University of Southern Queensland
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Dynamic Topologies for Sustainable and Energy Efficient Traffic Engineering in Communication Networks

A thesis submitted by

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Abstract

Energy consumption and related emissions have been in the public focus for some time. Contributions of the Information and Communication Technology (ICT) sector to increase the Greenhouse Gas (GHG) emissions are growing. Networks are responsible of a significant portion of the ICT energy footprint and are generally dimensioned for peak loads. For extended off-peak periods, resources continue to consume power, but are lightly used or unused. The goal of this project is to reduce power consumption in communication networks through network management techniques. This research investigates the concept of dynamic topologies, i.e. networks that adapt their topology according to traffic volume.

In contrast to related work, this thesis addresses networks where nodes are both emanating and consuming traffic. This requires power models for routers and a reduced functionality power-state is proposed that bridges local demands to a single interface.

The key aim of this study was to investigate power reductions that can be achieved by dynamic topologies. It proposes a novel network transformation and introduces mathematical programming models that result in energy-optimal topologies for given traffic loads. This part focuses on the optimisation problems and studies gains in static environments. Numerical results are presented for example networks using a large set of traffic matrices.

Efficient heuristics are necessary for larger networks as mathematical programming models cannot be solved in practical time frames. Two sets of algorithms are proposed to find minimal network topologies. These rely either on link utilisation or node gravity to decide whether active devices can be switched off. To avoid hot spots and link overloads, shortest path weight setting techniques are implemented.

Network resilience to failure is an important requirement of network operators. To account for resilience constraints, two additional programming models are formulated; one that protects individual links and one that protects traffic demands. Both models are studied and energy savings are compared to the original models.

To demonstrate the feasibility of the approach a potential implementation of dynamic topologies using Multi Protocol Label Switching (MPLS) networks is introduced. Most MPLS functions and nodes are not affected by the proposal. A flow tracking and topology tracking mechanism is required at the network ingress; and all nodes have to include a power management function that controls the power state of routers. The impact of changes in routing patterns on active UDP and TCP flows has been investigated and found to be minimal. Aggregated flow-based performance has been analysed and the results show that there is no discernable impact on network performance.

Adapting topologies of computer networks dynamically to traffic volumes is feasible and can lead to significant reductions in energy footprints. For the test networks, dynamic topologies reduce the average network power consumption, by 12-52 per cent depending on network load.

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

ABDELNOUR MOHAMED ALNOUR ALDRAHO

Signature of Candidate

Date

ENDORSEMENT

Signature of Supervisor/s

Date

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Publications

The following publications were produced during the period of candidature:
Aldraho, Abdelnour and Kist, Alexander A. and Maxwell, Andrew, "Performance Investigation of Dynamic Topologies in MPLS Networks", *International Symposium on Communications and Information Technologies (ISCIT)2012*, Australia, Gold Cost,2012.

Aldraho, Abdelnour and Kist, Alexander A., "Enabling Energy Efficient and Resilient Networks using Dynamic Topologies", In:*The Second IFIP Conference on Sustainable Internet and ICT for Sustainability (IFIP 2012)*, Italy, Pisa. 2012, pp 34-38,2012.

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Kist, Alexander A. and Aldraho, Abdelnour, "Dynamic topologies for sustainable and energy efficient traffic routing", *Computer Networks*, 55 (9). pp. 2271-2288. ISSN 1389-1286,2011.

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Chapter 1

Introduction

Climate change and global warming are major concerns in the world today and the rate of climate change has been linked to greenhouse gas (GHG) emissions. As GHG concentrations in the atmosphere increase, the planet's ecosystem is adversely affected [1]. Global temperatures are increasing [2] and potential consequences include rising sea levels and increasing sea temperature, leading to an increase of peak tropical cyclone precipitation rates [3].

The increase in emissions in the last 150 years are largely due to human activities [4] and major sources include transportation, electricity generation, industry, agriculture and commercial and residential activities. Greenhouse gas emissions can be categorised according to the economic activities that lead to their production. The IPCC Climate Change 2007 report [5] identifies the following contributions. Energy production, which includes burning of coal, natural gas, and oil for electricity and heat is the largest contributor to emissions, accounting for 26% of 2004 global greenhouse gas emissions. The industry sector is responsible for 19% of 2004 global greenhouse gas emissions caused by fossil fuels burned on-site at facilities for energy. Land-use, land-use change and forestry account for 17% of 2004 global greenhouse gas emissions. This includes emissions from deforestation, land clearing for agriculture, fires and decay of peat soils. Agriculture is responsible for 14% of 2004 of greenhouse gas emissions. Activities include the management of agricultural soils, livestock, rice production, and biomass burning. Transportation is responsible for 13% of 2004 global greenhouse gas emissions involving fossil fuels burned for road, rail, air, and marine transportation. Commercial and residential buildings are responsible for 8% of 2004 global greenhouse gas emissions and the emissions come from on-site energy generation, burning fuels for heat in buildings and cooking in homes. Waste and wastewater are responsible for 3% of 2004 global greenhouse gas emissions including methane from landfills and wastewater.

The Information and Communications Technology (ICT) sector contributed about 2% to the total annual global greenhouse gas (GHG) emissions in 2007 [6]. This contribution is expected to increase by 6% each year until 2020 [7]. The ICT sector has been widely advocated as being able to implement energy saving measures assisting other sectors in reducing their energy consumption [8] by applying the new technologies such as email, distance learning and video conference. At the same time, it is an energy consumer itself and therefore contributes to the increases in GHG emissions. Efforts to reduce energy use across the sector spans all ICT activities. Solutions to reduce the impact of ICT on global warming include green data centres [9] (servers, data storage systems and cooling systems), green hardware [10] (hubs, switches and computers), power management [11], and green networks and communications [12] (switches, gateways and links).

In traditional data centres, for example, energy cost accounts for approximately 30 per cent of the operating costs of a data centre [13]. In an Internet data centre report, the worldwide energy cost of enterprise data centres has been estimated to exceed 30 billion US dollars per year in 2008 [14]. Therefore, data centre efficiencies are a major focus of energy saving efforts in the ICT industry [15]. Personal computers (PCs) are also considerable power consumers as most computers run all the time. Gartner [16] has estimated that the number of installed PCs worldwide exceeded 1 billion in 2008 and is growing at a rate of nearly 12 per cent annually. This means that it may reach 2 billion by early 2014. In 2006, Bray [17] summarised the power requirements of computers. PCs require between 36W and 250W when active, and between 1W and 27W in low power mode. In 2004, the average computer and monitor used 30% of their energy while idle and 40% of their energy outside business hours [18]. As these devices are often not used, it is possible to reduce the energy footprint by encouraging the employees or users to make changes to their using of PCs habits [19]. Most discussions about green ICT refers to hardware, but software is also an important factor [20] as the software requirements tend to determine the hardware design, which in turn has a significant impact on the amount and type of hardware used. All of these factors affect the energy consumption of the systems.

In the last decade, Internet and network communication have become prevalent and most computing devices are now networked. As a consequence telecommunication networks have grown rapidly. This also means that telecommunication networks have become major energy consumers. Servers and communication networks consumed about 3% of the world's electric energy in 2008 and this portion is increasing at a rate of 16-20% per year [21]. Zeadally et al. [22] have estimated that telecommunication networks consumed around 31% of the total energy used in the ICT sector in 2011.

Power savings in networks can be achieved by changes to hardware and software, networking protocols, network traffic management and configuration. The majority of studies into ICT power usage have focused on individual devices rather than whole networks [23]. However, Giroire and Moulierac [24] focus on the operation of entire networks, albeit static networks. Some elements of the networks consume large amounts of electricity in order to operate. The possibility of reducing power consumption by switching off routers and links has been proposed by a number of studies, but they have not covered the dynamic topologies aspect. This research project focuses on potential savings using network management and optimisation techniques. The underlying rationale is based on network utilisation. According to [25] reduction of power consumption can be achieved by switching off network nodes and links while still assuring full connectivity and highest link utilization. ICT infrastructure is generally underutilised as it is dimensioned for peak loads and redundancy. Most servers, for example, normally operate at 20% to 30% of their peak load [26–29]. Backbone networks operate at similar utilisation levels, between 30% [30] and 50% [31,32]. Adapting the network topology to utilisation levels can potentially lead to a reduction in the number of active network devices. This in turn reduces the total power consumption in the network.

This research project consists of five major parts. The first part discusses the nature of dynamic network topologies to find optimal topologies to manage given traffic demands. The second part addresses how networks can deal with changing topologies, with a number of algorithms proposed to apply the network changes. The third part investigates network resilience in the context of reduced topologies. The fourth part proposes potential methodologies to change network topologies and suggests MPLS for that purpose. The final part investigates operational issues such as identifying suitable ways to trigger topology changes.

1.1 Motivation and Scope

Energy use and energy efficiency have been major issues in the last decades; specifically in relation to the consumption of fossil fuel and subsequent effects on climate change [33]. Governments around the world have begun to take actions to reduce carbon emissions. For example, the Australian government has established programs to reduce carbon emissions and it has encouraged the business sector to take practical steps to contribute to the reduction of the impact of climate change [34]. The Australian government has also set ambitious targets to reduce Australia's carbon emissions [35].

The ICT industry was one of the first sectors to make attempts to reduce greenhouse gas emissions [36]. Green networks are a key component that will help the ICT sector to reduce its impact on carbon emissions. Network infrastructure operates fully only for a fraction of the time. This leads to unnecessary power consumption, while the network is not being fully utilised. By focusing on green computer networks, there is an opportunity to reduce the impact of the ICT sector on the environment. This thesis focusses on the latter and will investigate the possibility of reducing power consumption by reducing the number of active nodes and links. A key constraint of this effort is that the level of network service must be maintained and the network devices will not be required to change in term of its hardware which is a significant point that helps to achieve the thesis target without network hardware changes.

The main goal of this project was to reduce the power consumption in communication networks without affecting the network performance. A number of steps were taken to achieve this goal. Assuming that the network traffic and topology information is known, the first step was to establish whether reduced topologies offer significant energy savings. To identify power optimal topologies for given traffic loads, mathematical problems were formulated that attempt to reduce the number of active devices. As network nodes often originate and terminate traffic it was necessary to identify standby options for routers and to develop a power model for routers. These assumptions were necessary to estimate power savings. The networking models that are introduced in this thesis are not technology specific and can be applied to any networking technology. As Internet Protocol (IP) networks are the dominant technology at the moment, these are the focus of this thesis.

In a second step, network resilience was included as another constraint for the network model, as this is an important operational requirement of network operators. These theoretical evaluations demonstrated that considerable energy reductions are feasible in both studied network topologies cases and the next step was to investigate how dynamically changing topologies could be realised relying on existing protocols and technology. The requirement of such a scheme is to maintain the forwarding information for multiple topologies and a solution based on MPLS has been developed.

1.2 Summary of Original Contributions

This work has used a generic router and link power model in combination with a novel network transformation model to formulate mathematical network models that minimise the power consumption of given networks. The work demonstrates that the concept of dynamic topologies is a feasible option to reduce the energy consumption of networks. A number of heuristics have been proposed to generate the optimal topologies in communication networks. Mathematical models have been developed that take resilience constraints into account and are used to evaluate savings. A potential implementation of the concept of dynamic topologies using MPLS has also been introduced and evaluated. Operational issues that impact on the feasibility of this proposal are also discussed.

The work that is discussed in this thesis has resulted in publications [37], [38], [39], [40], [41] and [42]. The main contributions discussed in the individual chapters are summarised below:

- Study of potential low power modes for routers and of a generic network power model that allows the evaluation of the power consumption of networks.

- Proposal of a node bypass transformation that allows optimisation problems to automatically reduce the number of nodes in networks.
- Development of optimisation problem formulations as Mixed Integer Linear Programs (MILP) for a multicommodity flow problem that reduces the number of active nodes and links.
- Study of numerical results for two network topologies investigating potential energy savings.

These results were published in [37].

The contributions of Chapter 4 include:

- Development of heuristics to find optimal network configurations that reduce power consumption of networks.
- Study of power consumption of reduced topologies in test networks.
- Evaluation of Open Shortest Path First (OSPF) weight setting as an enhancement to the heuristics to avoid link overloads.
- Implementation of a network emulator to study the performance of the proposed algorithms.

These results were published in [38] and [39].

The contributions of Chapter 5 include:

- Development of two multicommodity flow problem formulations to incorporate network resilience constraints.
- Analysis of the performance of the proposed network models to show the feasibility of the approach.

- Evaluation of numerical results comparing network power consumptions of networks with and without the resilience constraints.

These results were published in [40].

The contributions of Chapter 6 can be summarised as follows:

- Proposal of a mechanism to implement dynamic topologies in MPLS networks with minimal changes to current forwarding mechanisms.
- Analysis of the impact of topology changes on the performance of individual UDP and TCP flows.
- Design of a network management function, a flow tracker at each ingress router and a router function that is able to change router power states.
- Investigation of the impact on the real time traffic and non-real time traffic in dynamic topologies and discussion of the implications for energy saving.
- Discussion of the practical considerations to identify the suitable methods to upsize or downsize the topology.

Results discussed in this chapter led to two publications [41, 42].

1.3 Structure of the Thesis

The remainder of this thesis is organised as follows: **Chapter 2** provides the context to greenhouse gas (GHG) emissions and the contribution of Information and Communication Technology (ICT) to those emissions. A general overview of GHG emissions is presented and their impact on the environment is discussed. The link between ICT GHG emissions and global GHG emissions is established and their impact and contribution on global warming outlined. Specifically communication networks are investigated in more details. Teletraffic engineering, network management are also discussed as these are relevant to the solutions that are presented in the thesis. Finally, dynamic topologies as an optimisation problem are put into context.

Chapter 3 establishes whether the concept of dynamic topologies is feasible and whether energy savings are possible. The results provide an indication of what potential savings are likely. This chapter discusses mathematical models that are formulated as multicommodity flow problems. A network transformation is proposed and mathematical programming models for optimal topologies are introduced to reduce the energy consumption for a given network topology. Link flow formulation and node bypass transformation are presented to find optimal solutions. Integer Linear Programming (ILP) is used to solve the optimisation problems. Using a generic router power model, potential energy savings are evaluated for two topologies. Numerical results demonstrate the feasibility of the proposal.

In **Chapter 4** the ability to apply the network changes is investigated. The mathematical models that have been introduced in Chapter 3 have shown that the optimal topologies exist; however solving the mathematical programs is complex. This chapter proposes a number of heuristics: The *Lightest Node First* and the *Least Loaded Node* algorithms. Both algorithms use the link utilisation to decide whether an active device can be switched off or not. The *Least Loaded Node* algorithm calculates the load of the nodes while the *Lightest Node First* algorithm computes the capacity of the nodes to identify devices that can potentially be turned off. The *Shortest Path Weight Setting* is employed with those algorithms to prevent link overloads. As part of the algorithms, optimal weight sets are calculated that balance the traffic load in the reduced networks. Numerical results illustrate energy savings that are possible by reconfiguring the network.

Network resilience is a major concern for commercial communication network operators. In **Chapter 5**, a network resilience model is proposed based on the models discussed in Chapter 3. The aim is to protect networks from link failures and two alternative problem formulations are presented, one that protects links and one that protects demands. Numerical results are presented that highlight energy savings in networks with resilience constraints.

Potential implementations of dynamic topologies and related network protocol performance are discussed in **Chapter 6**. To realise dynamic topologies, networks have to maintain multiple topologies at the same time. An approach using MPLS and flow tracking is discussed in this chapter. Assuming such a mechanism, network performance at the flow level is investigated. Using Network Simulator 2 (NS2) the effects on User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) flows is investigated. The network performance is investigated by evaluating performance factors such as packet loss and throughput.

Chapter 7 discusses the findings of this thesis and outlines potential future work and open issues.

Chapter 2

Background

Worldwide Internet traffic transported by communication networks is rapidly increasing to be doubling each year since 1997 [43]. Communication networks consume a considerable amount of energy which has increased from 219 TWh per year in 2007 to 354 TWh per year in 2012 [44]. This growth is contributing to negative environment effects and climate change. Network optimisation and reduction of active network devices is one way to help reduce the impact of communication network traffic growth. This chapter discusses the motivation for the work in this thesis and provides the background in regards to the various efforts to reduce the power consumption of telecommunication networks. It briefly discusses greenhouse gas emissions and global warming, the role of the ICT sector in general; and more specifically, communication networks and energy efficiency. As this work largely focuses on traffic management and network optimisation, those topic are also discussed.

2.1 Greenhouse Gas Emissions and Global Warming

Greenhouse gases (GHG) emissions are the release of gases from either man-made or natural sources which trap heat in the atmosphere and create a greenhouse effect. They are generally recognised to be the cause of global warming [45, 46]. Emissions of GHG interfere with the balance of sunlight energy entering and leaving the atmosphere, causing it to retain heat, thus raising the temperature of the earth surface. GHGs have been identified as key contributors toward global warming [47].

Coal-fired and natural gas power plants are amongst the principal sources of GHG emissions from human activities, with deforestation and engine combustion also making significant contributions [48]. Many industries contribute to GHG emissions such as energy producers and the transport sector. Also, the ICT sector is one of these contributors.

Global warming has been identified by the World Health Organization [49] as one of the most important challenges facing human life on Earth. As global warming increases, so do the incidences influencing the environment in negative ways. Increasing global temperatures, for instance, are likely causes of extreme weather situations, together with considerable and increasing changes in rainfall volumes [50] and rises in sea levels. As a result of global warming further rises in global temperature up to $1.4\,^{\circ}\mathrm{C}$, can be expected in the twenty-first century [51]. The problems associated with the consequences of global warming are raising considerable concern among nations, individuals and researchers [52] [53].

Also, as stated by Koch et al [54], the major contributor to increases in GHG emissions is the power production and therefore has a negative impact on the environment. Industry sectors such as food processing, use electricity to run manufacturing plants. Electricity producers are responsible for large amounts of GHG emissions [55, 56].

The electricity sector is responsible for more than 35% of total energy related carbon dioxide emissions worldwide, the largest contributor of GHG emissions in 2004 [57]. The industrial sector was the second largest, representing 28% of total emissions for the same year, followed by transport, which represented 20%, and direct fossil fuel use in the residential sector contributing 8%. Other sectors, account for 14% of total emissions.

2.2 The ICT Sector and Energy Efficiency

This section will discuss the role of the ICT sector in the context of greenhouse gas emissions and energy efficiency. ICT is a contributor to energy consumption. In the last two decades the ICT sector has grown rapidly and the GHG emissions in the sector are largely caused by the power conumption of equipment. Sutherland [58] states that the ICT sector accounts for 2% of global carbon dioxide emissions in 2007. Worldwide, the ICT sector was responsible for about 23 Mt of carbon dioxide emissions in 2009 [59]. This includes networking, data centres and hardware.

The ICT sector is undertaking efforts to reduce its energy and carbon footprint by focusing on technical solutions as well as business processes, often referred to as Green IT. The sector is also advocated as an enabler for reducing power use in other industry sectors.

