ENERGY EFFICIENT NETWORK TOPOLOGY AND ROUTING MANAGEMENT

(エネルギーの効率的なネットワークとトポロジとルーティング)

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A DISSERTATION
PRESENTED TO THE GRADUATE SCHOOL OF

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In candidacy for the Masters Degree

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Abstract

Energy consumption in network resources, such as router and switches, are increasing rapidly, due to the exploiding number of Internet users and network transmission speed. In the next 10 to 15 years the Internet will undergo a substantial increase especially with respect to the bandwidth required by end-users. Since the current Internet already consumes a not-negligible percentage of the total world electricity, It is obvious that reducing power consumption in the network is a crucial issue hereafter. This paper proposes a traffic management policy to reduce the energy consumption by the network devices.

Reducing energy consumption has been an important part of networking research, with th most prominent topics pertaining to the energy consumption of servers and wireless devices. Unfortunately, the energy consumption of wired networks has been traditionally overlooked. The Internet users have been increasing 28% every year. Real-time traffic reaches nearly 14Tbps, the power consumption of network equipments has been extremely increasing. In 2008, the ICT power consumption grew 168GW and in 2020, it would be 430GW (newarly 2.6 times), that is nearly 8% increasing rate. In 2008, the power consumption of network equipments was 25GW and in 2020, it would grow up to 97GW (newarly 4 times), that is nearly 12% increasing rate. In Japan, the power consumption of routers is nearly 3.6 GW in 2010. So, IETF had started to discuss power consumption problem. The underlying network infrastructure, namely routers, switches and other network devices, still lacks effective energy management solutions.

This paper proposes a traffic management policy to reduce the energy consumption by the network devices.

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Contents

Chapter 1

Introduction

“Sustainable development” as proposed by the Brundtland Commission in 1987, the holding of the Rio conference in 1992, and the coming into force of the Kyoto Protocol in 2005 all contributed to steady progress in addressing environmental issues, fostering the awareness of the need to reduce environmental loads as a key to the development of any market economy. While the 20th century was an era of economic growth and increased energy consumption, the 21st century inevitably emphasizes effective use of limited resources and minimization of environmental loads to ensure sustainable development of societies and economies.

Although the 21st century is undergoing a rapid transition from the industrialized society typical of the 20th century to an advanced information society, there has been insufficient discussion on how to improve efficiency and minimize the consumption of energy associated with advanced information processing and communications. In particular, now that the service industry accounts for over 70% of the U.S., Japanese and other developed economies, a transition from hard innovation to 'soft' innovation and service innovation has become a significant issue. As information distribution technologies and services driving such innovations advance concerns have risen over the increasing amounts of energy consumed by information processing and communication.

1.1 The World's Energy Consumption - a growing problem

Abundant and economical energy is the life blood of modern civilizations. Oil, coal and natural gas together supplying approximately 85% of the world's energy supply. The other sources are Nuclear, Biomass, Hydro etc. Coal, nuclear and hydro are used primarily to make electricity. The increasing energy consumption of the world is a growing problem as thes sources are not endless. Clearly we live in the age of oil, but the age of oil is drawing to a close.

If oil production remains constant until it's gone, there is enough to last 42 years more. Oil wells produce less as they become depleted which will make it impossible to keep production constatn. Similarly there is enough natural gas to last 61 years and there is enough coal to last 133 years. Nearly everyone realizes oil and gas will become scarce and expensive within the life times of us. Inevitably, there will be a transition to sustainable energy sources. The transition may be willy-nilly or planned- the choice is ours.

Despites the facts, with the advent of new technology every year, the energy consumption is increasing with a very high rate. The magnitude of energy problem that may face future generations can be illustrated by the simple calculation. The population of the world in 1990 was approximately 5 billion people. The UN estimates of population trends show it contiuning to increase to around 8 billion by 2025, but stablashing towards the end of the next century at somewhere between 10 and 12 billion people. According to the US DOE (Department of Energy) outlook for energy use throughout the world continues to show strong prospects for rising levels of consumption over the next two decades, led by growing demand for end-use energy in Asia. World energy demand in 2015 is projected to reach nearly 562 quadrillion British thermal units (Btu).

The expected increment in total energy demand between 1995 and 2015 - almost 200 quadrillion Btu - would match the total world energy consumption recorded in 1970, just before the energy crisis of 1973. Two-thrids of all energy growth will occur in developing economies and economies in transition, with much of that growth concentrated in Asia. Energy growth in the developing countries of Asia is projected to average 4.2 percent per year, compared with 1.3 percent for industrialized economies.

The main point about the energy consumption are illustrated below. [1]

- Natural gas is expected to have the highest growth rate among fossil fuels, at 3.1 percent a year, gaining share relative to oil and coal. By 2015 natural gas consumption recorded for 1995, at a level equivalent to two-thirds of the oil consumption projected for 2015. Natural gas consumption in 1995 was only about 55 percent of oil consumption.

- According to US DOE prediction only about 8 percent of projected growth in energy demand over the next two decades will be served by non-fossil fuel sources. In fact, the non-fossil (commercial) fuel share of world energy consumption declines from 15 percent to 12 percent over the projection period. Thus, world carbon emissions are likely to increase by 3.7 billion metric tons, or 61 percent, over the 1990 level by 2015. The Climate Change Convention of 1992 commits all signatories to search for and develop policies to moderate or stabilize carbon emissions. However, even if all the developed countries were able to achieve stabilization of their emissions relative to 1990 levels, overall world carbon emissions would still rise by 2.5 billion metric tons over the next two decades.

- Per capita energy use in the worlds industrialized economies, which far exceeds the levels in newly emerging economies, is expected to change only moderately in the next two decades. In some emerging economies (for example, India and China), per capita energy use may double. Even with such growth, however, average per capita energy use in the developing countries will still be less than one-fifth the average for the industrialized countries in 2015.

- In the longer term, consumption of oil as the principal source of commercial energy today, will start to decline after the transition phase (between 2020 and 2060). It is expected that natural gas will continue to be used as long as price and availability are satisfactory but as reserves reduce or prices rise coal (which is usually less expensive than natural gas and its international prices are unlikely to rise) will command a greater proportion of the market. To maintain energy levels and because of world-wide environmental concerns some experts predict that coal will have to be utilized cleanly, where gasification process will be the most environmentally friendly way of its future utilization.

