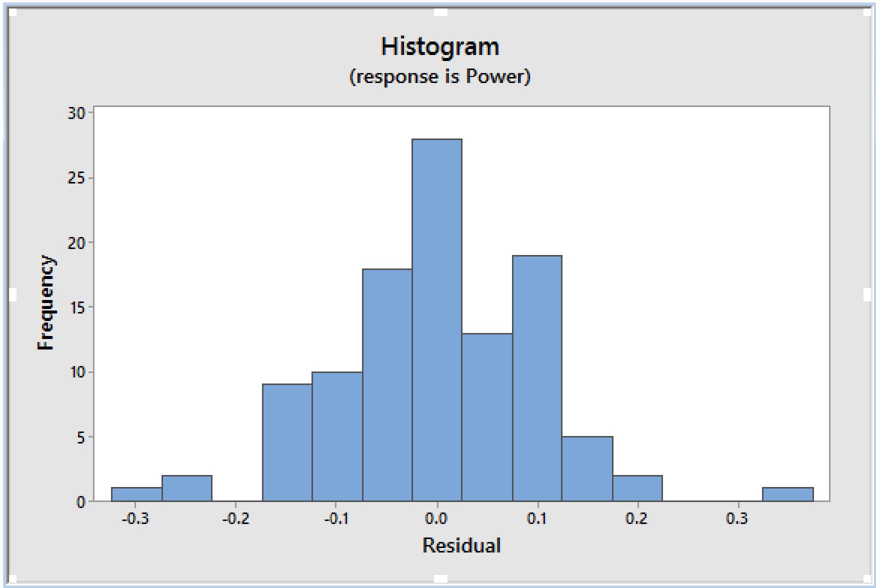

Figure 13: Histogram for Residual (Linear regression)

Figure-14 shows the main effects of the variable on the power consumption. And which indicates that, all three variables rather has a linear relation. From the graph it can be concluded that link load has rather less impact compare to other two variables namely bandwidth and number of connected pc. For a fixed bandwidth and number of pc connected, link load does not have that much impact on power. As multiple regressions analysis is used so it also considers the 2-way interaction. And in the equation only significant variables are shown.

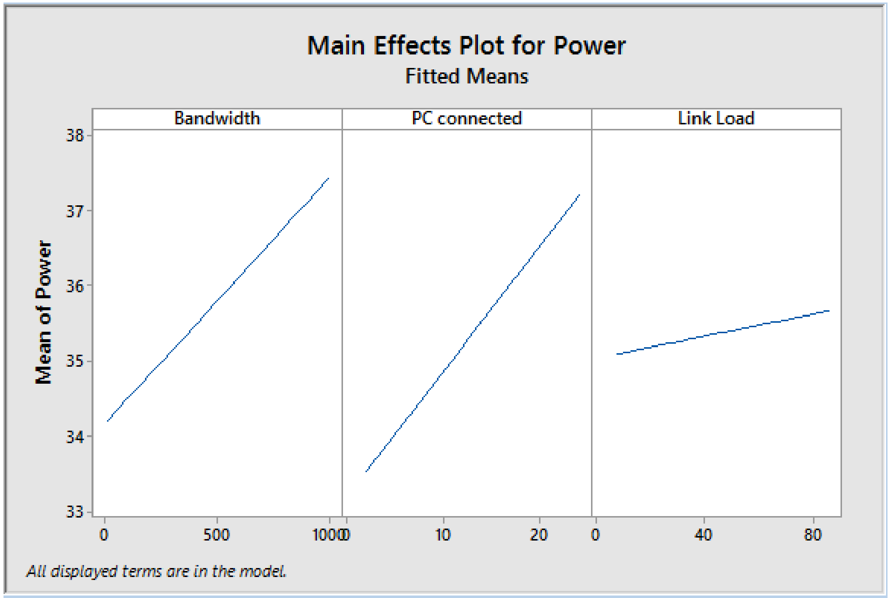

Figure 14: Main effect for power (Regression analysis)

Table.2 shows the F-value and P-value and which shows that pc has rather high F-value compare to bandwidth and link load. It is due to the nature of the value of the variable. All the P-value is indicating that all three terms were important for the equation.

Source	P-Value	F-Value
Link Load	0.177	1.85
Bandwidth (MBPS)	0.000	23.00
PC	0.000	216.09
Bandwidth (MBPS)*PC	0.000	6218.91
Link Load* PC	0.000	53.99
Bandwidth(MBPS)*Link Load	0.000	38.96

Table 2: F-value and P-value of factors (linear regression analysis)

Model has a R-sq adjusted value of 99.61%which indicates that whenever there is a variation in the value of y, 99.61% of it is due to the model (or due to change in x) and only 0.39% is due error or some unexplained factor.