The number of users around the world using the Internet has been increasing rapidly [60, 61], as has the development and proliferation of new (portable) devices. The rapid uptake of computers, the Internet and mobile phones has the capacity to double the volume of emitted carbon dioxide worldwide by the year 2020 [62]. Webb [63] highlighted in 2007 that if current treads persist, it is expected that the contribution will grow by 6% each year until 2020.

Energy use in the global ICT industry is the largest and most significant contributor to its carbon footprint, both within the information as well as the communication technology domains. In the ICT sector power is essential to enable both task operations and accomplishment [64]. Electricity is needed to run services, applications and equipment; and for related activities, such as manufacturing and distribution [65]. As presented in the European Commission in [66], the total electricity usage of the ICT sector in the European Union was estimated to be 119 TWh in 2005, which corresponds to 4.3% of overall electricity consumption, or 0.6% of total energy consumption. Also, for the U.S., it is estimated that ICT's share of electricity consumption was approximately 8% in 2008 [67]. The amount of energy consumed by the ICT sector is also increasing rapidly. Bilal et al. [68], for example, have observed that the energy consumption estimates for IT infrastructure for the year 2011 are double than those of 2006 because of the increase in the traffic and subsequent increase in the network hardware. The contributors to the ICT energy footprint is considerable. Plepys [69] has estimated that Internet equipment consumed approximately 8% of the total power in the United States in 2002 with the prediction to 50% growth within a decade. As predicted in [70], the energy consumption growth of telecom networks in the coming years is increasing.

Data centres are a major energy consumer of the sector [71] and their energy consumption is a major contributor to the rising GHG emissions. Berral et al. [72] identifies data centres as the principal parts of the problem. The power consumption of data centres is increasing rapidly [73]. In 2003, a typical data centre consumed about 40W per square foot energy, and in 2005 this figure has raised to 120W per square foot energy [74] because of the increase in traffic demand on the communication networks. Global network traffic has increased eightfold between 2006 and 2011 [75].
The third major category of contributors are hardware and devices within the ICT sector. A desktop computer requires 65-250W of electric power when in

use, and a colour monitor, another 40-150W; laser printers can need as much as 400W or more when printing, although considerably less if in standby mode; ink-jet printers use 12-30W while printing, but less than 5W while sitting idle [76]. Gartner [77] has estimated that desktop computers and monitors consumed 39% of all power used in ICT sector in 2002. Pritchard [78] has estimated that the total power consumed by servers represented 0.6% of total US energy consumption in 2005 and that the power use of servers doubled between 2000 and 2005.

Reducing the power consumption in the ICT sector could significantly reduce GHG emissions [79]. While the ICT sector has improved the power efficiency in other business sectors, there is a necessity to reduce the power consumption in the ICT sector itself. Therefore, many studies have identified the power consumption in the ICT sector from different angles such as power consumption in data centres, PCs and servers and networking and communications [80], [81].

Efforts in the ICT sector include both technical solutions as well as improved business processes. Use of state of the art technology in servers and data centres could reduce their consumption of electricity by 70 per cent [82]. For example, the use of DC power in data centres could reduce their energy consumption [83]. Cloud computing is also seen as a technology that can help to reduce the power consumption in the ICT sector [84]. Cloud computing is therefore one of the attempts that has been established by green computing that allow sharing of resources and shut down some of power-hungry data centres.

Efforts to reduce the energy consumption of computer networks include routing algorithms with sleep-cycle protocols for use in the network nodes [85]. The reduction of power consumption in networks investigated in [86] introduces new methods to control the power port and switching power in network devices by using multi layers in dynamic optimized routing. Also, the power consumption in computer parts was discussed in [87] and [88], introducing new methods to save energy in the hard disks by controlling the hard disk caching and memory and applying new technologies such as solid state drive technology (SSD).

Green computing is not a new practice in the industry [89]. The roots of energy efficiency computing can be traced back to 1992, when the US Environmental Protection Agency initiated an Energy Star program to promote energy efficient computing products [90]. Although green technology in the ICT sector covers a vast domain, it is limited to practices such as thermal management constraints [91] that help ICT companies reduce their contribution to greenhouse gas emission.

Research and innovation is developing new technologies to reduce the power consumption of ICT technology; however, this technology also has to be used. Green IT or green computing are umbrella terms referring to environmentally sound information technologies and systems, applications and practices [92]. The term often implies a focus on business rather than exclusively technical solutions and includes a focus on encouraging the use of energy efficient approaches such as virtualisation, informed purchasing, power management, lifetime analysis and recycling.

The ICT sector can also play an important role in helping other industries to reduce their energy footprint. ICT technologies can help to reduce GHG emissions of other economic sectors, even if the expected increase in the energy consumed by ICT equipment is counted [93, 94]. Kretschmer [95] and Plepys [69] agree that the information and communication technology revolution can be helpful for both the economy and the climate. Laitner [96] and Coroama and Hilty [97] have stated that information technologies can significantly reduce the use of energy, even though the ICT sector was responsible for about 2% of global GHG emissions in 2007 as found in [98]. The use of ICT technologies across other business sectors would lead to a reduction in the power consumption of those sectors. The potential of the ICT sector to help decrease environmental impacts from other sectors is discussed in [99] and Stallo et al. [100] estimate that ICT could potentially reduce global greenhouse gas emissions by 15% by 2020.

ICT use in the education sector is an example of energy conservation. The use of video and audio Internet services could reduce energy consumption by changing the traditional methods of communication. For example replacing transportation services to meet people with the use of video and audio Internet services. Irwin in [101] said that many companies encouraged their employees to use video and web conferencing to reduce air pollution effects. The ICT sector has improved their services to support other sectors that use services such as broadband Internet. This service can be used by the E-commerce sector and TV sector to deliver their services. As stated in [102] the bandwidth increase offered by broadband enables TV via the Internet. Fuhr et al. declared in [103] that E-commerce is based on the Internet spread and it is not affecting the environment. In distance learning offered by the education sector, the Internet service has the potential to decrease the transportation use and the GHG emissions that go with it as people take advantage of these new found educational opportunities [104].

2.3 Communication Networks and Energy Use

Communication networks have become more significant in the ICT sector to support and facilitate network tasks such as data transfer and sharing [105]. Therefore the power consumed by the communication network has increased rapidly [106]. Many studies have addressed the problem of the power consumption increase in communication networks including [107] and [108]. The European Union advised the ICT industry sector to improve the energy efficiency of communications networks and of ICT in general [109]. Over time, communication networks have become the significant consumer of power in the ICT sector. Communications networks contributed about 12% of carbon dioxide in 2002, but it is expected that this will increase by a factor of about 3 by 2020 [110]. Vereecken et al. [111] have examined the consumption of different ICT equipment in 2008 and found that network equipment was consuming about 12% of total ICT energy consumption, PCs were consuming about 5% and data centers were consuming about 12% of the total ICT power consumption globally.

There are many different ways to study the power consumption in network communications. Chabarek et al. [112] have presented a number of simple methods to estimate the energy consumption of network devices. Every network component has been evaluated to calculate a power footprint for a network topology. Two scenarios were compared: one with all devices turned on, and another where only network elements that guarantee the service remained powered on. Some studies, such as [113], have analysed the power consumption of server systems and routers in the US and provid information about the power consumption of office and telecommunication equipment for the year 2000. The results from that study could be helpful to understand the power consumption behavior in ICT equipment. Therefore, the study of power consumption in communication networks as discussed in this section has focused on three aspects in network communications, these being network hardware, network protocols and resource management [114].

The network communication devices are one of the largest power consumers in the IP network infrastructure. Therefore, some studies, such as [115] and [116] have targeted changing the network devices and using a dynamic link shutdown method to help reduce the power consumption of that device. Because the memory subsystem is a significant contributor to chip power consumption, Issenin and Dutt [117] implemented the synthesis of memory method in the data centre device and other supported methods which can lead to save the power in network on chip. One of the earliest studies of those dedicated to measureing the energy consumed by the new technology devices was the measurment of computer energy use by [118] and this study was followed by the study of the estimated total power use of office equipment by [119], [120], [121], and evaluation of the efficiency of improvements in that network equipment by [122] and [123].

Putting network elements into sleep modes is one of the key solutions to reducing power consumption of ICT equipment. This technique is also feasible to conserve power in networks as Gupta et al. [124], [125] showed as various components on Local Area Network (LAN) switches were to put sleep during periods of low traffic activity. Considerable effort is being made by large manufacturers such as Intel and Texas Instruments to make electronic devices more efficient [126].

To be able to put network interfaces and devices to sleep, changes to network protocols are required. Gupta and Singh [127] investigated LAN switches and routers and identified a number of concerns. This includes the time it takes to put components into sleep mode, methods to make decisions about whether devices should be put into sleep mode, and which devices in the network should be turned off.

Many studies have examined power savings in the wireless domain for battery operated devices which are often more costly to run. For wireless LANs using the 802.11 protocols, for example, 90% of the communications energy is spent during the radio listening and scanning operations [128]. Improving energy efficiency of base stations in cellular networks is discussed in [129]; while [130] discusses the use of routing control as a means to reduce energy consumption while remaining aware of Quality of Service (QoS) considerations. The authors propose a method using queuing theory and optimisation techniques to distribute traffic so as to reduce the cost function that comprises both energy and QoS.

Other ways to reduce the power consumption have been suggested. In studies [30] and [131] into the sleeping stage and the rate adaptation in the communication networks, the designs of two different power management schemes to reduce power consumption in the network were examined. A more recent study suggests the introduction of a new algorithm called GRiDA based on the link utilisation will reduce power consumption [132]. The algorithm switches off selected nodes and links in cases of particular link utilizations.

Another scheme is adapting the rate of network operation to current workload. Other proposals to conserve energy within networks that include using a dynamic link metric method and powering off links have been addressed [133, 134]. Gupta and Singh [135] suggest that there have been very few attempts at saving energy on network interfaces by using low power modes of Ethernet transceivers during periods of inactivity or low utilisation. Bianzino et al. [136] aimed to find routers and links that must be powered on so that total power consumption is minimised which can be achieved by using knowledge of a physical network topology including routers and links, the capacity of each link, the demand traffic, and the energy expenditure of each link and node. Also, the subject of that study is to flow conservation and maximum link utilisation constraints. In order to find the routers and links that must be turned on to minimize the total energy expenditure objective, the researchers used Integer Linear Programming (ILP) to specify the problem.

Gelenbe and Morfopoulou [137] have investigated optimised routing as a power saving mechanism in packet networks to identify the ability to reduce the power consumption in packet networks. Two schemes have been examined; shortest path routing and energy aware routing algorithm These are used to identify their capacity for reducing energy consumption through the proposed algorithm.

Energy efficient management to reduce the power consumption in a network is also discussed in the literature, identifying methods for power management, as well as targeting specific applications and techniques in the communication networks. For example, Chiaraviglio et al. [138] advocate an approach for power aware network management. The proposed method is applied to access networks and involves dynamic network planning based on the volume of traffic so as to reduce the number of active network devices. Recently, Ewa et al. [139] has proposed a framework for backbone network management. Where that study is discussing the minimisation of the energy consumption by considering the backbone network management to minimise energy consumption.

Energy requirements for data centre equipment have increased because of the increasing quantity of the equipment and the quality of the devices themselves. Research is investigating ways to manage and reduce power requirements. [140] and [141] discuss the power saving in servers and server clusters in data centres. These studies look at how the management of power consumption in related devices is addressed and the resulting enhancement of energy consumption by data centre devices and computers.

Kist [142] proposes a mechanism allowing load distribution for large scale server clusters with a load proportional GHG emissions footprint. An energy management mechanism has been proposed by [143] within the IEEE 802.3ah control scheme to switch optical network units to sleep mode and determine a suitable wakeup time schedule at the optical line terminal.

A reduction in power consumption can be achieved by managing traffic over the entire network. Once the Internet is connected to the computers, power consumption will increase. In this context, the application of power management can help to reduce power. One method allowing desktop computers to enter low power modes and retain network connectivity has been presented in [144]. The study shows that there is significant inactive time able to be used for power management.

2.4 Traffic Management and Network Optimisation

Traffic management can be broadly described as an attempt to optimise performance in operational networks based on specific performance objectives. Traditionally, these objectives have related to cost, device utilisation and QoS.

In technological terms this thesis focuses on the traffic management of IP networks to reduce their energy footprint. The energy consumption of networks is directly linked to the number of active devices that are running regardless of if it is forwarding traffic or not. To be able to turn devices off it is necessary to optimise the way traffic is routed in networks. Constraints in this case are QoS and energy use.

Routing is a complex process that involves network topology discovery, route calculations and packet forwarding. Each step has its own challenges. Topology discovery and route computation are done in the router's control plane with the aid of routing protocols, while packet forwarding is performed in a router's forwarding plane. In IP networks, routers in the same logical domain have to use the same routing protocols to enable communication of devices and a network-wide view of the topology. Once routers gather the necessary information through the routing protocol, they can compute next hop information for IP prefixes. Native IP routing protocols are based on next-hop destination-based routing [145]. When forwarding a packet, a router determines the outgoing interface based on the destination address of the packet and forwards the packet to the respective next router. The next router transmits the packet in the same manner and forwards the packet along the shortest path until it reaches its destination.

Routing protocols in IP networks are classified according to the scope of the routing performed. Routing protocols that operate inside an autonomous system, in which routers are under the same administration, are called intradomain (interior) routing protocols, also referred to collectively as the Interior Gateway Protocol (IGP). Exterior gateway protocols provide routing between separate autonomous systems [146].

The Open Shortest Path First (OSPF) packet routing protocol [147] is one of the most commonly used interior gateway protocols in IP networks. OSPF uses shortest paths for routing packets, applying the equal-cost multipath (ECMP) principle to cope with multiple shortest paths.

Traffic engineering is using the traffic flow of data entering and leaving the network to optimize network performance. The output of traffic engineering is an optimal set of paths which optimise link loads. The resulting set of paths can be used within the network to optimally control the flow and distribution of traffic across the network. Network congestion is one of the main issues resulting in reduced performance in IP networks. Congestion occurs when network resources are insufficient to accommodate offered load or when there is inefficient mapping of traffic streams to available network resources. However, setting up individual paths and optimally assigning traffic to them is not supported in traditional IGPs such as OSPF [148] and Intermediate System-Intermediate System (IS-IS) [149]. These protocols use shortest path routing with destination based forwarding which makes it difficult to achieve optimal link loads [150]. A forwarding mechanism that allows for a finer granularity, such as Multi Protocol Label Switching (MPLS) [151] is required.

Weight setting is another way to implement basic traffic engineering and load balancing with shortest path routing protocols.The idea was initially proposed by Fortz and Thorup [152]. In this study, a local search heuristic was proposed for optimizing OSPF weights assuming knowledge about the traffic matrix. However, the heuristics generating the weight set is computationally expensive. The cost function evaluation time can be improved as much as 85% using dynamic cost evaluation, when the previous solution and the current solution are only slightly different. It is desirable to do this because, if there is only one or just a few weight changes in the network, most of the routing patterns will not change (i.e. most of the flows are routed as before) with few exceptions; and the dynamic cost evaluation will update these flows only. In [153], Fortz and Thorup formalised the weight setting problem in OSPF/IS-IS networks and highlighted that the problem may be difficult to solve even for moderate sized networks. Other authors have built on their work, for example [154] investigated weight settings under a variety of different network objectives and [155] optimised link delays.

MPLS is significant for traffic engineering as it can direct traffic flows along predefined paths. It provides most of the functionality available from the overlay model that provide the client by emulated leased lines from the service provider which typically uses the virtual circuits of a Frame Relay or ATM service, in an integrated manner, and at a lower cost than the currently competing alternatives such as Frame Relay and ATM for traffic engineering. MPLS also offers the possibility of automating aspects of traffic engineering.

MPLS is a switching technology, which replaces traditional IP packet forwarding with label switching. IP packets are encapsulated in MPLS packets [156] and forwarding decisions within the MPLS domain are based on packet labels. This means packets follow predefined label-switched paths. This results on a much greater routing flexibility. In brief discussion, instead of routing the packets by forwarding packets router by router, paths are established for source-destination pairs. These paths are called label-switched paths (LSPs) and the routers that make up a label-switched network are called label-switching routers (LSRs). MPLS routers encapsulate the packets which are forwarded in a label-switching framework, with special headers called labels. The label contains information that can be used by the router to know the LSP that the packet belongs to. The router will use the ingress port and the LSP information to determine the next hop in the LSP. The network management function uses a set of configuration, performance, accounting and fault management functions. This component also collects traffic statistics that can be used for statistical analysis and capacity planning purposes.

2.5 Dynamic Topologies

The term dynamic topology has been used by the networking community in the past, in particular in the context of circuit switched networks. Dynamic network topology changes have been discussed to give an overview of the potential for power reduction in the networks. The aim in this type of study is to enable recovery from both predictable and unpredictable interruptions and achieve load balancing. Noakes et al. [157] have proposed an adaptive link assignment algorithm for distributed optimization of dynamically changing network topologies and a related routing algorithm [158]. Moose [159] investigates dynamic hierarchical networks that employ adaptive behaviour for variable demands. White et al. [160] introduces an analytical approach that addresses activation and deactivation of links in response to changed traffic conditions. In broad terms, these studies address the problem of a dynamically changing network configuration; however, these address different technology aspects and optimisation problems. These are not directly applicable to energy efficient network configuration. Router placement has been discussed as an option in the context of traffic engineering [161, e.g.], and in the context of wireless networks [162, e.g.]. While these publications do not directly relate to the dynamic topology problem, they discuss techniques that can be combined with the mechanism outlined in this project to offer greater savings.

A few studies do directly relate to dynamic topologies in the context of IP networks. A number of authors have identified power consumption as a main issue in high performance router design [163]. Solutions include the use of optics in routers [164] and energy efficient switching fabric design [165].

Power awareness in network devices has been investigated in [166] to minimise power consumption in network equipment. The authors of this work undertook benchmarking of two routers to estimate power use. Based on these measurements they developed a general model for router energy consumption and formulated the network design problem as a power aware mixed integer program.

Optimisation focuses on allocation of line cards per chassis and chassis over the target network. The optimisation problems are different from the scenarios discussed in this thesis, as routers do not inject or consume traffic. This research uses the reported measurement results to formulate the device power model in Chapter 3. Furthermore, the work in this thesis differs as it does not target a design problem and does not focus on the same level of detail in device configuration, but a generic solution that uses a set of predefined router energy states.

Chiaraviglio et al. [167] introduces a network design problem with the aim to reduce the total power consumed by the network. It outlines the optimisation problem as a linear program and proposes heuristics to solve the problem. The main difference of this approach and the optimisation problems discussed in this thesis are that nodes are unable to consume or inject traffic. In the discussed scenario, only nodes and links that are redundant can be turned off. The problem formulation is similar to classic network design problems with an energy consumption objective.