- The transition to a sustainable energy system requires that share of renewable energy sources will continually grow. Renewables combined with a system of new technologies, can contribute to a considerable extent to energy requirements in the time horizon beyond 2020. Report for the UN Solar Energy Group for Environment and Development suggests that using technology already on the market or at the advanced engineering testing stage, by the middle of the next century renewable energy sources could account for 60 percent of the worlds electricity market and 40 percent of the market for fuels used directly.

1.2 Rise in Energy Demand

Global energy needs and the related emissions of gases held responsible for global warming are set to rise by almost 50% by 2035 under current policies, (Fig: 1.1,1.2)

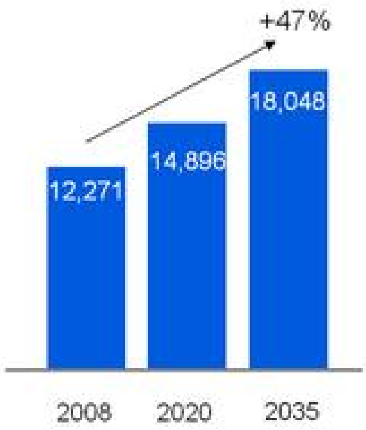


Figure 1.1: World Energy Demand (in million tonnes of oil equivalent)

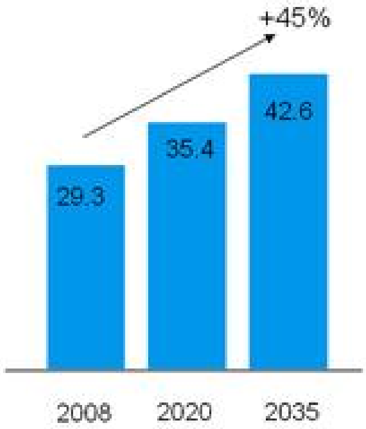


Figure 1.2: Energy-related Carbon emission (in gigatonnes)

driven by economic growth in the developing world, according to the International Energy Agency.

The challenge this poses is to deliver sufficient energy for equitable and secure social and economical development while avoiding environmental impacts that would compromise the capacity of future generations to enjoy the fruits of development.

Organizations with a focus on energy issues have identified energy efficiency as a foremost way of tackling the challenge. Highlights from the vast body of research published in recent years by international and non-governmental organizations include:

- Using energy more efficienty could deliver almost half of the abatement in carbon di-oxide emissions required by 2035 to limit global warming to 2 degree Celcius, according to the International Energy Agency's 2010 World Energy Outlook.

- The Intergovernmental Panel on Climate Change said in its 2007 report that in all the scenarios it considered for stabilizing the level of greenhouse gases in the atmosphere, 60-80% of the reductions would come from energy supply and use, and industrial processes, with energy efficeincy playing a key role in many scenarios.

- The electricity industry can contribute to sustainable development in a number of ways including by maximizing the efficiency and minimizing the environmental imapacts if the generation, transmission, distribution, and use of the electricity in a cost-effective manner. [2]

On the contrary the consumption of electric energy is increasing in a alarming way. The new advent of electric veichel will be a new on this race.

The recent post-Fukushima power struggle shows how serious the efficient use of energy is. The after effect of Fukushima power plant accident is, everybody related it agrees the more use of renewable energy. This would make power more valuable thing than ever.

1.3 Environmental Impact of Electricity Generation

The electricity industry is a major contributor to some of the most significant environmental problems facing our society. The generation of electricity plays a large role in local, reginoal, national and internation environmental issues, such as global warming, acid rain, ground-level ozone, air toxics, land use and water impacts. The environmental impact of electricity generation is significant because modern society uses large amounts of electricity power. This power is normally generated at power plants that convert some other kind of energy into electrical power. Each system has advantages and disadvantages, but many of them pose environmental concers.

1.3.1 Fossil Fuels

Most electricity today is generated by burning fossil fuels and producing steam withich is then used to drive a steam turbine that, in turn, drives an electrical generator. Such systems allow electricity to be generated where it is needed, since fossil fuels can readily be transported. They also take advantage of a large infrasturcture desinged to support consumer automobiles. The world7s supply of fossil fuels is large, but finite. Exhaustion for exactly when it will be exhausted. New sources of fossil fuels keep being discovered, although the rate of discovery is slowing while the difficulty of extraction simultaneously increases.

More serious are concerns about the emissions that result from fossil fuel burning. Fossil fuels constitute a significant repository of carbon buried deep underground. Burning them results in the conversion of this carbon to carbon dioxide, which is then released into the atmosphere. The estimated CO_2 emission from the world's electrical power industry is 10 billion tonnes yearly. This results in an increase in the Earth's levels of atmospheric carbon dioxide, which enhances the greenhouse effect and contributes to global warming. The linkage between increased carbon dioxide and global warming is well accpted, though fossil-fuel producers vigorously contest these findings.

Depending on the particular fossil fuel and the method of burning, other emissions may be produced as well. Ozone, sulfur dioxide, NO_2 and other gases are often released, as well as particulate matter. Sulfur and nitrogen oxides contribute to smog and acid rain. In the past, plant owners addressed this problem by building very tall flue-gas stacks, so that the pollutants would be diluted in the atmosphere. While this helps reduce local contamination, it does not help at all with global issues.

Fossil fuels, particularly coal, also contain dilute radioactive material, and burning them in very large quantities releases this material into the environment, leading to low levels of local and global radioactive contamination, the levels of which are, ironically, higher than a nuclear power station as their radioactive contaminants are controlled and stored.

Coal also contains traces of toxic heavy elements such as mercury, arsenic and others. Mercury vaporized in a power plant's boiler may stay suspended in the atmosphere and circulate around the world. While a substantial inventory of mercury exists in the environment, as other man-made emissions of mercury become better controlled, power plant emissions become a significant fraction of the remaining emissions. Power plant emissions of mercury in the United States are thought to be about 50 tons per year in 2003, and several hundred tons per year in China. Power plant designers can fit equipment to power stations to reduce emissions.