Linear Regression Equation:

Power (Watt) = 33.2708 - 0.000318Bandwidth +0.05156 PC-0.001329LinkLoad +0.000253 Bandwidth*PC + 0.000006Bandwidth*LinkLoad +0.000477 PC*LinkLoad

This equation provides power as output considering three input parameters.

The linear regression equation is comparatively simpler than the equation that we got from full factorial analysis. Full factorial model used two parameters on the other hand linear regression analysis model used three parameters. However from the co-efficient of linear regression model it can be seen that link load has one of the lowest co-efficient values.

Figure-15 and 16 shows the contour plot of power consumption. Where one variable is fixed and other two are in x-axis and y-axis. In the figure-15, A fixed value of link load is used which is 45%. Number of pc's were in the in the y-axis and bandwidth is in the x-axis. Different color is showing the different range of power consumption. And as it can be seen that with increasing of bandwidth and number of PC's power consumption is also increased. And even with 24 connections when there is a bandwidth of 10 or 100Mbps the maximum power consumption is 36 watt. For 1000Mbps, it takes only 10 pc's to get in that range.

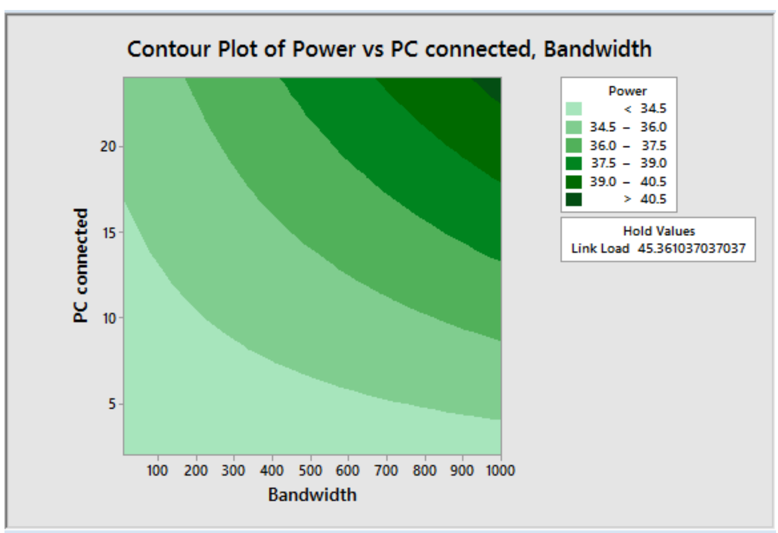

Figure 15: Contour plot of power vs pc, Bandwidth

In the figure 16, Number of connected pc were fixed. Here number of pc's were 24. And it clearly displayed that 10 mbps and 100 mbps is still in the 35-36 watt zone where 1000 pc starts directly from 37-38 watt zone.

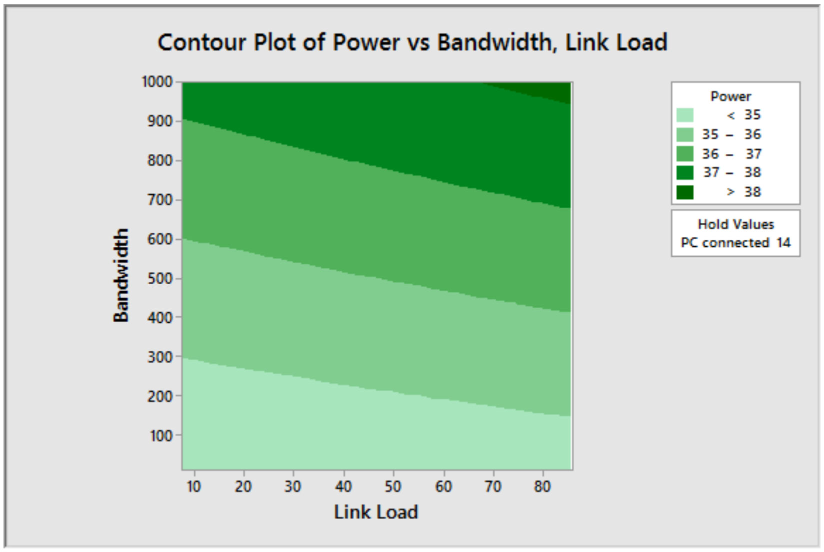

Figure 16: Contour plot of power vs Bandwidth, Link load

In the validation part a comparison between both full factorial model and regression analysis model is given.

7.2.2 Switch on Hibernation Mode

Now the analysis is done on based of the power consumption during hibernation mode. Though it is clear that hibernation decrease a large amount of power consumption compare to when switch is in operation mode. However the effect of bandwidth and number of pc connected during the hibernation period is not clear. Therefore full factorial analysis is done on the power consumption during hibernation where control variables where number of pc connected and bandwidth and response variable is same as previous power consumption.