Chiaraviglio et al. [168] use the results of [167] and evaluate an operational topology with realistic power usage figures for devices and propose a new algorithm that accounts for power consumption of devices. Furthermore, the study focuses on a specific star network topology with three different aggregation levels, whereas this work looks at a generic network topology. In [169] the authors focus on a much larger scale and use analytical and simulation results to estimate redundant network resources worldwide that could be turned off to save power. A number of studies target specific applications or techniques. Vasic and Kostic [170] present an “online energy-aware traffic management technique” that assumes equipment is able to adapt its power use to utilisation using rate adaptation and sleep states. This approach provides a solution for energy efficient traffic management; it does not address the dynamic topology problem. Wu et al. [171] discuss the routing and wavelength assignment problems with the new objective of reducing network energy consumption. The authors introduce ILP formulation and a number of heuristics to solve the problem. Node and link power down for unused connections in IP over Wavelength Division Multiplexing (WDM) networks is also discussed in [172].

2.6 Conclusion

There is a strong link between GHG emissions and global warming. GHG emissions have been increasing rapidly and are mainly caused by energy consumption. ICT is contributing to these emissions and governments and other organisations around the world have urged the sector to address energy efficiencies and reduce emissions. The main cause of GHG emissions in the ICT sector is the consumption of energy. Activities in the research community have focused on methods to reduce the power consumption in ICT devices such as computers, printers, network devices and data centres. This thesis focuses on the energy footprint of communication networks, specifically IP networks. It proposes traffic engineering techniques and introduces dynamic network topologies in an effort to reduce the number of active network devices.

This chapter has provided a broad overview of the field. Details of related research that pertain to specific work discussed in the remaining chapters are introduced in those chapters.

Chapter 3

Dynamic Topologies as a Multi-Commodity Flow Problem

One approach to increase energy efficiency in communication networks is to adapt the network topology to the network load. This chapter introduces the concept of dynamic network configuration at a topology level. The aim is to establish whether dynamic topologies can lead to energy savings for lightly loaded networks. To address different energy consumption behaviours of router hardware, a generic power model is introduced to serve as the basis for the investigations. Using novel network transformations, a multi-commodity flow problem is formulated that reduces the number of active nodes and links. Key differences to the other approaches are that in this model the nodes potentially emanate and terminate traffic. Four different low power models for routers are investigated and simulation results demonstrate that considerable energy savings are possible using this approach.

3.1 Introduction

Chapter 2 has established the relevance of energy efficiency and global warming. The impact of computer networking on global GHG emissions has also been discussed and potential approaches to reduce energy consumption in communication networks have been introduced. In particular, efforts in regard to hardware, protocols, software, and network management have been introduced. This work focuses on the latter and this chapter introduces mathematical models that allow quantification of possible energy saving by adapting the network topology to traffic demands. The infrastructure of a communication network has to grow with the increase in user demand. This section will briefly introduce the concept of dynamic topologies and multi-commodity flow problems.

This research proposes that the network actively change its topology to current traffic conditions. In dynamic topologies, links and routers can be switched into low power mode in response to traffic loads. There are two aspects of interest to this approach: potential savings from dynamically changing network topologies and the dynamics of routing protocols. The former is addressed in this chapter.

The modelling in this chapter focuses on network flows, rather than packets. The network flow assumptions are that classis network algorithms such as shortest path, minimum cost flow, and multi-commodity flow problems are applicable [173]. In this chapter, multi-commodity flow problems with regard to dynamic topologies will be studied. The aim of this work is to identify the potential to minimise the number of active elements in network communication, and therefore is to evaluate potential power savings from using dynamic topologies.

3.1.1 Motivation and Related Works

In addition to the background discussions in Chapter 2, this section briefly discusses related work that is specifically relevant to this chapter. The work in this chapter was undertaken concurrently or ahead of many other studies of energy efficiency in communications networks. The motivation for the problem formulations discussed in this chapter is to identify efficiency gains that are possible by changing network topologies.

Multi-commodity flow problem formulations have been proposed in the context of energy consumption [174, 175]. However, these studies have assumed that nodes are unable to consume or inject traffic. This means that only redundant links or nodes can be switch off. Marsan et al. [176] apply similar optimisation techniques to switching of devices to specific networks to achieve energy efficiency while [177] proposes to switch off links by using the QoS in the given network. Energy efficiency in wireless access networks is discussed in [178] and the power consumption of ad-hoc networks is investigated by [179]. Ledbetter and Smith [180] evaluate efficiency gains in equipment to provide more information and purchasing strategies for clients about how to select and use energy efficient equipment.

The modelling in this chapter uses Mixed Integer Programming (MIP) to solve the multi-commodity flow problems. MIP is a mathematical method that is widely used to solve optimisation problems [181]. ILP derived solutions can be tailored to either maximise or minimise packet delivery costs. In relation to sustainable network routing, ILP have been used to find solutions to the problem of minimising the power consumption in IP networks [182] and to investigate the possibility of switching off interfaces connected to unused links [182].

The research discussed in this chapter focuses on traffic engineering of generic network topologies to identify nodes and links that can be turned off in order to reduce power consumption in operational networks.

3.2 Notation

This section introduces the mathematical notation that will be used throughout this thesis. A network $G(N, M)$ consist of N nodes and M directed arcs. The flow of commodity k on arc (i, j) is denoted as x_{ij}^k and the unit cost of commodity k using arc (i, j) as c_{ij}^k. Arc (i, j) also has a fixed cost $g_{i,j}^k$. This cost is encountered if link (i, j) is active and it is independent of the traffic x_{ij}^k. The capacity of arc (i, j) is denoted by u_{ij}. Similarly, nodes have unit and fixed costs c_i^k, g_i^k and capacities u_i where, in practical telecommunication networks, costs are the same for all k. For this application, different commodities correspond to alternate traffic flows, between other origin destination pairs and the cost is the same for all pairs. h_i^k denotes the nodes standby cost. The constant $b^k(i)$ denotes supplies or demands at node i, $b^+(i)$ is the sum of all supplies at node i and $b^-(i)$ is the sum of all demands at node i. The variables δ_{ij} and δ_i are Boolean values that indicate if arc (i, j) and node i are in use, respectively. Integer constants γ_i and β_i indicate the maximum out-degree and in-degree of nodes, respectively.

Table 3.1 shows a summary of main variables and constants that are used throughout this thesis for the various mathematical models.

3.3 Assumptions and Node Standby Power Model

Power models are essential to estimate the amount of energy a network consumes. In communication networks, the main elements are links and routers. The architecture of routers is complex and the design varies according to size and the purpose of routers. For instance, core routers are different to those that are operating in the network edge [168]. Therefore, it is difficult to propose a universal power model that applies to all routers.

Table 3.1: Mathematical notation used throughout the thesis

Symbol	Explanation
x_{ij}^k	The flow of commodity k on arc (i, j).
c_{ij}^k	The unit cost of commodity k using arc (i, j).
$g_{i,j}^k$	The fixed cost of commodity k using arc (i, j).
u_{ij}	The capacity of arc (i, j).
c_i	The unit cost of node i.
g_i	The fixed cost of node i.
u_i	The capacity of node i.
h_i^k	The standby cost of node i and commodity k.
$b^k(i)$	The constant that supplies or demands at node i.
$b^+(i)$	the sum of all supplies at node i.
$b^-(i)$	The sum of all demands at node i.
β_i	The integer constant that indicate the maximum in-degree of node i.
δ_{ij}	A boolean variable that indicates if arc (i, j) is used.
δ_i	A boolean variable that indicate if node i is in use.
γ_i	The integer constant that indicate the maximum out-degree of nodes.
y_{ij}^{nm}	The flow of the commodity between link (n, m) accommodated by arc (i, j).
ϵ	A small number used as scaling factor.
a^{mn}	A right hand side vector with a positive supply of u_{ij} in row i and a negative demand of $-u_{ij}$ in row j for all links (m, n).

In this section, a number of generic router standby modes are introduced and cover the different router modes. Chabarek et al. [112] outline opportunities for low power and hibernation modes. For the discussions in this chapter, it is assumed that a router features a number of line cards, switching fabric, a main processor and power supply. Line cards are complex and may feature network processors, memory and line drivers. Regardless of the router's power saving state, it is assumed that links can be turned on and off individually, an assumption also used by [112]. Furthermore, for discussion in this thesis, it is assumed that components such as line cards can be powered down automatically.

At a conceptual level, Points of Presence (PoP), or individual Internet service providers' locations, have to handle three types of traffic: terminating traffic, emanating traffic and transit traffic. At a node level, this is related to the ability of nodes to inject or consume traffic. To apply the same concept to the routers, traffic can be local or transit traffic, which means that a local interface handles terminating and emanating traffic.

3.3.1 Standby Options

This research is suggesting that without major redesign, routers could support a number of low power modes, by essentially reconfiguring routers to a switching only mode. In this mode, local connections are bridged to neighbouring routers. This mode largely relies on line cards and switching fabric. Such configurations would be similar to flow based routers [183], and it is suggested that such routers operate at 20% of the power of conventional routers. This proposal is supported by the fact that such modes do not require routing functionality and that lightly loaded switching fabric consumes less power [184].

For the modelling in this research, a generic device is assumed. It has been widely acknowledged that power saving options are very limited in current devices, but emerging hardware will enable the implementation of diverse energy management features [170], [168]. A number of options are possible to allow routers in low power modes to handle terminating, emanating and transit traffic.

Based on these assumptions, a number of standby modes with reduced power consumption are possible and are explained in Figure 3.1.

(a) *router inactive* — neither local nor transit traffic is forwarded.

(b) *router active* — The node is operating normally, the local traffic is sent and received and the transit traffic is forwarded by any outgoing interface.

(c) *links-only* — only links can be turned off, all nodes remain active.

(d) *bridged-all* — local demands are bridged to one link, terminating traffic is received on one interface only.

(e) *bridged-local* — local demands are bridged to one link, terminating traffic is received on all interfaces.

(f) *default-gateway* — local traffic and all transit traffic is forwarded via one link only

(g) *bridged-many* — multiple bridged interfaces, with incoming and outgoing links are bridged, including the local to one outgoing link.

Figure 3.1 depicts alternative configurations (a) – (g) to visualise the different options. Arcs on the left of the nodes symbolise terminating traffic, arcs on the right symbolise emanating traffic and arcs on top of nodes indicate local demands. Option (a) and (b) show inactive and fully active states. Option

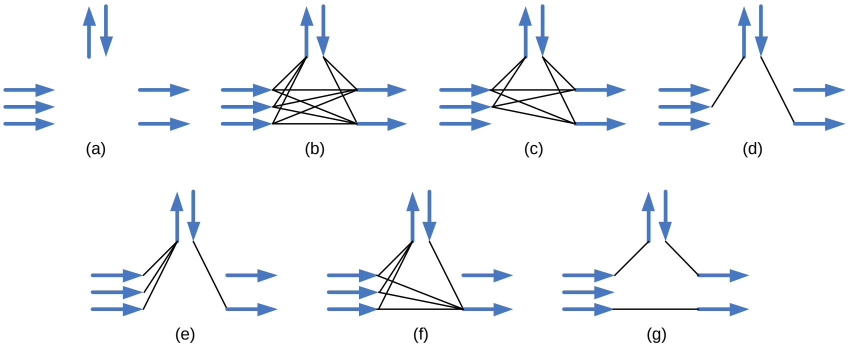

Figure 3.1: Low power state options

(c) shows that, the nodes are active while the links may be switched off. Option (d) suggests a simple bridge between ports, requiring the least functional support. Option (e) is similar, but it additionally allows for multiple terminating interfaces bridged locally. It does not require intelligence as all traffic is forwarded to the same local interface. Option (f) further allows for transit traffic. It does not require complex routing functionality, as all traffic is forwarded to a default gateway. Option (g) allows for additional interfaces to be bridged that only accommodate transit traffic and is thus outside the scope of this project. This work will focus on the *bridged-all* option for routers in power saving modes as it requires the least functional support in routers.

Reduced versions of the mathematical model that are developed in Section 3.6 can be applied to *bridged-local* and *default gateway*. Option (c) is covered by the model discussed in Section 3.4.1. The key aim of this section was not to propose new router designs, but to evaluate potential gains that dynamic topologies could offer if such standby modes are to be supported by routers. None of the suggested standby options require major redesigns of router hardware and are achievable with only minor changes to existing systems.

3.3.2 Power Consumption Estimates

A power consumption model is important to identify the ability for network power saving. As discussed previously, alternative power models for network devices have been suggested. Identifying actual power consumption values is more difficult as the devices differ in capacity and size. To evaluate the performance of the proposed mathematical models, practical power values are required.

To apply the proposed power model, a set of assumptions are used for the power demands of network devices. Following the discussion in Section 3.3, it is assumed that 10% of router energy consumption is load dependent. This load dependency is caused by functions such as routing table lookup, queuing, and forwarding. The remaining 90% of power consumption is assumed to be load independent.

The power model in this research is supported by a previously proposed energy model, with the power values based on the reported study results [112]. Routers consume a maximum of 600W, with links consuming a maximum of 80W. The power consumption of links is attributed to the line cards in the router. Switching links off and on can therefore be interpreted as a change of the line card mode.

It is assumed that the router has two modes of operation, a fully functional mode and a standby mode which does not support routing functionality. In standby mode, it is assumed that the router consumes 20% of the maximum power. The impact of load dependent power consumption in the low power modes is assumed to be insignificant.

For power calculations, it is assumed that the power consumption of line cards is attributed to the links. Each line card has only one port and the line card can be individually activated or deactivated. As the utilisation of the network processor depends on the traffic load, a higher variability of 20% has been assumed. Furthermore, it is assumed that link capacity is not a factor in power consumption[1], an assumption supported by [127] and [185]. However, the variable power consumption is scaled to the link speed. An unloaded link consumes 80% of the total power and a fully loaded link consumes 100% of the link power. If these models are applied to specific scenarios and technologies, these assumptions can be revised accordingly.

3.4 Multi-Commodity Flow Problem Formulation

The problem formulation is concerned with identifying the potential to apply energy reduction algorithms. To evaluate power reduction in dynamic networks, sets of mathematical models will be introduced and discussed. The presented formulations are based on the multi-commodity flow problem. Ahuja et al. [173] showed that traffic flows can be modelled as a multi-commodity flow problem. These can be expressed in link or path flow formulation.

In this section, the aim is to find the minimum topology for a given operational network, i.e. a set of active links and nodes. This minimum topology has to be able to carry all traffic demands. Link and router capacities, the traffic matrix, the fixed and variable power consumption of nodes and links are given; maximum link utilisation and conservation of flows are constraints; and the aim of the problem formulation is to find a topology such that the overall power consumption is minimised.

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[1] The data rate depends on the hardware of the link and the technology used; which in turn impacts on the power consumption. Links at similar levels of technical maturity consume energy at similar levels.

3.4.1 Intuitive Network Model

This section introduces an intuitive formulation of the dynamic topology problem that only accounts for fixed costs. The goal of the model formulation is to minimise the total cost, Z, of the operating nodes and links in the operational network topology. The equations (3.1) – (3.4) define the dynamic topology problem which accounts for fixed cost, which has instruct the particular capacitated multi-commodity minimum cost flow (CMCF) problem [167]. This problem is related to the optimal network problem [186].

$$\text{Minimize } Z = \sum_{i,j} \delta_{ij} g_{ij} + \sum_{i} \delta_i g_i \tag{3.1}$$

The minimum is subject to balance constraints, Equation (3.2), and bundle constraints, Equation (3.3).

$$\mathcal{N}\, x^k = b^k \quad \text{for all } k = 1, 2, \ldots, K \tag{3.2}$$

$$\sum_{k} x_{ij}^k \leq u_{ij} \delta_{ij} \text{ for all } (i, j) \in A \tag{3.3}$$

Where:

$\mathcal{N}$ is the node-arc incidence matrix and b is the right hand side vector that specifies supplies and demands. The balance constraint expresses the conservation of flow, as the sum of all elements $b(i)$ in b must be equal to zero. In the case of network traffic flows, there are only two non zero elements for each b^k: the flow source $b(s)$ and the flow destination $b(t)$. The commodities, k, correspond to the demands between source and destination nodes. Equation (3.3) limits the flows on links to the link capacity u_{ij}. If links are not active, the capacity is zero. Equation (3.4) imposes the additional constraint that if a node is turned off, all connected links are disconnected as well:

$$\sum_{j=1}^{N} \delta_{ij} + \sum_{j=1}^{N} \delta_{ji} \leq M \delta_i \quad \text{where } M \geq 2N. \tag{3.4}$$

If nodes do not consume or inject traffic, this formulation leads to practical solutions for core networks at this point, redundant nodes can switch off. If nodes have been assigned demands, the above formulation leads to a solution where all assumed nodes with assigned demands are always active, with only idle links switched off. In cases where the nodes are injecting and consuming traffic, an additional mechanism is required to handle local demands for nodes that are in standby.

3.4.2 Generic Link Flow Formulation

The optimisation problem that is discussed in this chapter is based on the link flow formulation of a multi-commodity flow problem. The formulation is extended by a bypass transformation to formulate an optimisation problem that minimises the number of routers for a given network load. This section discusses the generic problem.

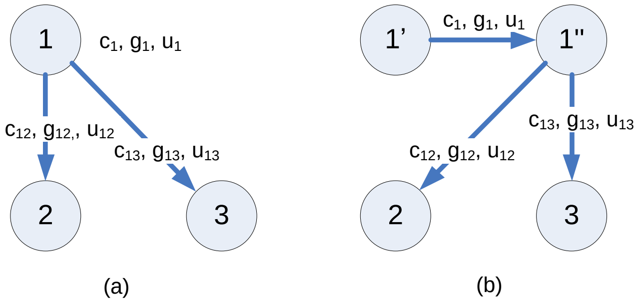
The generic multi-commodity flow problem can be formulated as a mathematical program shown in Equations (3.5) – (3.7) [173]. The aim is to minimise the cost Z of the objective function shown, in Equation (3.5).

$$\text{Minimize } Z = \sum_{K} c^k x^k \tag{3.5}$$

c^k is the row vector of link costs, c^k_{ij}; and x^k is the column vector of link flows, x^k_{ij}. As outlined above, for telecommunication networks, all c^k are equal. The minimum is subject to balance constraints, Equation (3.6), and bundle constraints, Equation (3.7), respectively.

$$\mathcal{N}\, x^k = b^k \quad \text{for all } k = 1, 2, \ldots, K \tag{3.6}$$

$$\sum_{k} x^k_{ij} \leq u_{ij} \quad \text{for all } (i, j) \in A \tag{3.7}$$



(a) (b)

Figure 3.2: Extended node splitting transformation: a) original and (b) transformed

As in the previous section, $\mathcal{N}$ is the node-arc incidence matrix and b is the right hand side vector. Without the constraints shown in Equation (3.7), the problem reverts to k single commodity flow problems.

This formulation does not impose capacity restrictions on nodes. However, in computer networks, nodes or routers are the main power consumers. To include node costs c_i, g_i and node capacities u_i, the node splitting transformation can be applied [173]. Nodes, i are replaced by a set of additional nodes, i' and i'', connected by a new arc (i', i''). This transformation does not affect the problem formulation, Equations (3.5) – (3.7); however, it changes the problem size. As a consequence of the transformation, the number of nodes is doubled and n additional arcs are introduced.