1.3.2 Nuclear Power

Nuclear power plants do not burn fossil fuels and so do not directly emit carbon dioxide; because of the high energy yield of nuclear fuels, the carbon dioxide emitted during mining, enrichment, fabrication and transport of fuel is small when compared with the carbon dioxide emitted by fossil fuels of similar energy yield.

While nuclear power plants offer a substantial source of power, there are a wide variety of dangers associated with the use of nuclear power. These dangers have created a general fear of nuclear power plants across the United States and much of the world. Nuclear power plants are dangerous from the initial mining operations to gather uranium all the way through the final stages of disposing the byproducts safely. Many scientists are attempting to address these dangers; however, the risks are still prevalent in the technology.

The greatest fear about nuclear power plants is a severe accident in the nuclear reactor. When the whole system or an individual component of a nuclear power plant causes the reactor core to malfunction, it is known as a nuclear meltdown. This occurs most commonly when the sealed nuclear fuel assemblies that house the radioactive materials begin to overheat and melt. If the meltdown becomes too severe, the radioactive elements within the core can be released into the atmosphere and around the area of the power plant. These radioactive materials are highly toxic to all organic life.Because of the geometric design of the reactor cores, a nuclear explosion is impossible; however, smaller explosions such as the release of steam are possible.

Nuclear meltdowns or disasters have occurred at various levels since the creation of nuclear power. The first known partial core meltdown occurred in Ontario, Canada, in 1952. Various disasters occurred in the following years, including the release of radioactive elements into the air on at least four occasions. The most significant disasters took place at Three Mile Island in Pennsylvania in 1979 and Chernobyl in Ukraine in 1986. The Three Mile Island accident was a partial core meltdown of a pressurized water reactor. It resulted in the release of 43,000 curies of krypton and 20 curies of iodine-131 into the environment. The Chernobyl disaster reached a level 7 (major accident), according to the International Nuclear Event Scale. Following an initial steam explosion that killed two people, the reactor was destroyed and nuclear fallout was spread around the area. It was necessary to evacuate 600,000 people, and an estimated 4,000 died from radiation-induced cancers. The latest one, following a devastating earthquake, in Fukushima, Japan is very fresh to everybody's mind.

1.3.3 Water usage

The amount of water usage is often of great concern for electricity generating systems as populations increase and droughts become a concern. Still, according to the U.S. Geological Survey, thermoelectric power generation accounts for only 3.3 percent of net freshwater consumption with over 80 percent going to irrigation. General numbers for fresh water usage of different power sources are shown below (Table 1.1).

	Water usage (gal/MW-h)		
Power Source	Low case	Medium/Avg case	High case
Nuclear power	400	400 to 720	720
Coal	300		480
Natural gas	100		180
Hydroelectricity		1,430	
Solar thermal	1,060		
Geothermal	1,800		4,000
Biomass	300		480

Table 1.1: Water usage of different power source

Chapter 2

Energy Issues Confronting the Information and Communications Sector

People tend to associate energy issues only with the energy used for transport, distribution and manufacturing. However, energy consumption related to information and communications technology (ICT) is now attracting global attention. To what extent does energy consumption of ICT (energy consumption of ICT equipment and infrastructure) contribute to total energy consumption and how it is expected to increase in years to come should be carefully evaluated. Controlling and restricting energy consumption is crucial to any discussion on sustainable economic development and industrial competitiveness.

2.1 Energy Consumption in the ICT sector

The bandwidth growth that the Internet will face in the near future representas a very challenging issue from the power consumption point of view. Nowadays, the 7-8% of the world energy consumption is absorbed by the ICT[3] and specifically the

Internet is responsible for about the 25% of this amount. Moreover, it is estimated that during the next 10-15 years, the traffic-bandwidth requirement will be up to 50-times higher than the current one. In this scenario, it is quiet intuitive that the power requirement will be the major constraint for the next generation network.

2.1.1 Perspectives and recent debate on ICT and energy

In the U.S., researchers estimated in the late 1990s the extent to which power consumption would grow as personal computers and other electronic equipment made their way into offices and as the Internet proliferated, and drew attention to potential problems.

Equipment Type	Residential	Commercial	Industrial	Total
Portable Computer	0.14	0.13	0.02	0.29
Desktop Computer	2.67	10.21	1.46	14.34
Server	0	1.6	0.23	1.83
Mini Computer	0	8.86	2.95	11.81
Mainframe	0	5.62	0.63	6.25
Terminal	0	1.83	0.61	2.44
Display	3.13	9.82	1.40	14.35
Laser Printer	0.10	5.36	0.77	6.23
Inkjet/Dot Printer	1.10	1.56	0.22	2.88
Copier	1.10	5.71	0.82	7.63
Fax	0.44	2.26	0.32	3.02
Total	8.7	53	9.4	71

Table 2.1: Best estimate of annual electricity used by U.S. office equipment in 1999, TWh/year [5]

Mark P. Mills estimated that the energy used by Internet-related equipment accounted for 8% of the total American energy consumption in 1999[4], initiating debate on ICT and energy issues in the U.S. Around the same time, Kawamoto and other in the End-Use Energy Forecasting Group of the Environmental Energy Technologies Division (EETD), Lawrence Berkeley National Laboratory, U.S. Department of Energy (DOE), reported the results of a detailed analysis of electricity used by 11 types of office equipment in FY 1999[5].

It was found that office equipment consumed 71 TWh of electricity in 1999, and when combined with 3TWh, the annual amount used by network equipment 8not including communications equipment), the total reached 75 TWh per year, which accounted for approximately 2% of national power consumption. Although much different from the estimate by Mills, the proportion of 2% was considered a more reliable reference value for 1999 because the analysis performed by Kawamoto's team was more exhaustive.