Figure-17 shows the effect of main variables. And it can be said that there is no actual pattern in the result. That means when the switch is in hibernation mode both bandwidth and number of connected do not have any sort of impact on the power consumption. Even though the Bandwidth curve looks slightly downwards, as the bandwidth increase the mean power decreases. However if we actually see the value wise difference from 10mbps to 1000mbps the mean power of difference is only 0.4 watt. And it is clearly visible that there is no pattern whatsoever with the number of connected pc. Power ranges about 1 watt for whole range 24 pc.

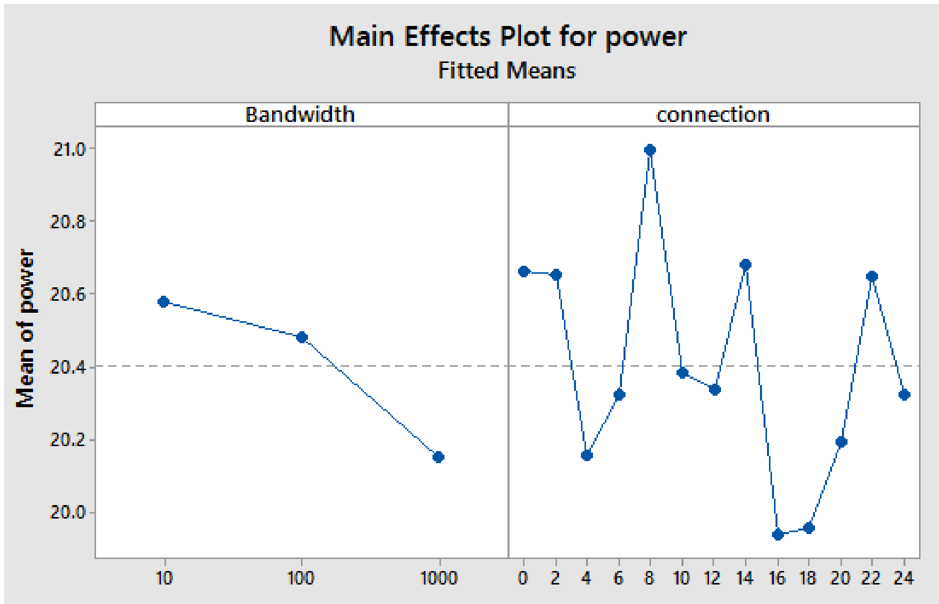

Figure 17: Main Effect plot for power during hibernation

The model automatically discards any interaction factor. There was no conclusive result that will show that bandwidth and number of link had any relation during hibernation mode. The table-3 also shows the F-value and P-value and it is explained earlier both f-value and p-value failed to reject the null hypothesis. Which means that, these two factors does not have any strong impact when the switch is in hibernation mode.

Source	F-Value	P-Value
Bandwidth (Mbps)	1.87	0.175
PC	0.84	0.610

Table 3: F-value and P-value in hibernation mode (Full Factorial)

Equation for power during hibernation mode:

Power (watt) = 20.4038 + 0.175 Bandwidth_10 + 0.076 Bandwidth_100 - 0.251 Bandwidth_1000 + 0.257 connection_0 + 0.250 connection_2 - 0.249 connection_4 - 0.079 connection_6+ 0.593 connection_8 - 0.022 connection_10 - 0.066 connection_12 + 0.276 connection_14 - 0.468 connection_16 - 0.446 connection_18 - 0.210 connection_20 + 0.245 connection_22 - 0.082 connection_24

So a general formula can be deployed because for a given scenario only three terms from the equation will be used.

Power (watt) = 20.4038 + αX + βY

Where X is bandwidth, Y is number of active PC connected and α, β are the co-efficient of the variables. Allocation of different bandwidth is possible for different ports. Then the number of variable will be increased. However the model has a R-sq value of 36% which explains that these factors has no effect what so ever in power consumption during hibernation period. So it can be said that, hibernation reduce the power consumption to a certain level however during the hibernation mode the power consumption is always same regardless of the link capacity and number of link connected.

7.3 VALIDATION OF MODELS

To check the validity of these two different models, predicted values from these models are obtained and then compared with real measured values. Random scenario is chosen in order to validate the model. Figure.18 shows the result of one scenario where bandwidth is fixed with

100 Mbps and a random link load value is chosen. And as we can see the measured value and the predicted value from the model is close to each other. In this case average percentage error for full factorial is .1% and for regression analysis is .09%. In the figure.19 a different scenario has been used. Here, number of connected pc was fixed. Here for this scenario 10 pc is used. For different bandwidth all the power consumption data is plotted with different link load. As we can see full factorial model provides a straight line for each different bandwidth it is because link load is not a parameter for the full factorial. However one important thing to notice that link load does not put a much impact on the result. Power consumption difference is always less than 1 Watt for maximum and minimum value of link load in any given scenarios. On the other hand regression analysis shows three different plot points for three different values of link load. Average percentage error for full factorial is .5% and linear regression analysis is .29% for this scenario.