Figure 3.2 (a) depicts an example network with nodes 1, 2 and 3 and the corresponding unit costs c_{12}, c_{13}, fixed costs g_{12}, g_{13}, and capacities u_{12}, u_{13}, respectively. Node 1 has also costs c_1, g_1 and capacity u_1 assigned. To include these node constraints, Node 1 is replaced by a capacitated link $(1', 1'')$, as depicted in Figure 3.2 (b). Node costs and capacities are reassigned to the new link accordingly. If all nodes in this network are transformed, the number of nodes increases from 3 to 6 and the number of links from two to five.

3.5 Node Bypass Transformation

The aim of this research is to develop a model that minimises the number of nodes in the network required to service a given network load. It also assumes that nodes are injecting and consuming traffic. If nodes are switched to standby mode, they are no longer able to route traffic. Therefore, it is necessary to bridge local demands to one of the neighbouring nodes. As discussed in Section 3.3, this can be done by disconnecting all but one interface. To reflect this in the network model, an extended node transformation in combination with modified problem formulation is proposed.

The goal is to introduce an alternative (virtual) connection to neighbouring nodes that does not rely on routing at the node level. To achieve this, a set of additional arcs are added to the node splitting transformation and additional constraints are introduced that limit the number of active arcs. The algorithm developed to transform the network is depicted in Figure 3.3 and explained in the following paragraphs.

The first main loop (Line 1) is executed for all network nodes i: An arc (i', i'') is generated and the node cost and capacity are assigned to the new arc. The out-degree $\gamma_{i'}$ and the in-degree $\beta_{i'}$ of node i' are set to one. The fixed cost $g_{i'i''}$ for the new arc (i', i'') is equal to the fixed cost of the original node g_i. While the link cost $c_{i'i''}$ is equal to the node cost c_i of the original node i. The capacity of the original node i becomes the capacity $u_{i'i''}$ of the newly generated link (i', i''). The loop for all demands k (Lines 4 – 8) sums emanating $b^+(i)$ and terminating demands $b^-(i)$ at the current node i, respectively. All demands are reassigned to the corresponding dashed nodes in the same loop; emanating demands to once-dashed nodes, terminating demands to twice-dashed nodes. The next loop (Lines 9 – 15) iterates through all arcs that are leaving node i. The source node is changed to the twice-dashed node and the out-degree of node i'' is increased by one. In the next step, bypass links

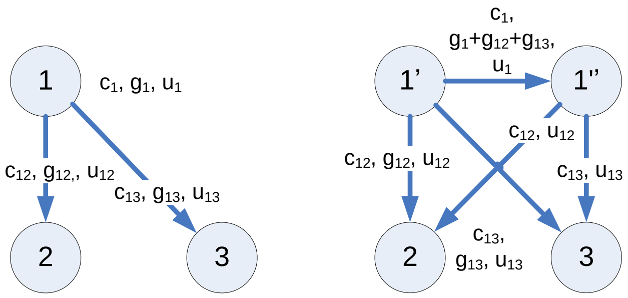
```
algorithm node-bypass-transformation

begin
    for all nodes $i$
        generate arc $(i', i'')$
        $\gamma_{i'} = 1$; $\beta_{i'} = 1$; $g_{i'i''} = g_i$; $c_{i'i''} = c_i$; $u_{i'i''} = u_i$
        for all demands $k$
            if $b^k(i) > 0$
                $b^k(i') = b^k(i)$; $b^+(i) += b^k(i)$
            else
                $b^k(i'') = b^k(i)$; $b^-(i) += b^k(i)$
        for all links $(ij)$ leaving node $i$
            change source node to $i''$
            $\gamma_{i''} ++$
            duplicate the link; change source node to $i'$
            $g_{i'j} += h_i/2$
            if $u_{i'j} < b^+(i)$
                $u_{i'j} = b^+(i)$
        for all links $(ji)$ terminating at node $i$
            change destination node to $i'$
            $\beta_{i'} ++$
            duplicate the link; change destination node to $i''$
            $g_{ji''} += h_i/2$
            if $u_{i'j} < b^-(i)$
                $u_{ji''} = b^-(i)$
end
```

Figure 3.3: Node Bypass Transformation Algorithm

are generated by duplicating the original link and connecting it to the once-dashed node. Costs are also duplicated; however, the capacity is reduced to the size of the emanating demands (Line 15). This limits the traffic on the bypass links to local demands. Half of the node standby power consumption h_i is assigned to the bypass link (Line 13). The final loop (Line 16) iterates through all arcs that are terminating at node i. The terminating end of the link is connected to node i' and the in-degree of node i' is increased by one. The arc is duplicated and its destination node is set to node i''. Half of the standby cost is added to the link's fixed cost and the link capacity is limited to the received traffic (Line 22). This transformation has the following effect: If a node is not in a standby mode, traffic is routed via the router link (i', i'') and all newly added bypass links are deactivated. If a node is in power saving mode, arc (i', i'') is deactivated and the node does not forward any transit traffic. Locally generated traffic is forwarded via bypass arcs emanating from node i', which are included between the router ingress (dashed node such as $1'$) and the destination nodes of the transformed network. As routed and bypass traffic are exclusive, only one arc leaving a dashed node can be used at one time. The additional arcs have the same capacities and costs than the original links. The same applies for terminating traffic: it is either forwarded via the route when it is active; or via one of the bypass arcs terminating at node i'' if the router is in standby mode. As above, only one terminating link at node i'' can be active at one time. A router in standby-mode encounters the fixed cost h_i. This transformation implements the *bridge-all* option discussed in Section 3.3.

Figure 3.2 (c) depicts an example of this extended transformation. For simplicity, only emanating arcs are shown. If the arc $(1', 1'')$ is active, Figure 3.4 (b) is replicated If either arc $(1', 2)$ or $(1', 3)$ is active, all traffic, originally routed via node 1 is routed via node 2 or 3, respectively. Traffic that originated at node 1 in the original network originates at the ingress, node $1'$. The proportional costs of the transformed network are given by Equations (3.8).



(a) (c)

Figure 3.4: Extended node splitting transformation: (a) original and (c) extended transformed network

$$c_{1'2} = c_{1''2} = c_{12} \quad , \quad c_{1'3} = c_{1''3} = c_{13} \quad , \quad c_{1'1''} = c_1 \tag{3.8}$$

and the fixed costs by Equations (3.9) and (3.10).

$$g_{1'2} = g_{12} + h_1/2 \quad , \quad g_{1'3} = g_{13} + h_1/2 \quad , \quad g_{1'1''} = g_1 \tag{3.9}$$

$$g_{1''2} = g_{12} \quad , \quad g_{1''3} = g_{13} \tag{3.10}$$

To make the transformed network equivalent to the original network, additional constraints are required: only one arc emanating from a once-dashed (such as $1'$) node can be used at one time and only one arc can terminate at a twice-dashed node at one time. If all arcs (i', i'') are used, the original network is replicated. If for node i' another emanating arc (i', j) is active and the corresponding termination arc is active, it is equivalent to a network without router i present. In this case, the demands of node i are assigned to node j. To enforce this limitation, the problem formulation has been adapted as outlined in the following section.

3.6 Node Bypass Problem Formulation

This section outlines changes to the multi-commodity flow problem expressed by Equations (3.5) – (3.7) that are necessary to accommodate the network transformation discussed in Section 3.5.

This formulation uses two additional constants γ_i, and β_i, that limit the out- and in-degree of nodes, respectively. For once-dashed nodes, γ_i equals one and for other nodes it is equal to the out-degree that corresponds to their connectivity. For twice-dashed nodes, β_i equals one, for all other nodes β_i is equal to the in-degree. The resulting mixed integer program is given below. The new objective function, Equation (3.11), includes an additional fixed cost g_{ij} for active links.

$$\text{Minimize} \sum_{kij} c_{ij}^k x_{ij}^k + \sum_{ij} \delta_{ij} g_{ij} \tag{3.11}$$

Restrictions that are required for the extended transformation are enforced by two additional constraints given in Equation (3.12) and (3.13).

$$\sum_{j} \delta_{ij} = \gamma_i \quad \text{for all } i \in N \tag{3.12}$$

$$\sum_{j} \delta_{ij} = \beta_j \quad \text{for all } j \in N \tag{3.13}$$

As before, the formulation requires mass balance constraints, given in Equation (3.14).

$$\mathcal{N}\, x^k = b^k \quad \text{for all } k = 1, 2, \ldots, K \tag{3.14}$$

If router i is active, traffic is routed via arc (i', i''), otherwise traffic is forwarded directly between i' and one of the connected nodes. To enforce this, the variable δ_{ij} has also to be included in the bundle constraint shown in Equation (3.15).

$$\sum_{k} x_{ij}^k \leq u_{ij} \delta_{ij} \quad \text{for all } i \in N \tag{3.15}$$

If feasible solutions exist, these models will find an optimal solution.

The problem formulation above has one limitation: demands can only be bridged for one hop. Therefore, only one router between the demand and next router can be turned off. This limitation is intrinsic to the overall problem formulation. If demands have to be forwarded for more than one hop, this requires routing functionality in the intermediate node and therefore violates the overall problem constraints.

From a modelling perspective, this limitation could be overcome by combining bridged nodes into one node and iteratively applying the optimisation again. However, as discussed above, this would have no practical application for the given problem set. This problem formulation provides a solution for the *bridged-all* standby option. Relaxed versions of the problem formulation can be used to implement *bridged-local* and *default-gateway* options as well.

To enable the *bridged-local* standby option, the following changes are required: Additional arcs for terminating demands are not necessary; therefore, Lines 18 – 22 in Figure 3.3 can be ignored and the in-degree constraint in Equation (3.13) is redundant. Terminating demands have to be connected to once-dashed nodes. Therefore, Line 8 has to be changed to $b^k(i') = b^k(i)$ and the standby power consumption has to be assigned to one link only; hence, Line 13 has to be changed to $g_{i'j} += h_i$.

To support the *default-gateway* standby option, the demand limitation of the bypass arcs has to be removed in addition to the changes outlined above; i.e. Lines 14 and 15 have to be removed. As the definitions are less restrictive than the original problem, they lead to simplified transformations and problem formulations. To minimise the network power consumption, costs correspond to energy usage and constraints are link and node capacities. Using this model, the number of routers and links that are necessary to accommodate the traffic can be determined.

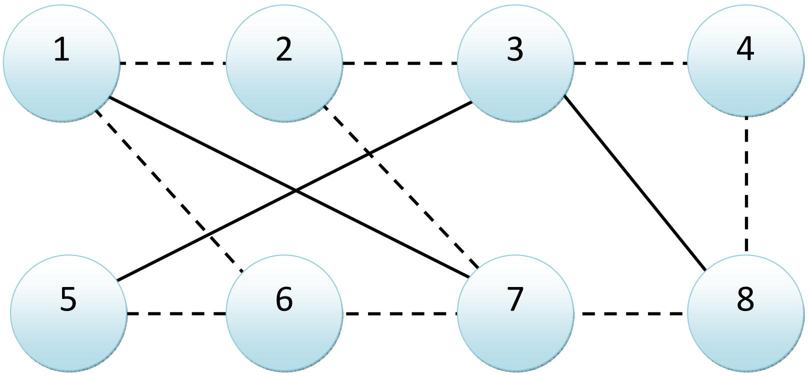


Figure 3.5: Test topology – Eight nodes.

3.7 Simulation Configuration

This section discusses numerical results evaluating optimal topologies. These results were found by analysing two test topologies with large sets of traffic matrices. The two discussed topologies do not cover all possible network configurations, but can provide some indicative results.

3.7.1 Test Networks

Two networks are used to evaluate the models; one with eight nodes and 24 unidirectional links; and one with 22 nodes and 86 unidirectional links. The former is inspired by the Australian Telstra network (AS1221) and the latter by a North American backbone. The networks are similar to the topologies that have been identified by the rocket fuel project [187] without including stub networks. The topologies are depicted in Figure 3.5 and 3.6, respectively. For the eight node network, links have nominal capacities of 1 Gbps (dashed

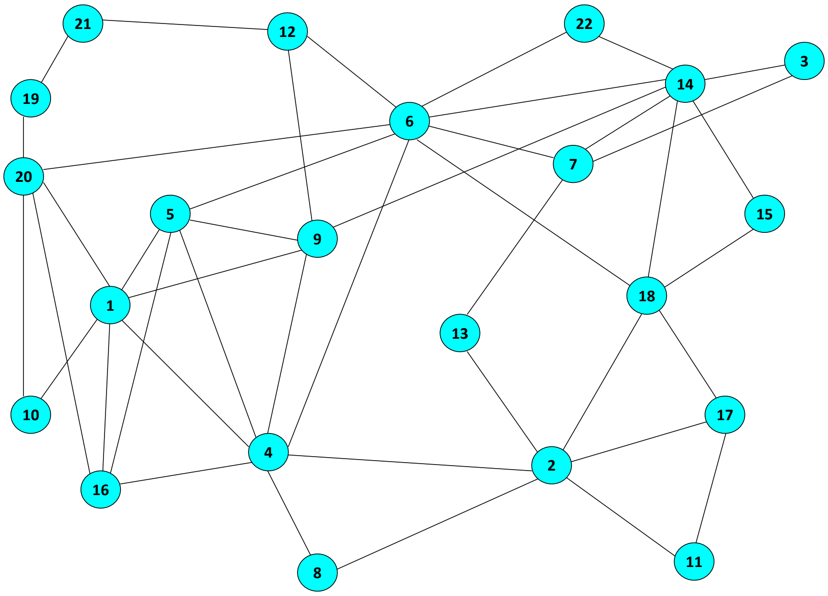


Figure 3.6: Test topology – Twenty Two nodes.

lines) and 10 Gbps (full lines), respectively. If link (ij) exists, link (ji) also exists. Nodes in this network have a capacity of 100 Gbps and do not pose a bottleneck. Traffic matrices for this network include 56 demands, i.e. the traffic demands between all routers.

The experiment used 3327 instances of traffic matrices which have been generated randomly. The matrices reflect traffic demands between origin and destination nodes, but not link utilisation. Realistic traffic matrices feature a demand distribution that reflects the size of the nodes in terms of connected link capacity. For the problem of dynamic topologies such a traffic distribution is advantageous as it accumulates traffic at fewer nodes. This results in more opportunities to put additional nodes into standby modes. A set of randomly generated traffic matrixes therefore underestimates the energy saving potential of a given topology. For the eight node network, random traffic matrixes were chosen as a worst case scenario.

To generalise the results, instances are grouped into 31 sets, according to the total demand of each instance. This traffic data has been used by a number

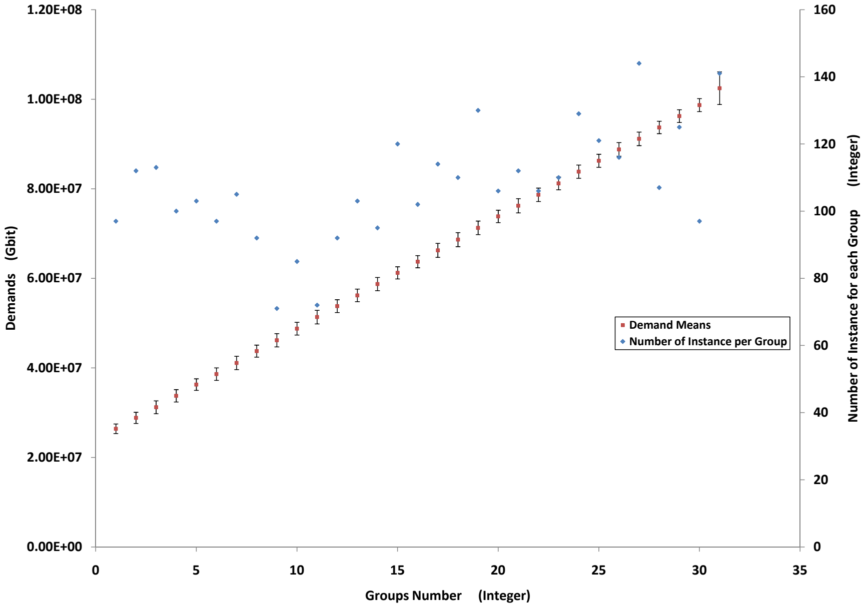


Figure 3.7: Demand Grouping.

of other studies [188]. For the investigations in this chapter, however, only traffic matrices that have feasible solutions for the eight node network are used.

Figure 3.7 depicts the number of instances included in each group. Most groups include more than 100 instances. Figure 3.7 shows the mean of total traffic demands per instance and corresponding 95% confidence intervals. The total demand changes from 2.64 Gbps to 10.21 Gbps, simulating different network load conditions. The maximum total sustainable demand for this network is approximately 10 Gbps.

The theoretical network capacity, i.e. the sum of all link capacities, is much higher, at 78 Gbps. The difference is due to the situation that demands are routed via a number of links between origin and destination. Furthermore, demands do not exactly match available link capacities. In the absence of any traffic engineering or optimisation, a network is fully loaded once one or more links become congested.

The 22 node topology (Figure 3.6) features link capacities between 256 Mbps and 8192 Mbps. Nodes have a capacity of 128 Gbps and therefore do not pose a bottleneck. Traffic matrices for the large network include 462 demands and are based on a gravity model; i.e. highly connected nodes attract more traffic. The process of how these traffic matrices are generated is described in [189].

These traffic matrixes follow the gravity assumption; however, this does not necessarily mean that they provide feasible solutions for the network. The traffic matrix instances are scaled with a load factor to cover the complete range of potential operating conditions. Previous work [189] indicates that this network reaches saturation at a total traffic load of about 60 Gbps. Above this load, individual links become overloaded. The theoretical capacity of this network is 212 Gbps. As discussed above, the value is not of practical relevance in this context. Only traffic matrixes providing feasible solutions for the unmodified network have been included.

3.7.2 Device Power Model

The minimum power consumption of the eight nodes network is limited by the fixed power consumption of eight nodes $(8 \cdot 540\ W = 4320\ W)$ and 24 links $(24 \cdot 64\ W = 1536\ W)$, 5856 W. A fully loaded network would consume 6720 W. This marks an upper bound and not a practical value as it implies that all nodes and links are 100% loaded.

For the 22 nodes network, an unloaded network will consume 17,384 W: 11,880 W by nodes and 5504 W by links. If all network nodes and links are fully loaded, the network consumes 20,080 W. These two values mark the performance baseline of the unmodified network.

3.7.3 Integer Linear Programming (ILP) Solver

The open source mathematical programming toolkit GNU LP Solver (GLPK) [190] and the SCIP tool [191] are used to solve the mathematical programs for the test networks. Alternatively, the commercial IBM ILOG CPLEX Optimizer can be used as a solver with reduced runtimes. Practical times to solve the problems vary greatly. On an Intel Xeon Processor E5504, 2GHz with 24 GBytes RAM it takes at most minutes for the 8 node network and on average about 4 hours for the 22 node network. As these problems are known to be NP hard, only a limited size problem number of topologies can be solved. The times are not suitable for online implementations; however, the aim of this chapter is to evaluate performance thresholds, and online algorithms will have to rely on suitable heuristics.