Since the 1999 estimation attempts, communication traffic has been increasing at an annual rate of 40%, and the major power consumer among ICT equipment has changed from office and home PCs to routers, the function of which is to route massive amounts of data. This suggests the need for an estimation that takes the ICT infrastructure more account. The electricity used by office equipment and home PCs has not grown so much due to the fact that their performance has improved, thanks to advances in technology to reduce power consumption in stand-by mode (low-load conditions). Such technology to interrupt the power supply to circuit blocks under low load, although effective for office equipment and home PCs, is difficult to apply to equipment used in the ICT infrastructure, whose chips and circuitss operate constantly under high-load conditions. Therefore, a consensus is being built in both government and industry that a debate is needed to consider the fundamental reeingeering of ICT devices and circuits as well as network arthictecture.

2.2 Energy Consumption of ICT infrastructure equipment

As the ICT infrastructure grows and communications traffic continues to rise, the increase in the number of installed servers, for sending and receiving information, and routers, for routing data, becomes increasingly significant. The Energy Conservation Technology Strategy, Trade and Industry in June 2002, estimated annual electricity consumption of servers in Japan to be 8.4 billion KWh and that of routers to be 3.6 billion KWh. These estimates for growth are becoming a reality today (Table 2.2).

	Item	Avg. Power requirements (W)	Installed units (FY 2000)	Operating Units (FY 2000)	Annual Operating hours (h/yr)	Annual power Consumption (MWh/yr)
Router	High-end ATM Switch	2,000	6,800	14,260	4,380	124,918
	High-end router	1,200		225,000	4,380	1,182,600
	mid range router	200		2,625,000	4,380	2,299,500
	Low-end router	30		15,000	4,380	1,970
	Subtotal			4,087,051		12,025,203

Table 2.2: Number of Routers and their power consumption

	2001	2004	2010	2015	2020
Traffic growth rate (40%)	1	2.7	21	111	597
Projected traffic (Tbps)	0.12	0.324	2.4	13	71
Routers' power consumption (100s of millions kWh/yr)	7.5	20	158	833	4478
Ratio to national power generation (assumed 920 billion kWh/yr)(%)	0.08	0.22	1.7	9.0	48.7
LSI operating Voltage (V)	5.0	3.3	25	1.0	0.8
Ratio of reduced power consumption of electronic equipment	1.0	0.44	0.25	0.04	0.03
Routers' power consumption with lower vlotage LSIs (100s of millions kWh/yr)	7.5	8.8	40	33	134
Ratio of national power generation (assumed 920 billion kWh/yr)(%)	0.08	0.1	0.4	0,4	1.5

Table 2.3: Projected power consumption of routers

By performing an in-depth analysis of the router structure and taking lower-power LSI chips and other relevant factors into account, Hasama Projected electricity consumption for routers together with growth in data traffic as shown in Table 2.3 [6]. His projection suggests, assuming communication traffic continues to grow by 40% annually as it did in the past several years, that the electricity used annually by router will increase 8 times to 15.8 billion kWh by 2010 and nearly 600 times to 447.8 billion kWh by 2020. This 2020 figure would account for an astonishing 50% of Japan's annual power generation, should the generation capacity remain around 920 billion kWh. Hasama's projection implies that if electricity consumption of routers grows without taking advantage of low-power LSI technology, Japan will face an energy crisis. Howerver, the figure of 48.7% is based on the wors-case scenario and will not becoma a reality if new LSi chips with lower power consumption continue to emerge at the current pace.

2.3 Concerns about increases in energy consumption associated with the expansion of global ICT infrastructure

The data in table 2.3 indicates that if the number of installed routers, which now exist mainly in developed countries, increases according to population distribution, a global energy crisis will occur surely. Especially in China, India and other countries that are experiencing rapid economic growth and have enormous populations, infrastructures for telephone, the Internet and TV are often built concurrently, and once these infrastructures are completed, communications traffic can increase explosively. Even though the pace of growth may level off eventually, the potential for tremendous increases in traffic in these regions poses a serious concern.

The problem is not limited to the number of installed units but extends to the growth in the speed and size of high-end routers residing on backbone networks. The top-of-the-line routers of Cisco Systems, a U.S. -based vendor, are desingned to use as much as 2MWh of electricity. Given that the Earth Simulator, Japan's fastes supercomputer, operates at 6-8 MWh, power consumption levels of these routers are high enough to redfine the traditional notion of routers. The Earth Simulator and many other supercomputers around the world consist of a few tens to hundreds of units placed in rows in a room as large as a gymnasium and require an air conditioning system that uses as much power as the supercomputer itself to cool the exhaust heat from numerous units. Unlike supercomputers,, whose ownership per country is very limited, top-end routers will have to be installed in substantial numbers across the world as long as the current communications networks architecture is retained.

People tend to be optimistic about the future of LSI power reductions because they have seen many electronic appliances successfully reduce their power requirements. Howerver, routers marketed in the future are unlikely to benefit from power reductions enabled by technologies to shut off the power to certain circuit blocks during low-load conditions and by smaller transistors, or so-called LSI scaling, which has traditionally played a key role in reducing power requirements. It should be noted that scaling technology faces challenges such as that in minature MOS transistors at 90nm or below in line width, gate leakage current offsets the power reduction effect generated by scaling and that lowering the transistor's threshold voltage is difficult becaus of process variation.

Now that the electricity purchased by the NTT Group is double the amount it was in 1990 and that next-generation core routers for communications are expected to require megawatt-range power, Japan is in urgent need to accurately ascertain its current status and plan actions to be takein in this area.

Chapter 3

Research issues in ICT

A debate on sustainable development often concentrates on restrictions, such as saving petroleum resources, but in the ICT sector, such a debate should start by determining from which standpoint the debate should be held. A common view is that the limitations of disposable income, combined with increased costs as a result of increased energy consumption, will naturally restrict the volume of information that people will be able to obtain. However, curtailing communications costs can be more difficult because the process of satisfying the desire for information may be more complex.

3.1 Green Evolution in Wireless network

The next generation wireless networks are expected to provide high speed internet access anywhere and anytime. The popularity of iPhone and other types of smartphones doubtlessly accelerate the process and creates new traffic demand. such as mobile video and gaming. The exponentially growing data traffic and the requirement of ubiquitous access have triggered dramatic expansion of network infrastructures and fast escalation of energy demand. Hence, it becomes an urgent need for mobile operators to maintain sustainable capacity growth and, at the same time, limit the electricity consumption.