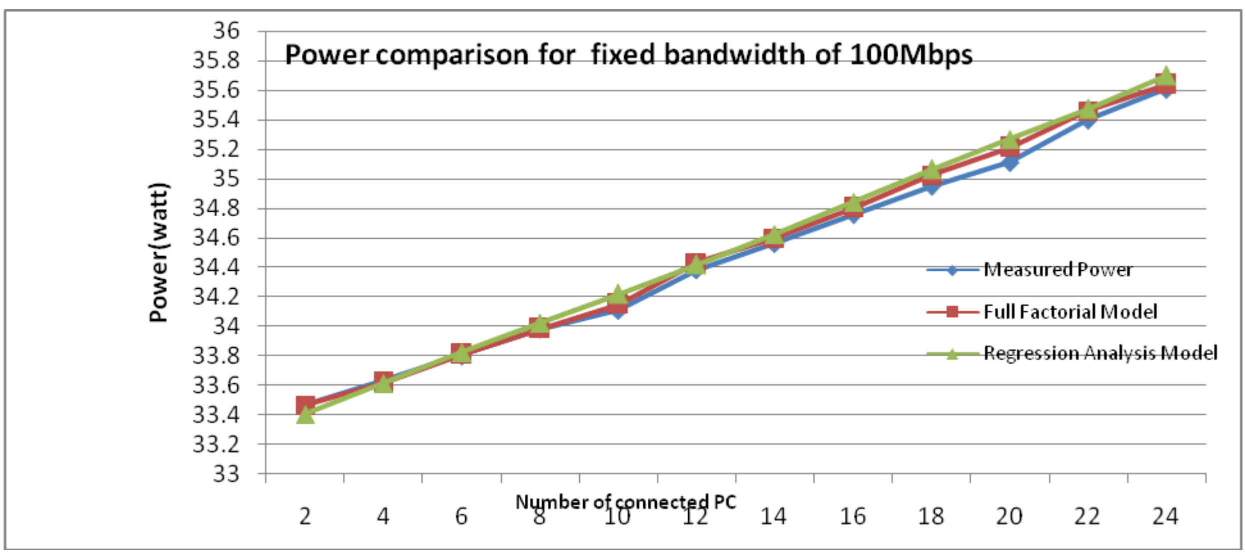

Figure 18: Power consumption comparison for fixed bandwidth of 100Mbps

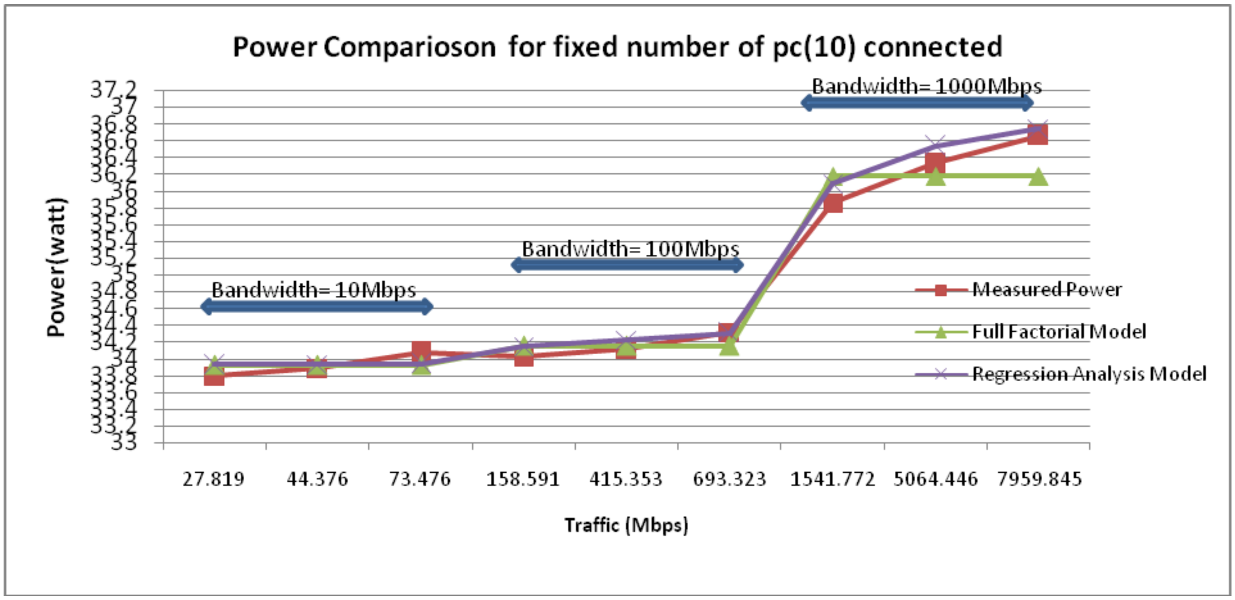

Figure 19: Power consumption comparison with change of link load where number of connected pc is fixed

By comparing the two equations provided by two different models, it can be observed that, for full factorial the model is rather complex where each combination has different co-efficient even though all of them are not used simultaneously. However, in regression analysis model, the equation is rather simple. But on the other hand due to complexity of the full factorial equation it is more versatile than the equation provided by regression analysis. Furthermore, a full factorial model provides a rather mean value of the power consumption for a given scenario. However, a regression analysis provides different value for different link load. For example, in figure.6 when bandwidth and link load are high, full factorial is providing a result which is little bit not accurate. However as mentioned earlier, the difference between values is never more than 1 watt.