To evaluate performance in this study, it is assumed that link utilisation is a sufficient measure for network performance. This assumption is widely used [192, 193]. If the effective link utilisation is below 100%, performance is acceptable, but above this threshold performance is insufficient. If links are over provisioned, this assumption does not necessarily imply that the actual link utilisation is 100%. All discussions in this chapter refer to effective link utilisation and not the real link utilisation.

3.8 Results

This section presents results that have been found by applying the mathematical model introduced in Section 3.4, to the test setup explained above. Numerical results are presented for the *bridged-all, bridged-local* and *default-gateway* standby options for the eight node network. In addition, the results are compared to the links-only options which correspond to an optimisation model that has been introduced by Chiaraviglio [167]. For the twenty two node network *bridged-all* and *link-only* standby option results are presented.

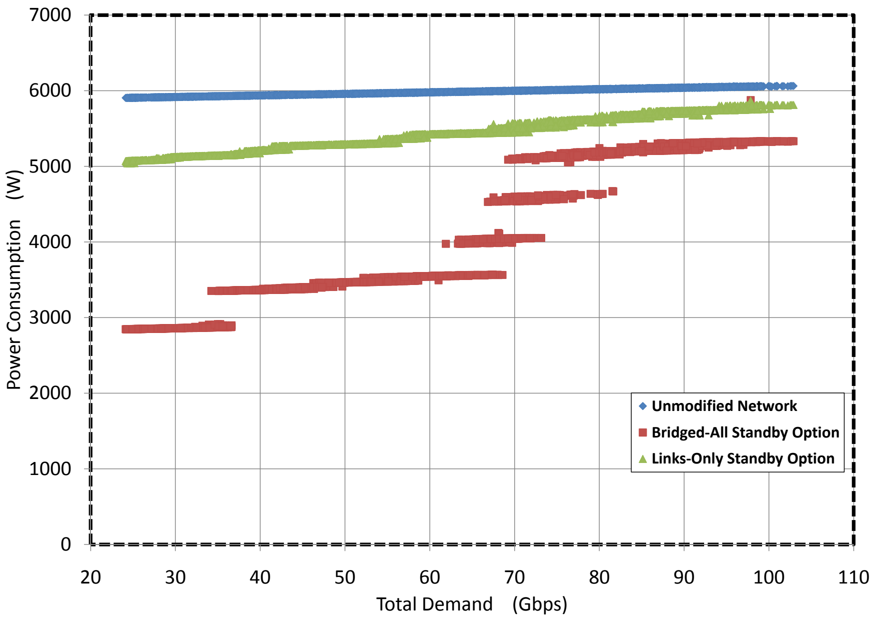


Figure 3.8: Power consumption versus total demand; eight node network; original network, links-only and bridged-all standby options.

3.8.1 Eight Node Network – Bridged-All

For nodes in standby, locally emanating and terminating traffic is bridged to individual links. Figure 3.8 depicts the network power consumption versus total traffic demand, as a scatter plot for all traffic instances.

The cloud on top (blue ◆) shows the energy consumption of an unmodified eight node network. In this case all eight nodes are active and the slope shows the impact of the variable network power consumption. As the nodes in this network are over provisioned and variable power consumption is scaled by capacity, the impact of variable power consumption is less than the theoretical maximum would suggest. This baseline depicts the minimum power consumption for an unmodified network.

The cloud below (green ▲) shows the results for the *link-only* option. In this case, all nodes remain active and only links can be turned off. At lower loads more links can be powered down, which leads to an increased slope. It shows improvement in comparison with the unmodified network. In both cases, the energy-use increases approximately linearly with demand. For higher loads more links are required and power values approach the baseline.

The lower clouds (red 🟥) show the energy consumption for the *bridged-all* option. Five distinct clouds and an additional single value can be identified.

Figure 3.9 depicts the number of active nodes versus the total demands for the same data set. The graph shows similar patterns to Figure 3.8. Individual clouds correspond to the number of active nodes. Three nodes have a fixed power consumption of 1620 W, five nodes in standby consume $5 \cdot 120\mathrm{W} = 600\mathrm{W}$. The fixed power consumption for a network with three active nodes due to nodes is therefore 2220W; approximately 650W are due to links and load.

For each additional activated node, the fixed power consumption is raised by 420W. The power consumption is reduced considerably in relation to the unmodified network as well as the *links-only* power option. The ability to reduce the network power consumption of the various standby options is discussed in Section 3.8.3 in more detail.

Figure 3.10 depicts grouped results for the number of active nodes that are required to accommodate given traffic loads. The graph shows the average number of nodes that are required for a particular demand group and the corresponding 95% confidence intervals. The graphs are similar to Figure 3.9, but also indicate how general the number of active network nodes is for a particular demand group.

Groups with a large confidence interval have no specific network representations. However, there are three traffic levels that result in a constant number of active nodes. For this particular example, topologies with three, four and seven routers provide topologies that cover a wide range of traffic conditions.

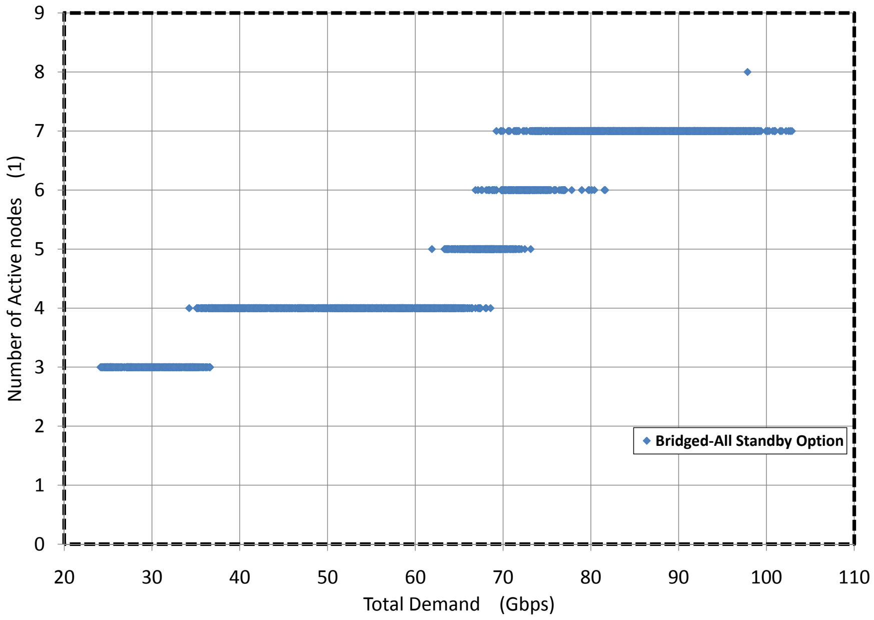


Figure 3.9: Number of active nodes versus total demand; 8 node network; bridged-all standby option.

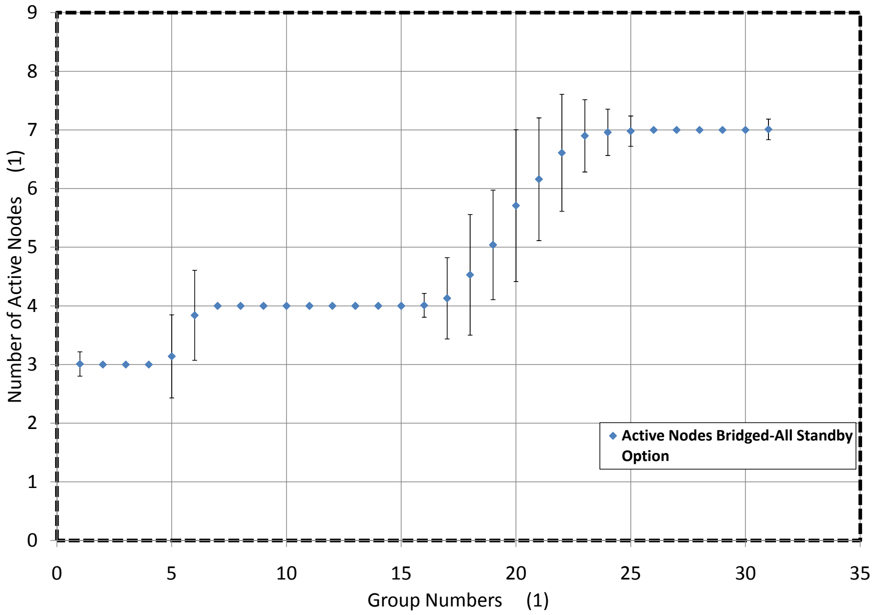


Figure 3.10: Number of active nodes versus demand groups; eight node network; bridged-all standby option.

Table 3.2: Active Node Count

Active	Total	Instance count where node # is active							
Count	Instances	1	2	3	4	5	6	7	8
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	519	0	29	519	0	25	8	502	498
4	1193	0	873	1193	0	432	93	1069	1112
5	225	0	78	225	1	224	148	225	224
6	210	10	203	210	16	210	201	200	210
7	1171	1	1171	1171	1171	1171	1171	1170	1171
8	1	1	1	1	1	1	1	1	1

Furthermore, it can be observed in Figure 3.9 that for most cases, seven active nodes are sufficient to service demands. Only one out of 3327 instances requires 8 nodes. These results indicate that implementation of an active dynamic topology network is feasible, especially, if network load levels can be detected, and effects of dynamic traffic rerouting are minimised.

These observations are further supported by Table 3.2. The table shows the frequency of active nodes in relation to the number of active nodes for the eight node network and the *bridged-all* standby option. The second column shows how many instances feature a particular number of the active nodes listed in the first column. The remaining columns show a matrix of how often a node was active as part of the total node count in each row. The table gives an indication of the importance of nodes are in the overall topology. In the network configuration, Node 1 was only used 12 times. In contrast, Node 3 is always active. Nodes 7 and 8 are active most of the time; and Node 6 is active for most of the higher loaded instances.

3.8.2 Eight Node Network – Bridged-Local and Default Gateway

Figure 3.11 depicts a scatter plot of the network power consumption versus the total demand for the *bridged-local* standby option. In this case, locally originating demands of nodes in standby are forwarded via one bridged link, while terminating traffic can be received via all terminating links. As expected, this does not lead to fewer active nodes than the first option. There is no major difference between both bridged options in terms of network power consumption.

Figure 3.13 depicts the number of active nodes versus the demand groups for the same data set. These results are also very similar to the *bridged-all* standby option. The only difference occurs at higher network loads for demand groups 25 to 30, where, for several instances six nodes are sufficient, though the *bridged-all* option requires seven nodes.

Figure 3.12 depicts the power consumption for the *default gateway* node standby option and Figure 3.14 shows the corresponding active nodes versus demand groups plot. This option provides the greatest saving as low demands up to Group 6 require only two active nodes. However, the number of nodes is not as specific as they were for the first two standby examples, as indicated by the higher confidence intervals in Figure 3.14.

3.8.3 Comparison of Power Consumption

Table 3.3 shows the mean power consumption for every fifth demand group for the standby options and quantifies power savings compared to the unmodified network. All three standby power options perform at a similar level for medium to highly loaded networks. For modestly loaded networks, *bridged-*

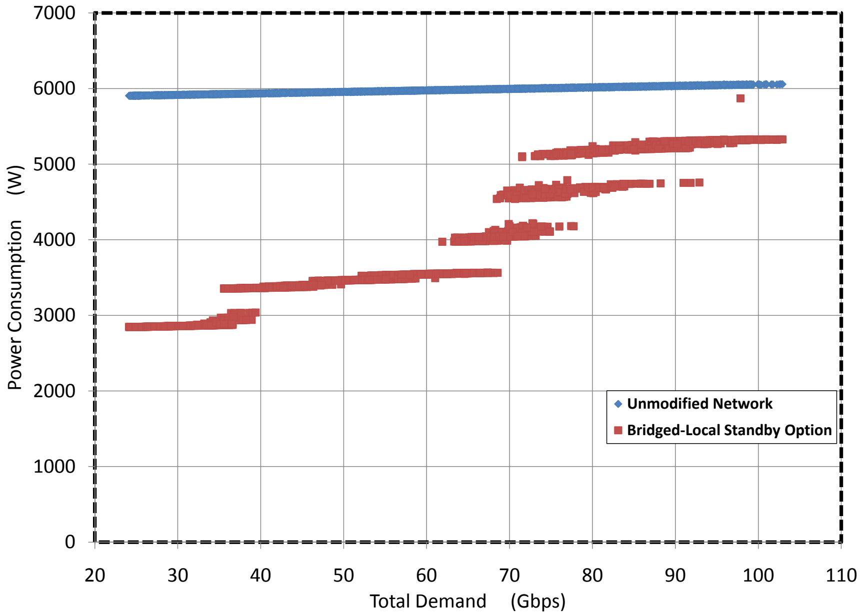


Figure 3.11: Power consumption versus total demand; 8 node network; original network and bridged-local standby options.

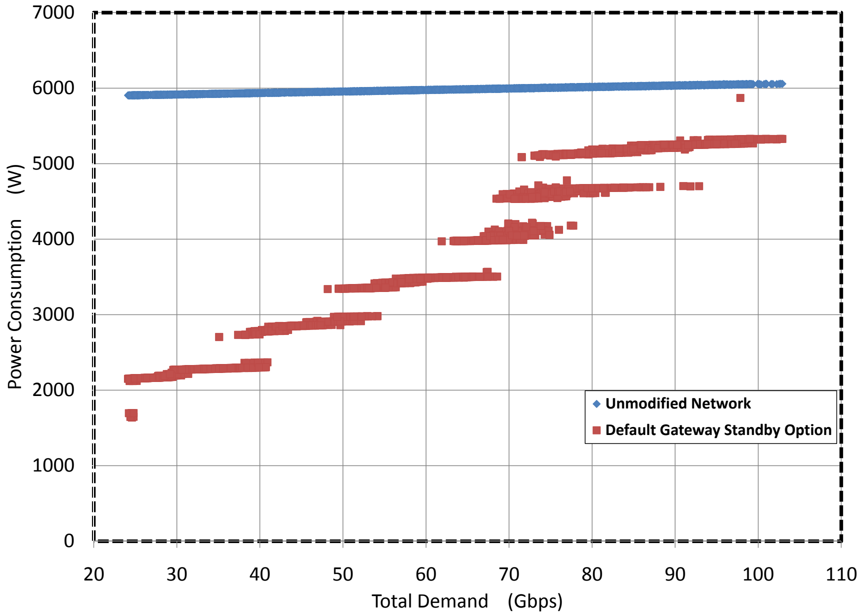


Figure 3.12: Power consumption versus total demand; eight nodes; original network and default gateway standby options.

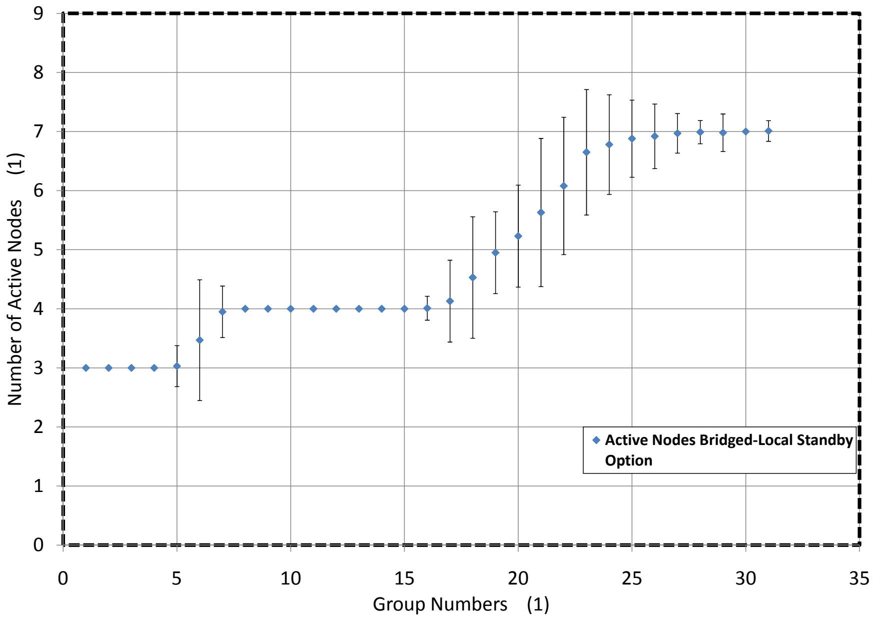


Figure 3.13: Number of active nodes versus demand groups; 8 nodes; bridged-local standby option.

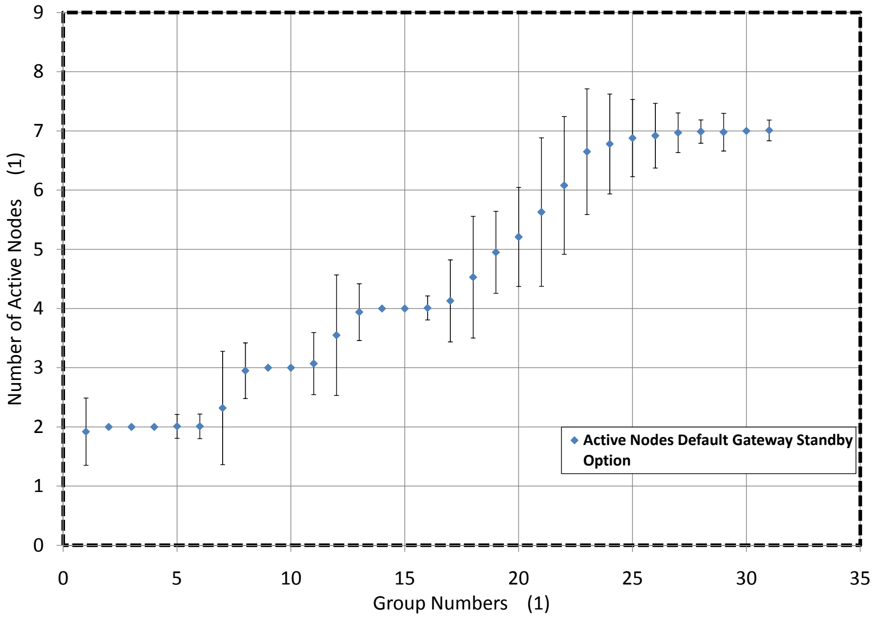


Figure 3.14: Number of active nodes versus demand groups; eight nodes; default gateway standby option.

Table 3.3: Power Consumption of the eight Node Network

Group Number	1	6	11	16	21	26	31
Original [W]	5906	5929	5953	5977	6000	6024	6049
links-only [W]	5071	5155	5288	5425	5532	5674	5778
Savings	14 %	13 %	11 %	9 %	8%	6 %	5 %
bridged-all [W]	2848	3280	3455	3552	4663	5214	5328
Savings	52 %	45 %	42 %	41 %	22%	13 %	12 %
bridged-local [W]	2847	3135	3453	3550	4419	5173	5322
Savings	52 %	47 %	42 %	41 %	26%	14 %	12 %
default gateway [W]	2115	2297	2950	3492	4398	5156	5300
Savings	64 %	61 %	50 %	42 %	27%	14 %	12 %

all and *bridged-local* operate at a similar level, while the default gateway offers the greatest savings. Once the network reaches a load of about 50% to 60%, the number of active nodes increases rapidly and power reductions are lessened.