The escalation of energy consumption in wireless networks directly results in the increase of greenhouse gas emission, which has been recognized as a major threat for environmental protection and sustainable development. European Union has acted as a leading flagship in energy saving over the world and targeted to have a 20% greenhouse gas reduction. China government has also promised to reduce the energy per unit GDP by 20% and the major pollution by 10% by the year of 2020. The pressure from social responsibilities serves as another strong driving force for wireless operators to dramatically reduce energy consumption and carbon footprint. Worldwide actions have been taken. For instance, Vodafone Group has announced to reduce its CO2 emissions by 50% against its 2006-7 baseline of 1.23 million tonnes, by the year of 2020. [7]

To meet the challenges raised by the high demand of wireless traffic and energy consumption, green evolution has become an urgent need for wireless networks today. As has been pointed out in [7], the radio access part of the cellular network is a major energy killer, which accounts for up to more than 70% of the total energy consumption for a number of mobile operators [8]. Therefore, increasing the energy efficiency of radio networks as a whole can be an effective approach. Vodafone, for example, has foreseen energy efficiency improvement as one of the most important areas that demand innovation for wireless standards beyond LTE [8].

Green Radio (GR), a research direction for the evolution of future wireless architectures and techniques towards high energy efficiency, has become an important trend in both academic and industrial worlds. Before GR, there have been efforts devoted to energy saving in wireless networks, such as designing ultra-efficient power amplifier, reducing feeder losses, and introducing passive cooling. However, these efforts are isolated and thus cannot make a global vision of what we can achieve in five or ten years for energy saving. GR, on the other hand, targets at innovative solutions based on top-down architecture and joint design across all system levels and protocol stacks, which cannot be achieved via isolated efforts.

3.1.1 Research Activities

In the academia, several workshops dedicated to green communications have been organized to discuss the future green technologies. For instance, IEEE has two green communication workshops in 2009, in conjunction with ICC09 and Globecom09 and at least three more in 2010, in conjunction with ICC10, PIMRC10, and Globecom10, respectively.

On the other hand, research projects on GR have sprang up under different international research platforms during the latest years. Optimizing Power Efficiency in mobile RAdio NETworks (OPERANET), a European research project started in 2008, deals with the energy efficiency in cellular networks. In UK, GR is among Core 5 Programs in Mobile VCE since 2009, targeting at parallel evolution of green architectures and techniques. Moreover, Energy Aware Radio and neTwork tecHnologies (EARTH) [9], one of the integrated projects under European Framework Program 7 Call 4, starts its ball rolling to develop green technologies at the beginning of 2010. Most recently, GreenTouch, a consortium of industry, academic, and non-governmental research experts, sets its 5-year research goal to deliver the architecture, specification, and roadmap needed to reduce energy consumption per bit by a factor of 1000 from the current level by the year of 2015.

3.2 Research on Reducing Energy Consumption in Wired Network

Reducing energy consumption has been an important part of networking research, with the most prominent topics pertaining to the energy consumption of servers and wireless devices. Unfortunately, the energy consumption of wired networks has been traditionally overlooked. The Internet users have been increasing 28% every year [11]. Real-time traffic reaches nearly 14Tbps [12], the power consumption of network equipments has been extremely increasing. In 2008, the ICT power consumption grew 168GW and in 2020, it would be 430GW (newarly 2.6 times)[13], that is nearly 8% increasing rate. In 2008, the power consumption of network equipments was 25GW and in 2020, it would grow up to 97GW (newarly 4 times)[13], that is nearly 12% increasing rate. In Japan, the power consumption of routers is nearly 3.6 GW in 2010 [14]. So, IETF had started to discuss power consumption problem [15]. The underlying network infrastructure, namely routers, switches and other network devices, still lacks effective energy management solutions.

3.2.1 Research Trends

Existing research on router power management treats routers as isolated devices and focuses on reducing power consumption at hardware component level. There are link-level solutions which put line-cards to sleep when there is no traffic on the link[16], however, the power saving from opportunistic sleeping is limited by the inter-arrival time of packets.

Complementary to component-level and link-level solutions there are network-level solutions. Today's networks are designed and operated to carry the most traffic in the most reliable way without consideration of energy efficiency. A network usually builds many redundant links and aggressively over-provisions link bandwidth to accomplice potential link failures and traffic bursts. While thes redundant links and bandwidth greatly increase the network reliability, they also greatly reduce the network energy efficiency as all network device are powered on at full capacity altime but highly under-utilized most of the time. Intuitively, when there are multiple paths between the same origin-destination pair, and the traffic volume on each path is low, one can move the traffic to a fewer number of paths so that the other paths do not carry any traffic for an extended period of time. Routers that have idle links can then put the links to sleep for energy conservation. This approach can be combined with component-level and link-level solutions to achieve higher network energy efficiency.

Network-level solution require network-wide coordination of routers. The challenges are two-fold, namely how to manipulate the routing paths to make as many idle links as possible to maximize the power conservation, and how to achieve power conservation without significantly affecting network performance and reliability. Since power-aware traffic engineering uses fewer number of links at any moment, it is important to make sure that links are not overloaded and packets do not experience extra long delays.

While some overprovisioning is necessary, it is possible to reduce the energy consumption by dynamically reducing the avaiable capacity, and bringing links back up as needed. For example, network utilization in off-peak hours may decrease significantly which allows for a reduction in capacity while still leaving enough spare bandwidth for unexpected traffic shifts. It is natural to consider powering off routers or line cards during period of low utilization. Even Though today's backbone routers can not put line cards in "sleep mode", or bring shutdown interfaces back up quickly, these advances will come in the years ahead, especially if the approach offer a big energy savings.

Chapter 4

Energy Consumption of Network Element

In order to evaluate the energy saving of any policy, it is fundamental to rely on an effective energy consumption characterization. We take special care in the definition of a general model, describin the devices' energy consumption as a function of their utilization and capacity.

4.1 Router's Energy Consumption

Idle energy is defined as the energy consumed by the card when, powered, with all links connected but not tranferring any data. In practice it is the least amount of energy required to keep the card functional. Table 4.1 list the idle power profile of the 10G NICs [17].