8. DISCUSSION

With the advancement of computer networks communication rate has been increased abruptly. This also results more power consumption. In the subsection *green network strategies* few techniques have been discussed for lowering the power consumption. Zouaoui, Labit and Albea(2014) also explained some new method like dynamic adaptation and smart sleeping that are in the pipeline. If the Ethernet switch behavior is explainable then the controlling will be more efficient. To keep this in mind, this thesis work's goal was to provide a model that can define power consumption pattern. Here a model for power consumption of Ethernet switch has been provided based on different parameters. Ethernet switch is only a small part of the whole network. The term green networking means greening of whole network architecture. It focuses on environment and as well as methods are needed to be cost-efficient. To put an effective impact on the environment through ICT, it is needed to know the power consumption of the whole global network architecture. This work is another effort towards this target. Although according to Bianzino et al. (2010), in a year, the maximum amount of power is consumed by Ethernet switch compare to any other networking device. Nevertheless, there are several devices like wifi hot-spot, and router that is needed to be considered in order to get the global architecture. Moreover, experiments are done in only one Ethernet switch. Result may vary for different switches. These things are needed to be considering for future. From this work few remarks has been made. They are described below.

Measuring the power consumption and carbon footprint of a cluster of switch:

This work provides a model which is capable of measuring the power consumption of an Ethernet switch depending on its bandwidth and number of connected links and link load even though according to our analysis amount of link load is not an issue. However a huge part of network infrastructure is built by connecting several switches in other words cluster of switch. There are several network infrastructures of companies that are based on Ethernet switches. Now in this model power consumption of a single switch is measured. Therefore, in a cluster of switches if all the switch are considered as a unit and power consumption is measured separately then the total power consumption of that switch cluster can be measured. As in the equation number of connected link is considered as a parameter so one switch can be connected with another switch and will be considered as single link for each switch. Here only the number of active link is mattered. So, if there are some numbers of switches inter-connected to build the network infrastructure of a company then the overall power consumption can be measured just by summing up the individual switch's power consumption. For example, let us consider a small business where network infrastructure is build with four switches. They alone consume p_1, $p_{2,}$ $p_{3,}$ p_4 Power respectively. Then the total amount of power, P consumes by the infrastructure would be: $\mathbf{P = p_1 + p_{2+} p_{3+} p_4}$

Therefore, in a cluster of switches, if n is the number of switch and p is the individual amount of power consumption then total power consumption,

$$\mathbf{P} = \sum_{k=1}^{n} p^k$$

Now, if same sort of work can be done for routers then it is possible to measure the power consumption of whole wired network infrastructure.

Moreover Rondeau et al. (2015) mentioned the correlation between the power consumption and carbon emission on the book. Therefore with help of these models another model can be created to calculate the carbon footprint produced by Ethernet switch. With proper development of a global model for overall network architecture of the power consumption it is therefore possible to reduce or at least control the global carbon footprint caused by networking devices.

Hibernation vs. Poweroff - which one is better:

This work consists of a part analyzing the power consumption pattern of the Ethernet switch during hibernation period. From that part it can be easily conclude that hibernation reduce the power consumption to a great level. Certainly a lot compare to when the switch is in active mode. However there is always a question may arise that hibernation reduce the power consumption no doubt but it does consume power then why not just power off the switch which will consume no energy at all. Therefore here are some points for explaining the situation.

Quality of Service:

Table-4 shows a comparison between power off and hibernation mode. It can be seen that both hibernation and power off take ample amount of time to get start and ready to send the data. However hibernation mode is 30 second faster than the power off in both cases.

Mode	Time to wake up (get a stable power)	Time to get ready to send a data
Switch in Hibernation mode	240 seconds	260 seconds
Switch Power off	270 seconds	290 seconds

Table 4: Comparison between switch off and hibernation

The time difference between power off and hibernation is not so much. 30 seconds can be critical for few cases. However for office works and other companies where the work is not time constrained 30 seconds will not have that impact.

Hardware reliability:

Frequent power on and power off can cause extra load that will ultimately can reduce the life span of a computer network device. Disk drives are particularly vulnerable in this sort of situation. On the other hand, if the device is on all the time then it will become heated and high temperature also greatly reduces the lifetime of network equipment. Therefore keeping the device always on is also not a good choice.