Power consumption and active node graphs support this observation. This effect of power saving is the same for all standby options. The overall results suggest that *bridged-all* is the best option as it requires the lowest level of functionality and offers excellent power savings. The difference in comparison to the links-only option shows the potential for dynamic topologies to reduce the networks energy footprint.

3.8.4 Twenty Two Node Network – Bridged-All

To complement the comprehensive results discussed for the eight node network topology, this section introduces a smaller set of instances with results for the 22 node network using the *bridged-all* standby option. The results indicate that when the model is applied to a larger network, with more realistic traffic matrices, similar power savings are possible.

Figure 3.15 depicts the network power consumption versus the total demand as a scatter plot for the 22 node network. The top row of data points (blue ◆) show the energy consumption of an unmodified 22 node network with all nodes active. This marks the baseline power consumption for the original network. The data points below (green ▲) show the results for the *link-only* option and the lowest set of data points (red ■) show the energy consumption for the *bridged-all* option.

Figure 3.16 depicts the number of active nodes versus the total demand for the same data set. The minimum number of nodes encountered in this topology is six. This suggests that at least six nodes are necessary to provide sufficient connectivity to service all network endpoints. The minimum fixed power consumption of six active and sixteen standby nodes is 5160W, with approximately 2000 W of additional consumption due to links and loads.

This network has no single network configuration occurring for low loads; however, configurations with between six and ten active nodes can be observed. If the network load increases above around 50%, the number of active nodes increases rapidly. The maximum number of active nodes that are seen for this configuration is 20, suggesting that two nodes are redundant.

3.9 Discussion

The aim of this chapter has been to address the generic network problem of minimising energy consumption for a given traffic load. The study has been based on currently available network hardware. The introduction of standby

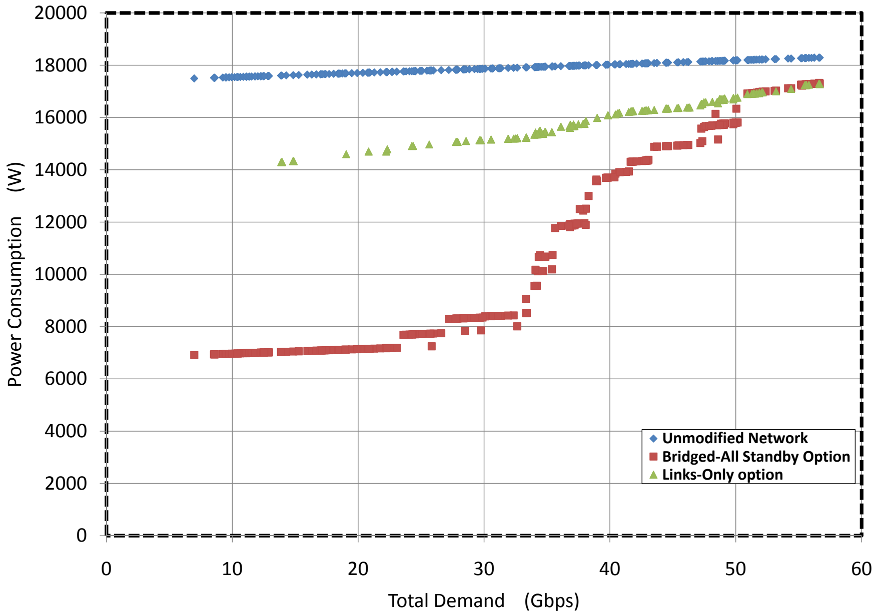


Figure 3.15: Power consumption versus total demand; 22 nodes; original network, links-only and bridged-all standby options.

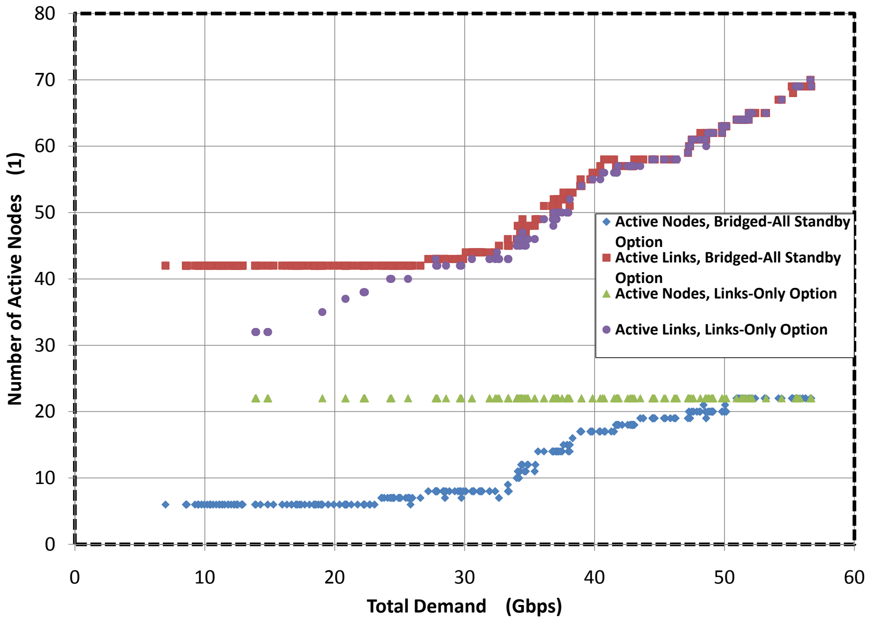


Figure 3.16: Number of active nodes versus total demand; 22 nodes; bridged-all standby option.

options for reduced functionality in routers is envisaged that will yield lower energy footprints. These do not require major architectural changes, but some systems in the network topology have to be adapted. For example power supplies currently consume approximate 30% of the total energy of a router and options are required that these scale with load.

The study of network devices and standby options in routers is important to identify potential reduction in energy consumption. Current routers consume a lot of energy in standby mode and there is significant potential to improve this. Some techniques discussed in Section 3.1.1 could help to address this problem. More advanced devices would have a load proportional power profile. In the models discussed in this chapter, this means that the load-proportional power component is higher than the fixed component. However, the proportion of fixed to variable power consumption has no direct impact on the accuracy of the model. The model will work in the same way for all proportions. Furthermore, if the energy consumption is entirely has only a variable component, then there is no need to turn any nodes off as the network always operates at the most power efficient level. As future devices are likely to have higher load dependent power components, this model can be used to evaluate decision-making thresholds where it becomes uneconomical to turn nodes off. If the variable power component increases, the slope of the lines in the graphs will increase as well because the traffic load has increased, which means more nodes are required to manage the increased traffic load. At the same time, the power saving gap between optimised and original network will reduce.

If networks are able to adapt to traffic demands, network power consumption can be reduced considerably. To allow router standby modes, minor modifications to routers are required. It is worthwhile looking into the protocol dynamic aspects of dynamic topologies, as these mechanisms allow for substantial power savings in communication networks. As these problems are

NP-hard, applications are limited to medium sized networks. However, these models can be used in network planning applications and to benchmark the performance heuristics which can be applied to larger networks. Practical online applications of the dynamic topology problem have to rely on local information, as other approaches are not scalable. This point has also been made by Vasic and Kostic [170] and has driven their approach to the problem.

3.10 Conclusion

In the past, most research has sought solutions to the problem by proposing mechanisms to reduce energy consumption in the devices themselves. As demonstrated in this chapter, the power consumption problem can also be addressed by adapting networks to traffic loads.

This chapter has investigated using dynamic topologies to adapt where network traffic demands are changing over time. It has also evaluated the ability of selected dynamic topologies reduce power consumption. This chapter has also introduced a generic multi-commodity flow problem and a generic power model for the power consumption of routers.

This study has shown that the application of dynamic topologies in the communication network can lead to significant power reductions, the target of this investigation. This means that further investigations of the dynamic aspects of this study are feasible.

Conventional routing protocols are not practical for implementing dynamic topologies as they can take several minutes to converge, leading to packet loss and service disruptions. Further investigations have to address questions such as how the transitions between states is managed, how load information is obtained and distributed and how the networks are dynamically reconfigured.

The mathematical models developed are able to be modified to take other aspects into account in the future, such as performance guarantees, service levels and the resilience of the dynamic topologies with multi-commodity flow problems.

Chapter 4

Algorithms to Generate Dynamic Topologies

Network topologies that adapt to the network loads have been investigated in Chapter 3 and theoretical models have been developed that generate reduced topologies for given traffic demands. The complexity of the mathematical program formulations means that only small networks can be readily solved at this time.

Heuristic methods can generate reduced topologies for larger network by applying complex formulations with proper constraints. In this chapter algorithms are introduced that are able to identify routers and links that can be switched off to reduce the power consumption. To do this, these algorithms either evaluate the network load or the capacity of nodes. The performance of the algorithms is compared to the optimal results that were generated in Chapter 3 using mathematical models.

4.1 Introduction

The solutions to solve multi-commodity flow problems, and generate minimal topologies presented in the previous chapter are based on linear programming techniques. The Integer Linear Programming (ILP) formulations are able to generate optimal solutions by using network flow problem formulations. However with increasing network size, these problems becomes too difficult to solve within practical time frames.

In the context of this thesis, a number of heuristics are introduced and investigated in order to identify and find the optimal solutions for the reduction of power consumption in the resulting dynamic topologies. Link utilisation is a simple but suitable measure for network performance and this parameter is widely used by similar studies [192].

It is assumed that system performance is acceptable if the effective link utilisation is below 100%; above this threshold, performance becomes unacceptable. This is only the effective link utilisation and the actual link utilisation has to be below 100%. Some Internet Service Providers (ISPs) maintain actual link utilisation below 50%, otherwise links encounter unacceptable queuing delays and/or packet loss. This project seeks the optimal reduced topology solution based on the link utilisation. All discussions in this chapter refer to effective link utilisation and not to actual link utilisation.

In general, routers are the main energy consumers in conventional communication networks [194]. For this reason, the algorithms focus on techniques that are able to optimise the number of active nodes for a given traffic load and topology. Since routers have a major load-independent power component, network optimisation will optimise the overall network power consumption. The proposed algorithms differ in the type of information used to make decisions about the network topology.

Two basic algorithms are investigated: the Lightest Node First (LNF) algorithm relies only on topology information; and the Least Loaded Node (LLN) algorithm that requires traffic data. If nodes are turned off as part of optimisation, their local demands have to be bridged to other nodes. These algorithms have been created based on the concept of algorithm design and analysis outlined in [173].

A number of options have been proposed in Section 3 as to how these demands can be reassigned. In this discussion, local demands of deactivated nodes are transmitted via single emanating links, and terminating demands are received on single interfaces. To deactivate a node, all but one emanating and one terminating arc are removed. In this algorithm, the capacities of the remaining arcs are reduced to equal the demand of the node. This prevents additional traffic being routed via the remaining active arc. It is assumed that networks in this study use shortest path routing, such as the Open Shortest Path First (OSPF).

4.2 The Lightest Node First Algorithm (LNF)

This algorithm relies on topology information to identify nodes and links that can be removed for current traffic loads. The underlying assumption of this algorithm is that nodes which have a higher number of connected links are more important in a network topology.

The LNF algorithm evaluates the gravity of a node, which is the maximum capacity of node, by adding the capacity of all connected links. Nodes with the lowest gravity value are turned off first. The concept of gravity has been used in the context of traffic matrix estimation and network optimisation in other studies [195]. Figure 4.1 shows the pseudo code of the proposed LNF algorithm.

```
algorithm LightestNodeFirst()

1   calculateNodeGravities()
2   while $LinkUtilisation < Threshold$
3       removeNodeWithLowestGravity()
4       findAllShortestPaths()
5       loadNetwork()
6       calculateLinkUtilisation()
7   end
8   restoreLastNodeRemoved()
```

Figure 4.1: The Lightest Node First Algorithm

Initially, the algorithm calculates the gravity of all nodes and creates an ordered list of nodes that could potentially be switched off. As part of the while loop, the node with the lowest gravity is removed (Line 3). The connected links to this node are switched off except for the link that is used to bridge the local demand, which is bridged to the neighbouring node with the highest gravity that can accommodate the additional traffic. The neighbouring node is then removed from the candidate list of nodes that can potentially be turned off. This is necessary as nodes that route bridged demands have to retain their routing functionality and can therefore not be placed into a standby mode. As this was the neighbouring node with the highest gravity it is also unlikely to be turned off.

The shortest path is calculated in the reduced network (Line 4). The network is loaded and the maximum link utilisation is calculated. If the utilisation is below threshold, the loop is executed again. Otherwise the algorithm terminates and restores the last node that has been removed. This restores the last feasible solution set. The resulting set of nodes and active links represents the solution. The running of the algorithm is required time which is complex to measure. The time complexity or the worst case complexity is a function of the problem size and indicates the largest amount of time needed by the algorithm to solve a given network problem. So, the size of a network problem is a function of how the problem is stated. Therefore, the problem size can be expressed as:

$$n \log n + m \log m + m \log C + m \log U \tag{4.1}$$

Where:
n is the number of nodes and m is the number of links. C represent the largest arc cost and U is the largest arc capacity, $m \leq n^2$, $\log m \leq \log n^2 = 2 \log n$.

The running time of the algorithm could be cnm and by applying the big O notation, the running time will be $O(nm)$. The iteration to find all shortest paths can be specified by $n^3 \log n$ and the iteration for the whole algorithm can be described by $n^2 m$. Therefore, the running time of the algorithm could be expressed as a function of a problem size and the worst case complexity function will be:

$$n^2 m + n^3 \log n \tag{4.2}$$

Also, to ignore the constants, big O notation can be used, resulting in:

$$O(n^2 m + n^3 \log n) \tag{4.3}$$

4.3 The Least Loaded Nodes Algorithm (LLN)

Instead of focusing on the gravity of nodes, this algorithm looks at the traffic load of nodes and the routers with the lightest load are removed first. The underlying assumption is that lightly loaded nodes are less important in the network topology. Figure 4.2 shows the pseudo code of the algorithm.

```
algorithm LeastLoadedNode()

while $LinkUtilisation < Threshold$
    removeNodeWithLowestLoad()
    findAllShortestPaths()
    loadNetwork()
    calculateLinkUtilisation()
end
restoreLastNodeRemoved()
```

Figure 4.2: The Least Loaded Node Algorithm

As in the LNF algorithm, the main loop tests if link utilisations are below the threshold. If this is the case, the lightest loaded node is identified and deactivated. The shortest paths are calculated and the network is loaded with traffic. To deactivate a node, all but one emanating link and one terminating link are deactivated. The terminating link is assigned to the neighbouring node with the highest load that is able to accommodate the additional traffic, then the node will removed from the list. These steps are executed until at least one link exceeds the utilisation threshold. Then the last node that was removed is returned, restoring the last feasible solution. This set of active nodes and links represents the solution.

When considering the calculation time and complexity, the iteration to find all shortest paths can be specified by $n^3 \log n$ and the iteration for the whole algorithm can described by n^3m. Therefore the running time of the algorithm could be expressed as a function of a problem size, with the worst case complexity function being:

$$n^3m + n^3 \log n \tag{4.4}$$

Also, the big O notation will apply to remove the constants and the equation will be:

$$O(n^3m + n^3 \log n) \tag{4.5}$$

4.4 Improved Heuristics using Weight Settings

The algorithms presented here can lead to moderate energy savings because traffic is accumulated in a smaller network without any traffic management. However, network links can become overloaded quickly as nodes are removed. This is particularly seen in networks that use shortest path routing, as these networks are not able to redistribute uneven traffic loads.

One possible solution to this problem is to introduce weight settings. As mentioned earlier, shortest path protocols are the most commonly used inter-domain routing protocols. Traffic is forwarded one hop at a time along the shortest path to the destination. By default, link cost is configured as the inverse of the capacity.

The weight of the links that are used by the routing protocol to calculate the shortest paths can be changed by the network operator. The weight setting technique, originally proposed in [192], optimises link weights. The technique leads to new shortest paths that are able to distribute traffic loads more evenly. These techniques have been widely discussed as a means to address traffic distribution and various efficient methods have been proposed to solve related optimisation problems [196].

Both algorithms, LLN and LNF, can be extended to include weight settings. An additional function, *findOptimalLinkWeights()* is included after the respective *removeNode* functions. The link weight is changed dynamically according to the changes in the active link numbers. The weight setting calculations are based on the algorithms reported in [196] to calculate an optimal weight set which is then used to calculate shortest paths and link loads. Based on the traffic demand for the given topology and applying the method proposed in [196], LP is used to find the new optimal weight settings. After that, the new routing matrix, containing the new weight settings, will be applied to the topology. Other steps in the proposed algorithms however remain the same.

4.4.1 The Lightest Node First Algorithm with Weight Setting

As above, the underlying assumption of this algorithm is that nodes having a higher number of connected links are more important in a network topology. The *LNF Algorithm with Weight Setting* (LNFWS) evaluates the gravity of a node by adding the capacity of all connected links. Nodes with the lowest gravity value are turned off first. Figure 4.3 shows the pseudo code of the modified LNF algorithm with Weight Setting.

The key change in this algorithm is the *findOptimalLinkWeights()* function. It is used to calculate a new optimal link weight set before the shortest paths in the reduced network are calculated.

```
algorithm LightestNodeFirst()

calculateNodeGravities()
while $LinkUtilisation < Threshold$
    removeNodeWithLowestGravity()
    findOptimalLinkWeight()
    findAllShortestPaths()
    loadNetwork()
    calculateLinkUtilisation()
end
restoreLastNodeRemoved()
```

Figure 4.3: The Lightest Node First Algorithm With Weight Setting

4.4.2 The Least Loaded Nodes Algorithm With Weight Setting

As before the focus of this algorithm Least Loaded Nodes Algorithm With Weight Setting (LLNWS) is traffic load and the *findOptimalLinkWeight()* function has been added. Figure 4.4 shows the pseudo code of the algorithm.

4.5 Evaluation and Analysis

This section discusses numerical results that have been generated by applying the algorithms to a basic network with a large set of traffic data. The LNF, the LLN, the LNFWS and the LLNWS algorithms have each been implemented in C++ to form a custom tool. The tool calculates shortest paths,

```
algorithm LeastLoadedNode()

while $LinkUtilisation < Threshold$
    removeNodeWithLowestLoad()
    findOptimalLinkWeight()
    findAllShortestPaths()
    loadNetwork()
    calculateLinkUtilisation()
end
restoreLastNodeRemoved()
```

Figure 4.4: The Least Loaded Node Algorithm With Weight Setting

loads the network with traffic and calculates link utilisation. Network power consumption is calculated based on link loads and node/link status.

4.5.1 Test Network and Traffic Data

To evaluate the proposed algorithms, a network topology that consists of 8 nodes and 28 directional links has been used. Figure 5.1 depicts the network topology previously introduced and used in Chapter 3. The experiments used a set of 3327 instances of traffic matrices, ranging from lightly to highly loaded. These instances have been classified into 31 demand groups according to load. These groups allow average calculations for typical traffic loads. Total demand varies between 10.21 Mbps and 26.4 Mbps. Further details on traffic data and grouping may be found in Chapter 3.