Table 4.1: 10Gbps NICs-Idle power consumption

Network Element	Idle power[Watt]
Intel (Base-T)	21.2
Solarflare(Base-T)	18.0

NICs may contribute significantly to server energy consumption: While NIC power consumption may seem insignificant, it is high enough that we consider it worth factoring in when designing server farms. Typical modern servers have a baseline power draw of between 150-250W depending on hardware configuration. The measured NICs, on the other hand, show a power consumption of between 5-20W. The presence of a 10G NIC increases baseline power consumption between 2.0-13.3%, a figure large enough to warrant careful consideration of which 10G interconnect should be used in the servers.

It is generally accpted that network device energy consumption grows linearly between a minimum value E_0, which corresponds to the idle state, and a maximum value M, which corresponds to the maximum utilization [21]. Furthermore, a null energy consumption is assumed when the device utilization is equal to 0, in which case the device is set to a OFF or sleeping state.

For what concerns the actual values of parameters E_0 and M, we rely on the energy figures available in the literature. Table 4.2 summarizes the parameters.

Table 4.2: Energy consumption parameters in Watts, for different network element.

Network Element	E_0 [Watt]	M [Watt]	Ref.
(0-100] Mbps links	0.48	0.48	[18], [19]
(100-600] Mbps links	0.90	1.00	[18], [19]
(600-1000] Mbps links	1.70	2.00	[20]
1 Gbps links	7.9	9.0	[17]
10 Gbps links	21.2	21.4	[17]

R. Sohan at el. in [17] compares a number of single and multiport (dual and quad) 1G configuration with the 10G NICs in test set in order to determine those that provide the best performance-to-power ratios. They focus on NICs adapted for the Base-T physical layer as this is the most prevalent wiring infrastructure in modern datacenters. Table 4.3 presents the characteristics of measure 1G NICs. The result lead to the following observations:

Table 4.3: 1G NICs-Performance and power characteristics.

NIC	Media	Throughput (Gbps) Theoretical	Actual	Active Power (W)
Intel 1G	Base-T	2	1.7	1.9
Broadcom Multiport (2*times* 1G)	Base-T	4	3.3	7.0
Intel Multiport (2*times* 1G)	Base-T	4	3.3	3.6
Intel Multiport (4*times* 1G	Base-T	8	5.7	12.5

- **Throughput efficiency decreases as the number of ports increase:** The data shows that throughput does not scale in relation to the number of ports. While it is unlikely that any NIC will achieve its theoretical throughput (duet to host and protocol overheads), it can say that the single port NIC is able to achieve 85% of the theoretical bandwidth, dual ports are able to achieve 82.5% of theoretical bandwidth but quad port devices are only able to achieve 70% of theoretical bandwidth. In comparison to 10G NICs are able to achieve up to 93.5% of theoretical bandwidth

- **Power consumption increases in correlation to the number of ports:** As Table 4.3 illustrates, the power footprint of the multiport NICs increase in relation to the number of ports on the device. Focusing on the Intel single and dual port NICs, it is noticed that the average active power consumed per port remains approximately the same (1.8-1.9W) for the single and dual port variations. Furthermore, power consumption actually increases to 3.125W for the quad port NIC. However, this increase is likely to be due to the fact that the quad port NIC is manufactured by Silicom and thus uses a different physical layer implementation to the single and dual port NICs.

Table 4.4 illustrates the results for the Intel Multiport(4$\times$1G) devices. This table shows that the multiport network element has the character of linear relation between power consumption with the active links.

Table 4.4: Mutiport NICs-Idle power consumption.

Network Element	Links	Power[W]
Intel Multiport(4×1G)	0	7.9
	1	9.0
	2	10.1
	3	11.2
	4	12.3

4.2 Energy Consumption Model

Figure: 4.1 shows the graph of energy consumptions of network devices.

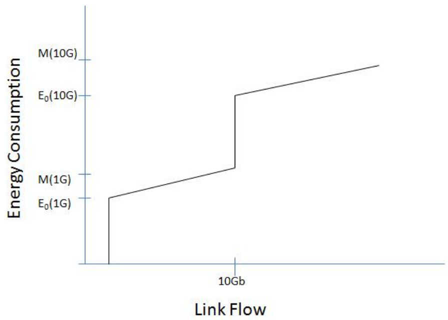


Figure 4.1: The device energy consumption

According to the discussion on Section ??, we can get the total energy consumption of a network link by adding the idle state energy E_0 with the active energy of E_A, which is corresponding to the utilization of the link. We introduce α as the utilization of the link which can be denoted by $\frac{l_{i,j}}{c_{i,j}}$ where $l_{i,j}$ denoted the load of the link (i,j) and $c_{i,j}$ denoted the capacity of the link (i,j). Therefore the active energy of a link is as in the Equation.4.1.

$$E_A = \alpha(M - E_0) \tag{4.1}$$

As a result the total Energy consumption of a link is as in the Equation 4.2

$$\begin{aligned} E &= E_0 + E_A \\ &= E_0 + \alpha(M - E_0) \\ &= (1-\alpha)E_0 + \alpha M \end{aligned} \quad (4.2)$$

Where, E_0 and M is static value depend on link load $l_{i,j}$. If load is less than 10GB, E_0 and M take the value of $E_0(1G)$ and $M(1G)$, otherwise these take the value of $E_0(10G)$ and $M(10G)$.

Therefore, the energy consumption of a link is a function of link load and its capacity. The energy consumpion of a link (i,j) can be expressed by the Equation. 3.

$$E_{ij}(l_{i,j}, c_{i,j}) = (1 - \frac{l_{i,j}}{c_{i,j}})E_0(l_{i,j}) + \frac{l_{i,j}}{c_{i,j}}M(l_{i,j}) \quad (4.3)$$

Where $E_{i,j}$ indicates the power consumption of link (i,j) where $i, j \in N$. An $l_{i,j}$ and $c_{i,j}$ are the load and the capacity of the corresponding link. The consumption is the summation of the idle energy and the utilization percentage multiply with the remaining energy between idle energy and the maximum energy.