Convenience:

Hibernation mode can be scheduled Using command line interface of the switch. By scheduling one can put a switch in hibernation mode and it will automatically be on at predefined time. On the other hand switch cannot be power on and off automatically by scheduling. However by using rack power distribution units (PDUs) it can be done. There are companies like Raritan, they manufacture intelligent rack PDUs that can be used for both distribution of power and also metering the power.

In the end it can be said that the effect of hibernation compare to power-off of the switch does not show that much potential. Because when a switch is powered off it consumes nothing however switch in hibernation mode still consumes 20 watt. Hibernation saves 30 seconds than power-off however for a company if the power on time of the switch schedules 10 minutes before the actual office time then these 30 seconds will not have any impact. And the automatic power-on can be done by PDU which is actually same as scheduling. The only point that remains is the longevity of the hardware. A longevity test is needed to run in order to find out the longevity difference between a switch which is frequently turned on and turned off and a switch which is frequently hibernated.

Adaptive Link Rate is smart choice:

From our experiment is it clear that bandwidth is one of the main parameter which has impact on power consumption. Adaptive link rate is therefore is very effective regarding reducing power consumption. As we have discussed earlier that energy efficient Ethernet is already enabled in new model of switch. According to Miercom Lab testing report (2013) EEE saves considerable amount of power compare to normal mode. However EEE does not modify the link rate rather it sends the link to low power idle state. Where there is no traffic except some pulse signal to keep the link alive. However as we have discovered from the experiment that link load hence traffic has really less impact on the power consumption. Therefore if ALR can be implemented on top of EEE then more power can be saved.

There are many cases where adaptive link rate can be very effective. Every office has its peak hour and off peak hour. In peak hour they have maximum amount of traffic in the network. However during off-peak hour the traffic rate is low. For example, according to the experiment, one switch can save up to 5 watt of power in a hour just by reducing the link rate from 1000mbps to 100mbps. But there is one thing to notice that, the link rate should only be reduced when there is less traffic that can be handled by the reduced link rate. In the beginning the main problem of adaptive link rate was transition time. Blanquicet (2008) proposes some new technique which reduced the transition time but it is still not enough. More research is needed to be done in order to smoother and faster transition.

QoS and Green networking Tradeoff:

It is very hard to maintain quality of service and green networking at the same time. From the beginning the network system is designed on the basis of quality of service. Every network engineer's goal was to provide highest quality of service to the user. Green networking is a new research field. The motto of green networking is to reduce power consumption and carbon footprint. However every time a new protocol has been introduced it has to compete with the current available protocol which is giving best quality of service. It is not possible to reduce something without degradation. Therefore tradeoffs are needed to be made to achieve more sustainable eco friendly network system. For example, scheduling of hibernation mode can be done half an hour after office time and it will again start half hour before office starts. By this it will save power at the same time provide full service during office period. Adaptive link rate causes little delay for shifting from one link rate to another. This delay may reduce the quality of service. Therefore the better algorithm is needed to design which will exchange link rate without hampering quality of service.

Designing green network with maximum quality of service is difficult but not impossible. An optimum set point is needed to be chosen in order to cover both sides.

9. CONCLUSION

This thesis work presents a novel way to study the simultaneous effects of multiple variables on the power consumption of the Ethernet switch using Design of Experiment (DoE) method. Statistical analysis is conducted only with the test data and data is taken based on one switch. However the work that has been presented is not limited to the measurement of Ethernet switch. Two kind of model is presented here. And a comparison of both models is also discussed. Result helps to understand the effect of bandwidth or link capacity and number of connected pc on the Ethernet switch and link load over power consumption. The model provides an equation for measuring power consumption based on these variables. This equation can be used for calculating power consumption and hence carbon footprint of the switch. A separate set of experiments is also done on hibernation mode of the switch. This experiment shows that during hibernation mode bandwidth and number of connected has no strong impact over power consumption. The method for calculating power consumption for a switched network and a comparison between hibernation and power-off mode are also discussed. The goal of this work is to forward towards green networking and sustainability. A network architecture that will consume less power and at the same time it will be efficient and feasible. This thesis work is a small step towards that big goal. Findings of this thesis work can be used to find out the power consumption of the Ethernet switch and which eventually help to find out a way to reduce the power consumption.

However, there is a scope of several future works that can be done on basis of this thesis work. First of all, this work provides the power consumption model based on only one switch (CISCO 2960X model). Therefore same experiment can be done using different models of switch in order to validate the power consumption model. Secondly in this work communication was only between switch and PC. But in the real network it is rarely only switch to PC communication. Complex networks are built and there are several different sort of communication only from switch perspective for example switch to switch communication and also switch to other network devices like routers. During switch to switch communication energy efficient Ethernet (EEE) can be integrated in the model and effect of EEE can be observed. EEE can bring new perspective in this power consumption model which is yet to explore. Thirdly there is future scope for doing similar kind of experiment for other networking devices for example router, wireless access point and so on. As discussed earlier network architecture is combined of several switches, routers and access points. In the discussion section it is explained that how it is possible to measure the power consumption of a network with only switches. Therefore if it is possible to find out the power consumption equation for all the different element of the network separately, then by combining all the result it is possible to measure and ultimately control the overall power consumption of the whole network architecture on the basis of these parameters.