4.5.2 Network Power Consumption

To evaluate potential reductions in power consumption of the network, power usage is calculated for different traffic loads. The power models in this chapter are based on the assumptions previously discussed in Chapter 3. It is assumed that 90% of router energy consumption is not load dependent and 10% is load dependent. Routers in standby consume 10% of the fixed cost. Power consumption of line cards is attributed to links and 20% of the total power consumption per link is load dependent.

Absolute power values of routers and links are assumed to be 600W and 80W, respectively. Also, it is assumed that the power consumption of links does not depend on their capacity; however, power per Kbps changes as the proportional power consumption is scaled with capacity. The principal results of the study in this chapter are not impacted by the particulars of the power model, such as the ratio between fixed and variable power consumption. A larger proportion of variable power would only increase the slope in the power consumption graphs in Section 4.6.

4.6 Simulation Results

This section presents numerical results for the network power consumption after applying each of the algorithms. The algorithms have been tested under the same conditions as the models in Chapter 3. The number of active nodes and the overall network power consumption of each algorithm is discussed.

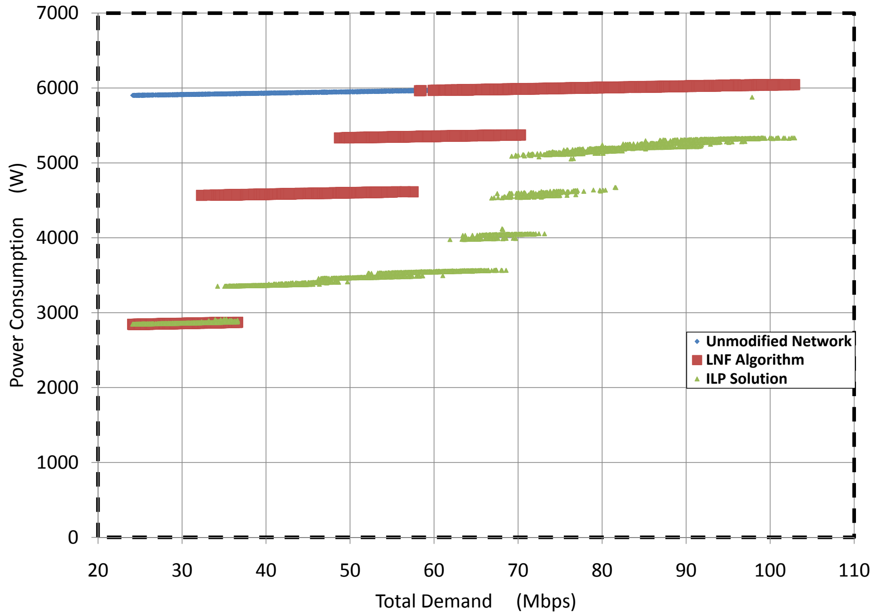


Figure 4.5: Network power consumption, LNF algorithm vs. ILP

4.6.1 Lightest Node First Algorithm (LNF)

The LNF algorithm prioritises nodes by the capacity of their connected links as describe previously. Figure 4.5 depicts a scatter plot of the network power consumption versus the total traffic demand. The top clouds (blue ♦) shows the power consumption of an unmodified 8 node network and the bottom clouds (green ▲) show results for the more computationally expensive ILP model. The dark, bold clouds (red ■) in between depict results for the LNF algorithm. Three distinct clouds can be identified. The cause of different power levels is the number of active nodes. Figure 4.6 depicts the number of active nodes for the same data set. A comparison of cloud patterns in both graphs indicates that the distinct clouds correspond to particular active node counts. For this example network with eight nodes, only configurations with 3, 6, 7 and 8 nodes occur.

Figure 4.7 shows the number of inactive nodes versus demand groups. The bars indicate 95 per cent confidence intervals. For lightly loaded networks a topology with 3 nodes is sufficient; highly load instances require 8 active nodes.

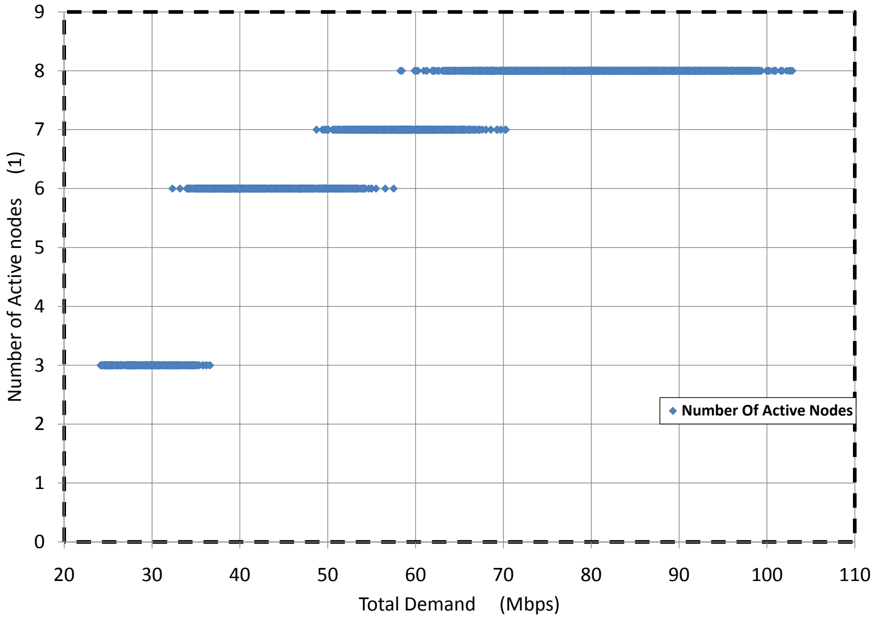


Figure 4.6: Active nodes, LNF algorithm

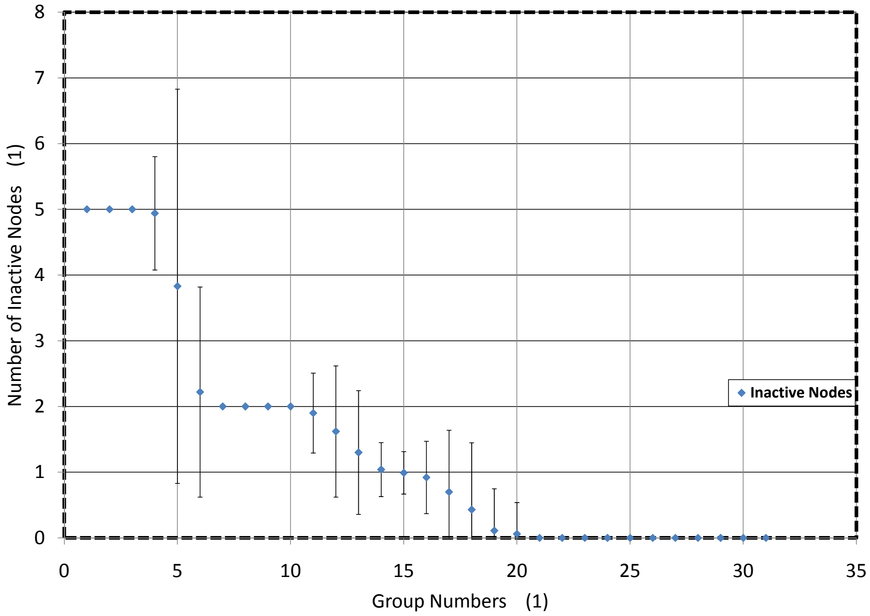


Figure 4.7: Grouped results, inactive nodes, LNF algorithm

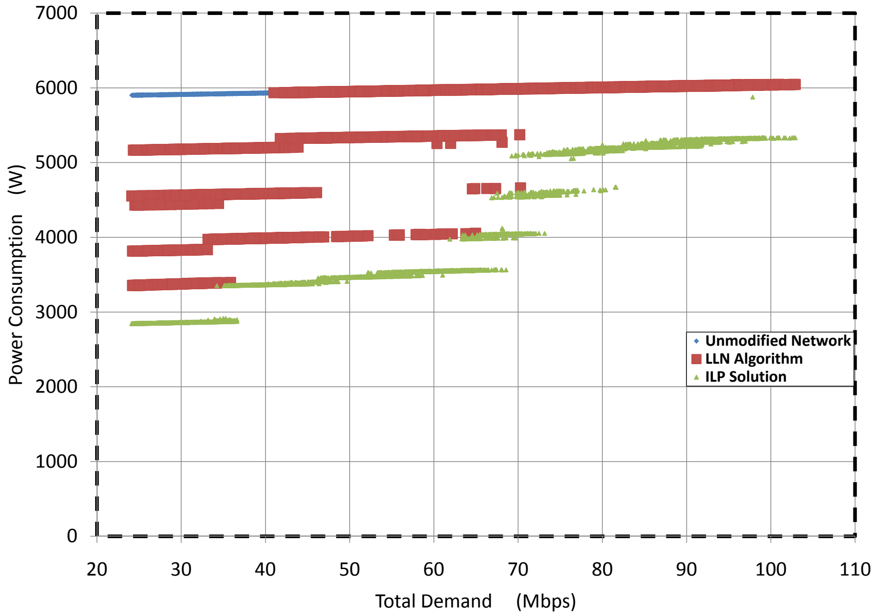


Figure 4.8: Network power consumption, LLN algorithm vs. ILP

The graphs also demonstrate that the power consumption of the modified networks is below that of the original unmodified network. The effect is more pronounced for lightly loaded networks. This is expected as they provide more opportunities to turn nodes off. The size of the confidence intervals indicates how general the number of nodes is for a particular demand group. For Groups one to three, five nodes are always inactive, while, for group five the number of inactive node varies between two and five.

4.6.2 Least Loaded Nodes Algorithm (LLN)

The LLN algorithm takes the load of each network node into account. A similar set of graphs is presented as for the LNF algorithm. Figure 4.8 depicts a scatter plot of the energy consumption versus the total demand for both the original and the modified networks.

Figure 4.9 depicts a scatter plot of the number of active nodes versus total demand and Figure 4.10 depicts grouped results for the active number of nodes

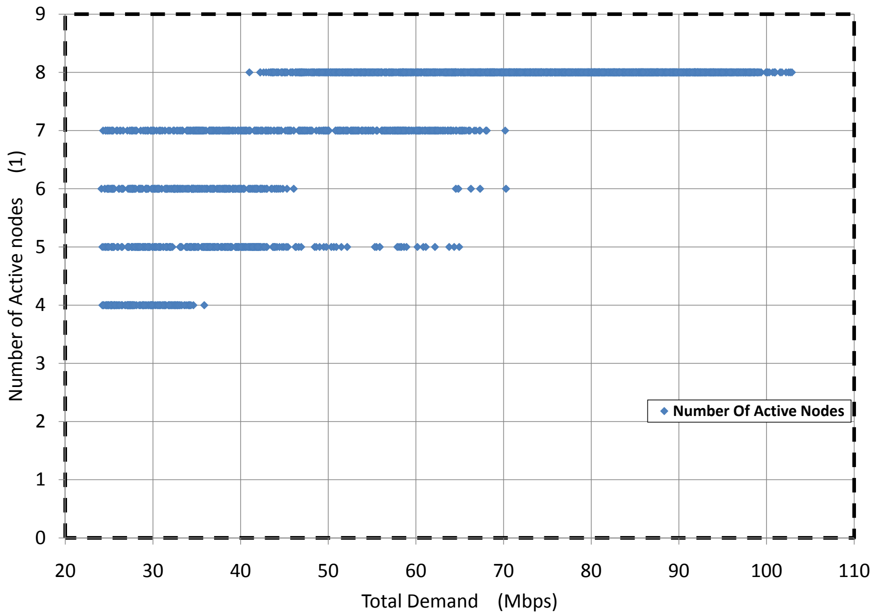


Figure 4.9: Active nodes, LLN algorithm

versus traffic demand. The bars indicate 95% confidence intervals.

For a lightly loaded network, this algorithm leads to greater energy savings. However, for highly loaded networks the algorithm fails to detect redundant nodes in the network topology. The cloud patterns in Figures 4.8 and 4.9 and the larger confidence intervals in Figures 4.10 for this algorithm also suggest a higher variability in topologies for given traffic loads.

4.6.3 Lightest Node First Algorithm With Weight Setting (LNFWS)

The *LNF Algorithm with Weight Setting* (LNFWS) prioritises nodes by the capacity of connected links as well as considering the weight of each link. Figure 4.11 depicts a scatter plot of network power consumption versus total traffic demand. The top cloud (blue ♦) shows the power consumption of an unmodified 8 node network, with the clouds below (red ■) show the results for LNFWS optimised networks. Four distinct clouds can be identified.

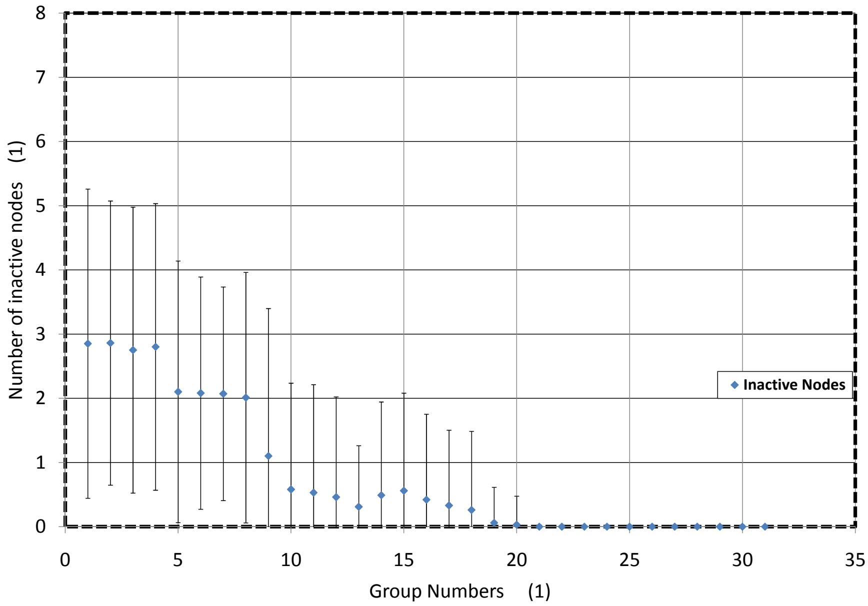


Figure 4.10: Grouped results, inactive nodes, LLN algorithm

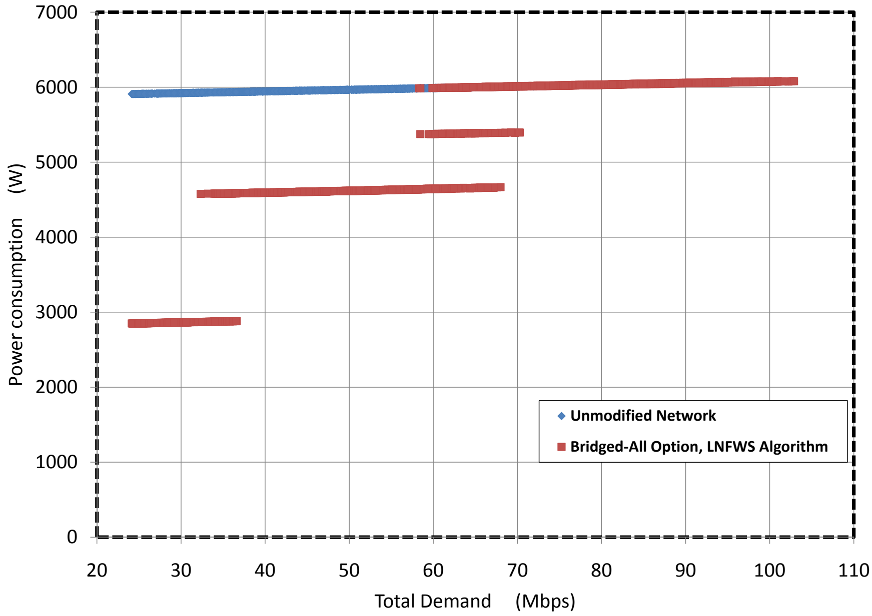


Figure 4.11: Network power consumption, LNFWS algorithm

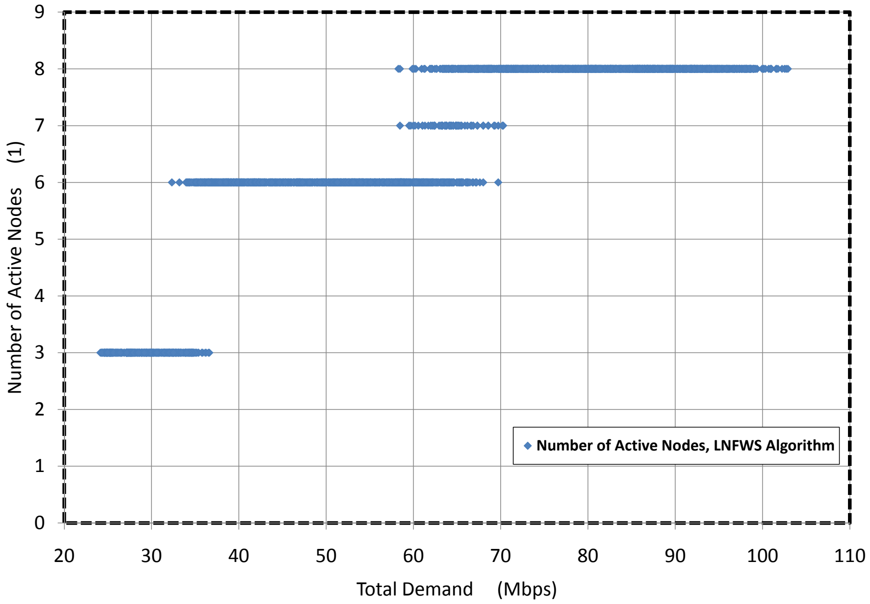


Figure 4.12: Active nodes, LNFWS algorithm

Figure 4.12 depicts the number of active nodes for the same data set. As before, distinct clouds correspond to particular active node counts. For this example, in the network of eight nodes, only configurations using either 3,6,7 or 8 nodes occur.

Figure 4.13 shows the number of inactive nodes versus demand groups. The bars indicate 95% confidence intervals. For lightly loaded networks a topology with 3 nodes is sufficient, however, highly load instances require all nodes to be active. The calculated power consumption of the modified networks is below the power consumption of the unmodified network. This effect is more pronounced for lightly loaded networks as these present more opportunities to turn nodes off.