Chapter 5

Energy aware Network Management

In backbone networks, the line cards that drive the links between neighboring routers consume a large amount of energy. Since these networks are typically overprovisioned, selectively shutting down links during periods of low demand seems like a good way to reduce energy consumption. In order to reduce the energy consumption of the network, we introduce a concept that realizes a low power consumption network by aggregating traffic on specific numbers of links and powering off link ports of routers that are not used.

While the problem forulation bears similarity to that of traditional traffic engineering research. the main contribution of this workd is the solution results. Traditional traffic engineering and energy-aware traffic management have two opposite optimization goals: the former tries to spread traffic evenly to all the links, while the latter tries to concentrate traffic to a subset of the links. It is though unclear whether one can achieve significant power saving while still maintaining acceptable link utilization in real networks.

5.1 Basic Idea and Assumptions

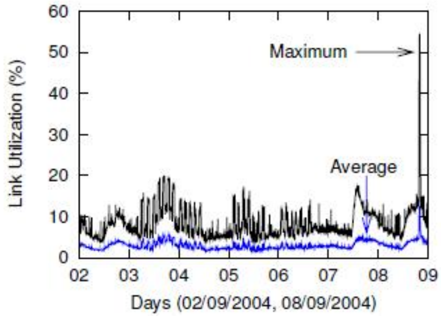
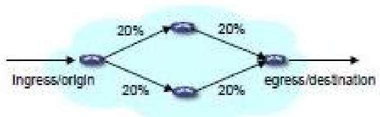


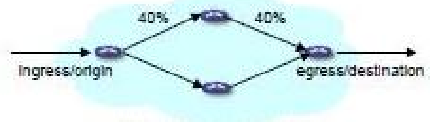
Figure 5.1: Maximum and average link utilization in the Abilene network

Today's wide-area networks usually have redundant and over-provisioned links, resulting in low link utilization during most of the time. Figure 5.1 shows the maximum and average link utilization under OSPF routing in Abilene, a large US education backbone, during a typical week. The average link utilization is only about 2%, the maximum fluctuates mostly between 10% and 20%, and only one rare event pushes the maximum over 50%. Such behavior is common in large commercial networks as well.

High path redundancy and low link utilization combined also provide a unique opportunity for energy-aware traffic engineering as illustrated by the example in Figure 5.2. Traditional traffic engineering spreads the traffic evenly in a network (Figure 5.2a), trying to minimize the chance of congestion induced by traffic bursts. However, in power-aware traffic engineering (Figure 5.2b), one can free some links by moving their traffic onto other links, so that the links without traffic can go sleep for an



(a) Traditional



(b) Power-aware

Figure 5.2: Different traffic engineering goals

extended period of time.

5.2 Low power Consumption Network Topology

Unless a link aggregation technique is applied, the amount of power consumed in one network link is constant regardless of the utilization. That is, the power consumption of links during off-peak periods, equals that of busy times of the network. However based on traffic demand, all links in the network need not necessarily be powerd on. Therefore it is possible to save energy consumption of the network by aggregating traffic on specific links and powering off those are not used.

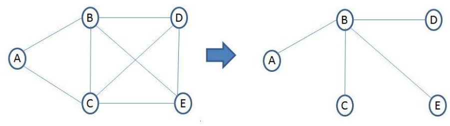


Figure 5.3: reconfiguration of a low power consumption network

In a reconfigured power-saving network, performance deterioration, such as delay and traffic congestion, is concerned for there are few links in the network compared to the original one. Therefore calculation method to determine the minimum set of links to use in the network that is capable of transferring all communication traffic under specific QoS restriction is necessary. By generating all topologies with different paterns of links powered off, it is possible to derive an optimum topology.

To find out the optimal network topology regarding to the energy consumption we propose the algorithm as below:

Optimal network topology algorithm

Objective: Find a optimal network topology that can carry the traffic demands with fewer link

- Step 1: *Initial topology*: take the topology information as initial topology and mark all link as temporary.

- Step 2: *Commence iteration*: Find out the path according to the shortest path algorithm for all required source-destination and compute the load for every link according to the path information associated with the traffic demand.
- Step 3: *Lowest loaded link*: find out the lowest loaded link that is not marked with final.
- Step 4: *Evaluation* : remove the lowest loaded temporary link and Evaluate whether the new topology is a feasible topology to carry out all traffic demand. If possible then remove the link from the topology otherwise mark the link as final.
- Step 5: *Move to next candidate*: go to the next iteration

Stop Criterion: when every link of the topology having the final tag.

In this algorithm, we focus on saving power by removing links and getting a power optimal network topology. This removing of link is not necessary a permanent physical removal of a link. It might be operated by the auto switching off the link cards or putting link cards into sleep mode. Line-cards contribute a significant portion to the total power consumption of a router. Table 5.1 shows a typcial configuration of a Cisco 12000 series router with low to medium interface rates and table 5.2 shows its budget of in use power consumption. All the line-cards together consume 508 watts, about 43% of the router's total power budget. This particular configuration uses relatively low rate interfaces (less than 1Gb/s) and the router is also of an old model. With faster interfaces (10Gb/s or even 40Gb/s) in newer routers, line-cards' power consumption will constitute an even larger part of the entire system's power consumption. Besides direct power savings, turning of links may also give indirect savings.

Table 5.1: The Configuration of a CISCO 12000 Router [22]

Slot	Cardtype	Watts
1	OC3-4-POS-X	90
2	GE-4	106
6	OC3-POS-16	100
7	OC12-ATM-4	122
8	OC3-4-POS-X	90
5,9	GSRP	38
16,17	CSC10	19
18∼22	SFC10	64
24,25	ALARM10	33
29	BLOWER16	178

Table 5.2: The power budget of a CISCO 12000 routers [22]

Slot	Category	Watts
1,2,6,7,8	line cards	508W
5,9	Route processors	76W
16∼22,24,25,29	Chasis components	602W

5.3 Shutting off cables in bundled links

Removing entire links from the topology often reduces capacity and connectivity too much, and leads to transient disruptions in the routing protocol. In core networks, pairs of routers are typically connected by multiple physical cables that form one logical bundled link[23] that participates in the intradomain routing protocol. Bundled links are also sometimes called aggreagate links or composite links, and they are standardized by IEEE 802.1AX [24]. Link bundles are prevalent because when capacity is upgraded, new links are added alongside the existing ones, rather than replacing the existing equipment with a higher capacity link. For example, a 40Gbps bundled link may comprise of four OC-192 cables with capacity of 10Gbps each. Bundled links are also necessary when the aggregate capacity of the bundle exceeds the capacity of the fastest available link technology. In today's backbone networks, a vast majority of links would be bundled, with bundles consisting of two to approximately twenty cables, a majority between the two extremes. The approach above can be used for bundled link by switching down individual cables in the bundle (and the line card that serve them) during periods of low utilization.