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Appendices

Appendix-1: Screenshot for powerSpy2

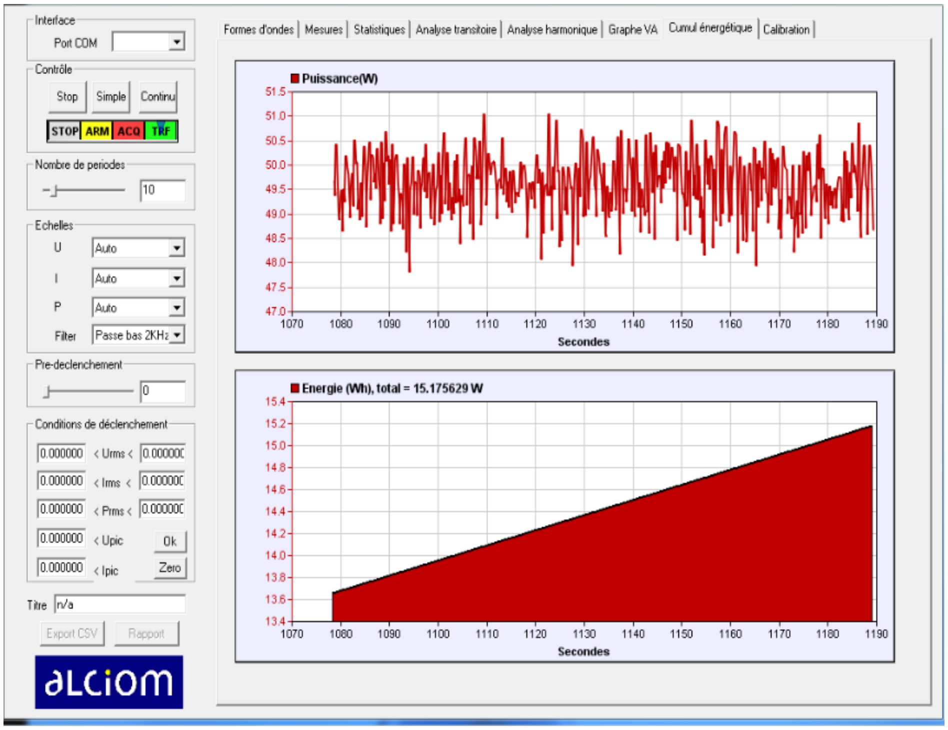

Figure 20: Live Power Reading

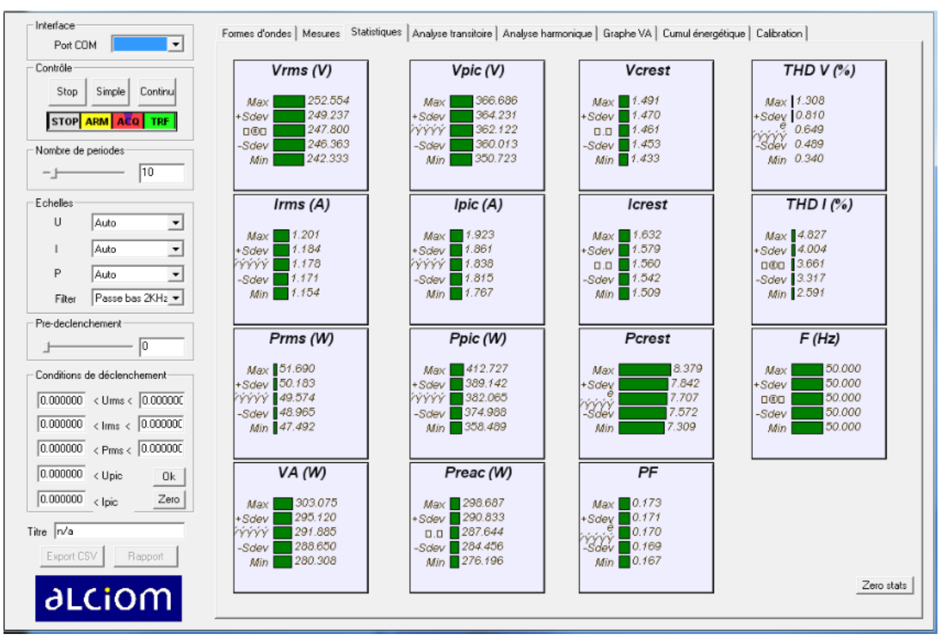

Figure 21: power reading with minimum maximum and average

Appendix-2: Screenshot for Jperf.