Chapter 6

Performance Evaluation

6.1 Performance Evaluation

We evaluate the link reduction rate of the proposed algorithm when setting different values for the traffic flows via simulations. We used four sample networks, as shown in Figure 6.1, to determine the basic characteristics of our approach. Networks 1-4 mirror the typical backbone networks used to evaluate routing performance in [25]. The characteristics of the networks are shown in Table 6.1.

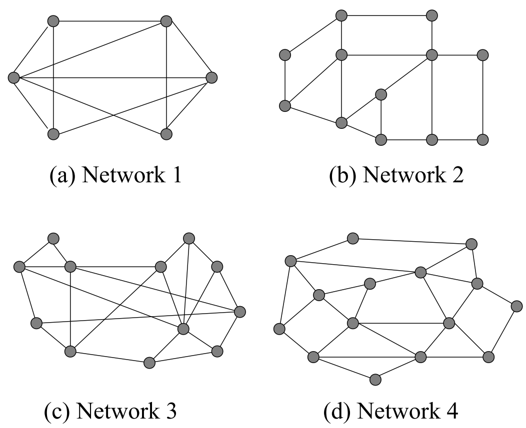


Figure 6.1: Sample networks.

The simulation is conducted without including QoS restrictions in order to evaluate the basic characteristics of the proposal. The simulation specification is as follows:

Table 6.1: Characteristics of networks

Network type	No. of nodes	No. of links (bidirectional)	Average node degree
Network 1	6	10	3.67
Network 2	12	18	3.00
Network 3	12	40	3.33
Network 4	15	27	3.60

- Link capacity: standardized as 1.0 for all links
- Inter-node traffic: uniformly generated
- Shortest Path Search: Dijkstra's algorithm.

6.2 Results and Discussions

Table 6.2 shows the reduction of link for the different type of traffic matrix, for the sample networks presented in Figure 6.1.

Table 6.2: Link reduction for the different Traffic mattrix

Network type	Total no of link	Reduction of Link (in %)for Matrix where highest congestion r is		
		r≤0.3	r=0.5	r ≤ 0.8
Network 1	10	50%	20%	10%
Network 2	18	33.3%	22.2%	11.1%
Network 3	12	30%	15%	5%
Network 4	15	29.6%	22.2%	11.1%

It is obvious that reduction of link is totally depend on the traffic matrix. the Table 6.2 reflects that clearly. With the increase of worst congestion in links decrease the reduction rate of link. For this reason we thoroghly checked the affect of traffic matrix on this performance for the network 3.

Figure 6.2 shows the reduction rate of links versus the traffic load achieved by our proposed algorithm. The proposal achieve a maximum of 35% of reduction.

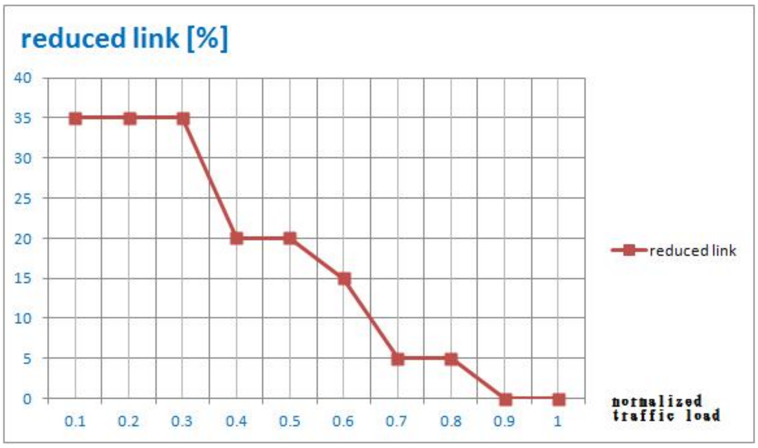


Figure 6.2: comparison of link reduction due to change of traffic load

As this performance of link reduction is highly dependant of the nature of traffic matrix, there should be a traffic regulator in the network which monitor the network traffic flow and reactively decide the links state.

6.3 Future Enhancement

To find out the basic character of this proposed routing management, we used a fixed traffic matrix in this work. But in real world this is not possible. The traffic is changed over time. To use this approach network operator can be find out the appropriate adjustment with the network and the traffic character. For an example, it can be easily assumed the highest traffic of a particular time. Therefore find out the exact topology for the different time according to the pick hour or Off pick hour.

This approach can be enhanced by considering the fluctuate traffic over time. And also considering the QoS of networking would be interesting to find out a complete routing scheme under low energy consumption.

Chapter 7

Conclusions

7.1 Conclusions

Energy consumption of the Internet is becoming increasingly important and researchers are working on various schemes to improve its efficiency. High path redundancy and low link utilization in today's large networks provide unique opportunities for power-aware traffic engineering. By switching traffic onto fewer number of paths, one can free some links from carrying data taffic and put them to Off mode under the constraints of link utilization and path length., and also balance the network load afterwards. In this paper we propose to find the optimal topology for the network that consumes the least energy and still give the required performance. At first we discuss about the energy model for the network devices and the find out the character of the energy consumption by the network devices. Then we set our objective as to minimize the total energy consumption by whole network. And then we find out the topology with minimum links to carry the traffic flow.

Performance Evaluation via simulation shows that this proposal is able to achieve considerable power savings with minor impacts on the network peroformance. If this draw the attention of the scholars further enhancement can be done easily with respect to QoS requirement and fluctuated traffic mattrix over time.

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