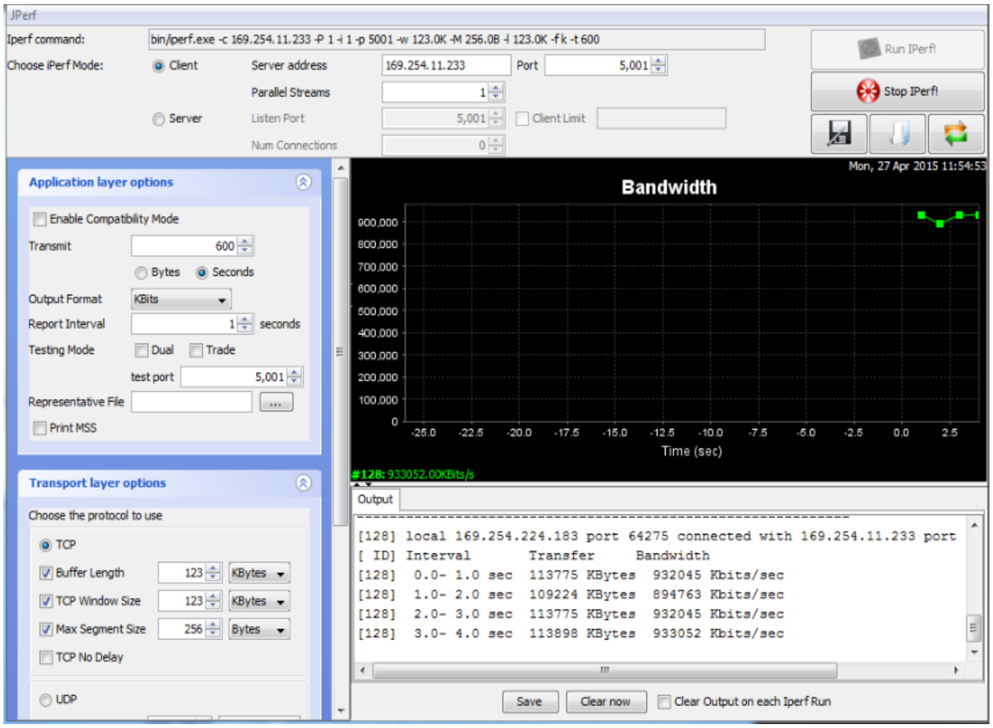

Figure 22: Client Side of the connection

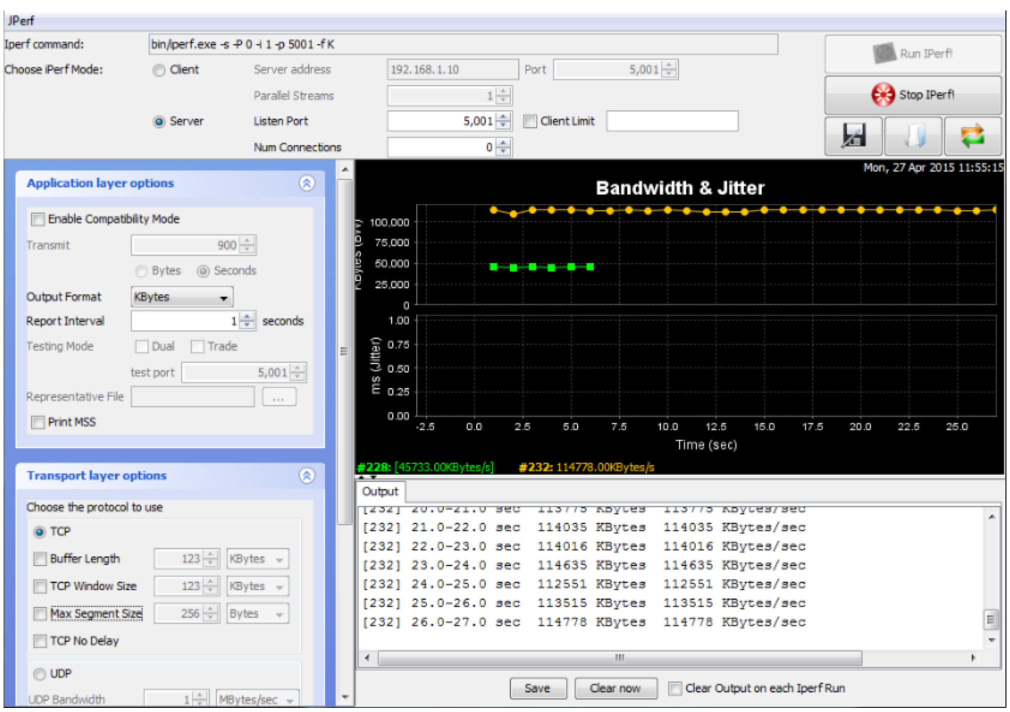

Figure 23: Server SIde of the connection