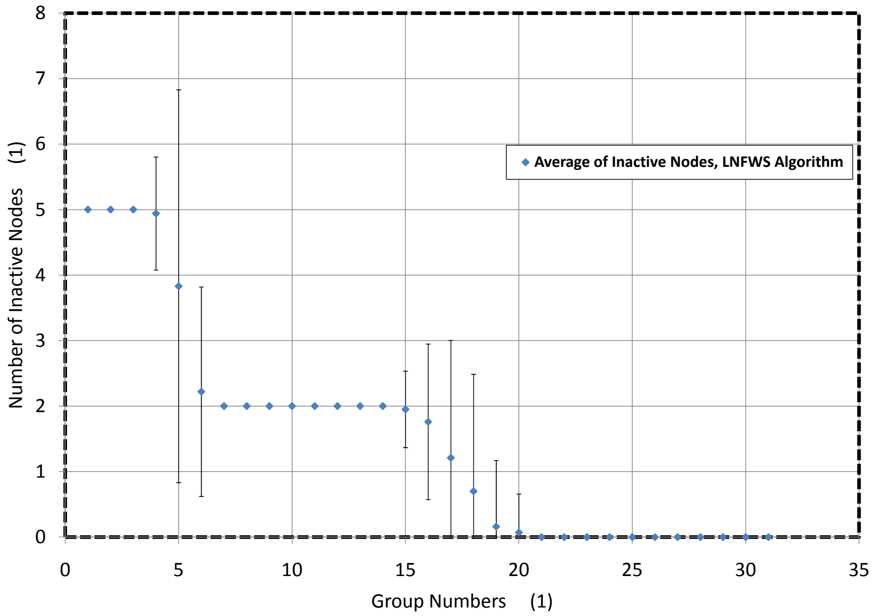


Figure 4.13: Grouped results, inactive nodes, LNFWS algorithm

4.6.4 Least Loaded Nodes Algorithm With Weight Setting (LLNWS)

The *LLN Algorithm with Weight Setting* (LLNWS) takes the load of network nodes into account. The same set of graphs is presented as for the LNFWS algorithm. Figure 4.14 depicts a scatter plot of energy consumption versus total demand for the original as well as the modified networks. Figure 4.15 contains a scatter plot of the number of active nodes versus total demand and Figure 4.16 shows grouped results for the active number of nodes versus traffic demand. Confidence intervals of 95% are indicated by the error bars. As for the LNFWS algorithm in lightly loaded networks the algorithm leads to greater energy savings. However, for highly loaded networks the algorithm fails to detect the redundant nodes in the network topology. The larger intervals for this algorithm also suggest a higher variability in topologies for given traffic loads, similar to that seen for the LNF algorithm.

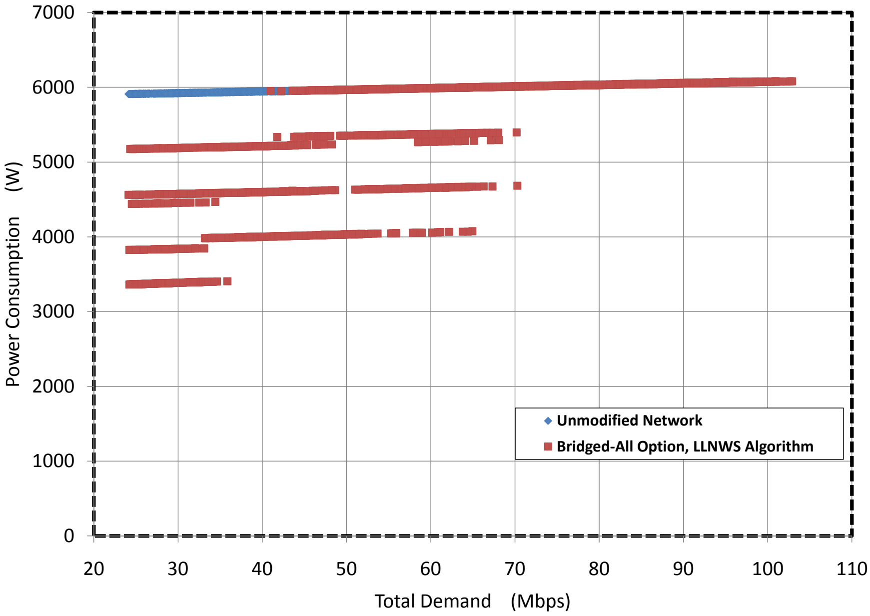


Figure 4.14: Network power consumption, LLNWS algorithm

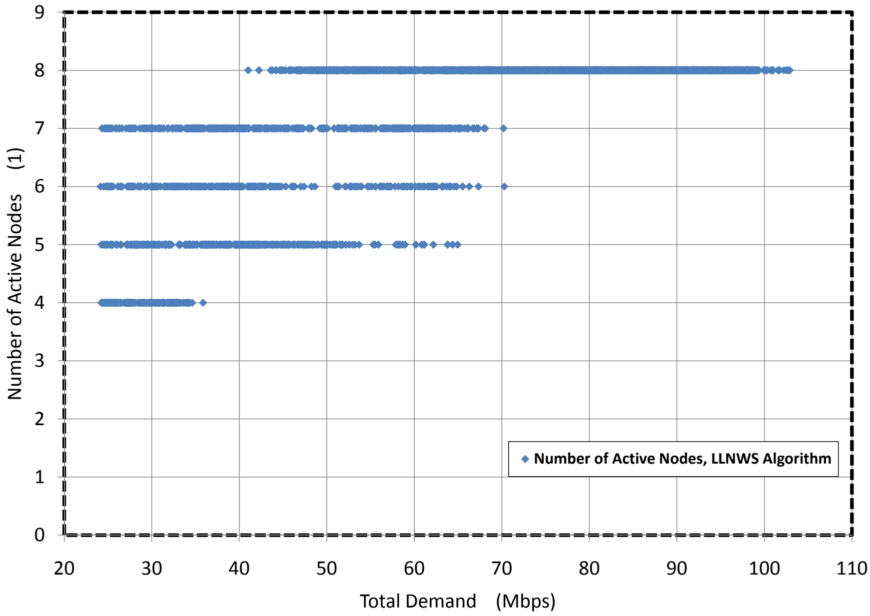


Figure 4.15: Active nodes, LLNWS algorithm

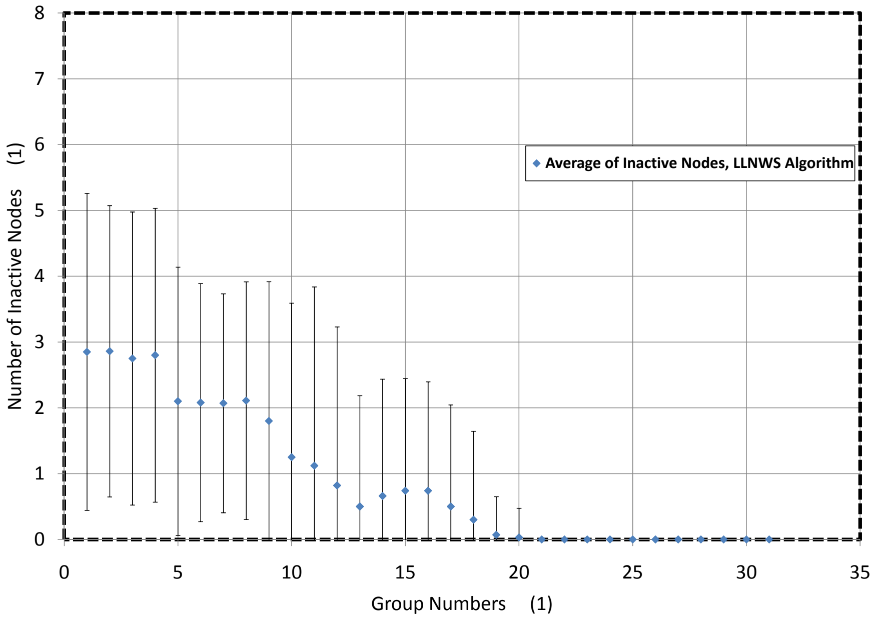


Figure 4.16: Grouped results, inactive nodes, LLNWS algorithm

4.7 Discussion

Numerical results for a number of sample instances are summarised in Table 4.1. The average power consumption is given for the unmodified network, the dynamic configuration derived by each algorithm and the ILP model. The table also compares dynamic topologies with the unmodified static topology.

It is interesting to note that algorithms that apply weight settings exhibit a similar performance to their non-weight setting equivalent. However, for the LLN and LNF algorithms, it can be observed that the flow has low traffic loads. It also produces more specific results for particular demand groups. The higher correlation between demand groups and number of active nodes are visible in Figures 4.5 and 4.7. These results indicate that node capacities are more important than traffic loads in the network.

The situation is mirrored by the LLNWS and the LNFWS algorithms. Again, the LNFWS produces more specific results for higher demand groups, visible in Figures 4.11 and 4.13.

Table 4.1: Power Consumption [W] of the eight Node Network

Group #	1	6	11	16	21
Original	5906	5929	5953	5977	6000
LLN	4026	4533	5597	5638	5994
Savings	32%	24%	6%	6%	0.38%
LLNWS	4026	4533	5142	5511	5994
Savings	32%	24%	14%	8%	0.38%
LNF	2851	3538	4610	5376	5977
Savings	52%	40%	23%	10%	1%
LNFWS	2851	3538	4610	4675	5977
Savings	52%	40%	23%	22%	1%
ILP	2848	3280	3455	3552	4663
Savings	52%	45%	42%	41%	22%

Both algorithms (the LLN and LNF algorithms) are not able to approach the optimal results found by ILP model, for moderately and highly loaded networks. This is partly due to the shortest path algorithms and could be alleviated by weight setting. Using weight setting techniques can reduce the consumption of the power in the reduced network more effectively than algorithms that are not using weight setting techniques. The LFNWS and the LLNWS algorithms are able to calculate the shortest path and link load which leads to prevention of the immediate link becoming overloaded.

4.8 Conclusion

In this chapter, the optimal solution for the traffic load in the dynamic topologies network has been evaluated to emphasise the potential to reduce the power consumption of communication networks. A number of heuristics have been proposed in this chapter that assist in finding optimal topologies for given traffic loads. Ultimately, these algorithms attempt to reduce the number of active network elements. All algorithms have been simulated under the same conditions as part of the evaluation.

For the LLN and LNF algorithms, results indicate that even simple optimisation algorithms are able to find topologies with much smaller energy consumption than the original network configuration. The effect is particularly evident in lightly and medium loaded networks. As networks operate around these load levels most of the time, dynamic topologies have the potential to provide significant power savings and consequently reductions in GHG emissions.

While the LNN and LNF algorithms were able to find topologies for lightly loaded nodes, the power reduction results are still below the optimal results for the given topologies as links quickly overload. The LLNWS and LNFWS algorithms presented in this chapter enhance these algorithms and it has been shown that there is reasonable reduction of energy when the weight setting has been applied.

This work has focused on the static case and the results showed that reduced topologies can facilitate a wide range of traffic conditions. Dynamic reconfiguration of networks under load and related implications on the operation of routing protocols will be discussed in Chapter 6. Before this, Chapter 5 investigates network resilience as another constraint of the optimisation problem.

Chapter 5

Dynamic Network Topologies and Network Resilience Constraints

Network resilience to failures is a major concern for network operators and any optimisation scheme must take this into account. This chapter revisits optimal topologies and includes resilience constraints. It introduces the concept of resilient dynamic topologies where networks have the ability to reduce the number of active nodes and links during lightly loaded periods while maintaining resilience to link failures.

The aim in this chapter is to demonstrate how to protect networks from any unexpected link failures. Two mathematical programming models are formulated: One that protects links and one that protects demands. Using a sample network, energy consumption of networks with dynamic topologies and networks with resilient dynamic topologies are compared. The numerical results show that the resulting optimised topologies are resilient to link failures and have smaller energy footprints.

5.1 Introduction

Energy efficiency and network resilience have become a key focus of the commercial as well as research networking communities. Previous chapters have focused on energy efficiency; this chapter explores traffic engineering by employing dynamically changing network topologies with a strong emphasis on network resilience. With the prevalence of IP networks resilience, the ability of a network to sustain faults or disruptions has become a major concern for service providers. An industry survey [197] highlights that reliability, network usability and network fault protection are key concerns for major network carriers. Failures can be caused by fibre cable cuts, for example, but also by natural disasters, such as floods, cyclones and bush fires.

Network resilience in this context refers to the ability of networks to continue to operate despite one or more link failures. Operating networks typically requires balancing loads on the network to ensure effective use of the existing link capacity, ensuring that traffic shifts due to planned equipment maintenance and that unplanned failures do not impact on network users. This already difficult task is further complicated by the application of network reduction procedures by the dynamic topologies proposed in this thesis. As discussed in the previous chapters, the topology in reduced networks will operate with the minimum number of links and nodes. This makes failure critical as no backup resources are allocated. Ensuring resilience to link outages for dynamic topology is a significant step to make this concept usable for operational communication networks.

5.2 Related Works

Resilience in IP networks is an important research area [198] which focuses on detecting and recovering from link and node failures. While a number of mechanisms focus on reachability and the provision of fast rerouting bypass failed network devices [199], the challenges of congestion and performance have not been widely addressed. These aspects are particularly important as hotspots and overloaded links are largely caused by link failures [200].

As overlapping failures can lead to a large number of failure scenarios, mechanisms that rely on their enumeration are not practical [201]. Markopoulou et al. [201] have characterised failures affecting IP connectivity from Intermediate System-Intermediate System (IS-IS) routing updates analysed from an operational IP backbone network. This work proposes a probable failure model that can be used to generate realistic failure scenario and can be used as an input to traffic engineering problems and network design. Wang et al. [202] introduce the Resilient Routing Re-configuration (R3) mechanism as a routing protection scheme. Tests applying R3 have achieved near optimal performance, at least 50% better than existing schemes.

Multi-topology routing [203] is another scheme that has been proposed to protect against link and node failures and improve the mechanisms for fast rerouting [204]. Multiple routing configuration schemes have been shown to guarantee recovery from all single failure scenarios [205]. A single mechanism was used to handle both link and node failures without knowing the root cause of the failure.

Investigations of large scale failures in IP networks [206] show that a new approach for intradomain routing, reactive two phase routing, allows fast recovery from large scale failures with the shortest possible recovery paths. This recovery has succeeded in finding the shortest recovery paths for more than

98.6% of failed routing paths with reachable destinations. The application of path protection and traffic engineering [207] enables reliable data delivery and load balancing.

Any well designed recovery strategy has to take into account the different resilience requirements of the single traffic flows in order to avoid excessive usage of bandwidth for standby links [208]. In the same study, an extension to existing Quality of Service (QoS) architectures was presented as a Resilience-Differentiated QoS (RD-QoS) that integrates the signalling of resilience requirements with the traditional QoS signalling. Multi-path routing and local failure reaction have been investigated in [209] to provide uninterrupted QoS to applications. This means that network resilience has been improved to support real-time applications that required an uninterrupted bandwidth.

Network resilience in multilayer networks has been introduced in [210] and describes key issues associated with the implementation of restoration in a multilayer network. The network resilience in future optical networks has been discussed in [211], focusing on the reliability performance improvement of the optical network and on recovery in multilayers in those networks. Network resilience has been discussed in [212] using shared protection for single link failures.

Kvalbein et al. [213] proposed resilient routing layers as a method for network recovery. The method involves calculating the fully connected topology and subsets, termed layers, which are used to forward traffic in the case of network failures. Details are introduced in [214] to present new scheme for fast recovery from node and link failures.

The researchers have studied network resilience by proposed mechanisms which target link and node failures. The studies have considered protecting links and nodes from failures by address different areas of network communication including routing reconfiguration and topology routing which was discussed earlier. However, the network resilience for dynamic topologies in terms of energy efficiency has not been addressed to date and will be the subject of this chapter.

Some of previous studies have used ILP to formulate the network resilience problem. This work also uses ILP to solve the formulation problem. Also, the network resilience in this study is based on backup of links or demands and rerouting the traffic on the active links and nodes whereas most of studies have addressed the network resilience by discussing ways to quickly recover from network failures and how to reconfigure the network to prevent their failures.

5.3 Problem Formulation

This section introduces two Mixed Integer Linear Programming (MILP) models that result in reduced topologies resilient against single link failures of active links. To protect against link failures, networks can either protect the capacity of individual links; or protect all demands. The former leads to simpler optimisation problems, the latter requires less additional capacity. The aim of these problem formulations is to turn off as many nodes as possible to reduce the fixed power consumption of nodes. Local demands of nodes that are turned off are bridged to neighbouring active nodes. At the same time, the aim is to protect the remaining network against single link failures. This excludes links to nodes that are operating in standby. A link failure for access links to these stub nodes requires the router to power up.

5.3.1 Problem (1) - Links are Protected

The following optimisation problem protects the capacity of all links. The objective function is given in Equation 5.1.

$$\text{Minimize} \sum_{kij} c_{ij}^k x_{ij}^k + \sum_{ij} \delta_{ij} g_{ij} + \epsilon \sum_{ijmn} y_{ij}^{mn} \tag{5.1}$$

The aim is to minimise energy consumption, i.e. proportional costs $c_{i,j}^k$ and fixed costs g_{ij} of active nodes and links. Backup traffic y_{ij}^{nm} does not cause any power consumption in operational networks as these flows are used only when links fail. However, additional traffic in the case of a failure should be minimised. Hence the scaling factor ϵ, a small number, is used.

The following constraints are required: Links have to accommodate normal traffic and reserve some capacity for traffic caused by failing links. The balance constraints for both traffic sets are independent. Equation 5.2 shows the mass balance constraint for normal traffic:

$$\mathcal{N}\, x^k = \; b^k \quad \text{for all } k = 1, 2, \ldots, K \tag{5.2}$$

Where:
$\mathcal{N}$ is the node-arc incidence matrix and b is the right hand side vector, which specifies supplies and demands. Equation 5.2 expresses the conservation of flow, as the sum of all elements $b(i)$ in b must be equal to zero. The commodities, k, correspond to the demands between source and destination nodes. Equation 5.3 depicts the mass balance constraint for backup traffic that is caused by the failure of link (n, m):

$$\mathcal{N}\, y^{mn} = \delta_{mn}\, a^{mn} \quad \forall\, (n, m) \in A \tag{5.3}$$

Where:
a^{mn} is a right hand side vector with a positive supply of u_{ij} in row i and a negative demand of $-u_{ij}$ in row j for all links (m, n). No artificial links are included, i.e. demands that are emanating from once dashed nodes or terminating at a

twice dashed node are excluded. If the link (m, n) does not exist, a^{mn} equals zero. Equation 5.4 show the bundle constraint. Links have to accommodate all normal flows x_{ij}^k and the backup capacity v_{ij}.

$$\sum_k x_{ij}^k + v_{ij} \leq u_{ij}\delta_{ij} \quad \forall\,(i,j) \in A \tag{5.4}$$

The backup capacity constraint is depicted in Equation 5.5.

$$y_{ij}^{mn} \leq v_{ij} \quad \forall\,(n,m) \in A \tag{5.5}$$

v_{ij} denotes the upper limit for any backup flow on link (i, j). A failing link (n, m) cannot be part of the backup topology. This is enforced by the disjointness constraint in Equation 5.6.

$$y_{ij}^{mn}\gamma_{ij} = 0 \quad \forall\,(i,j) \in A, (n,m) \in A/m = i, n = j \tag{5.6}$$

Flow y on link (i, j) protects link (m, n) and therefore is not allowed to use link (m, n). γ_{ij} indicates if a link is protected. If γ is equal to zero, the link cannot accommodate backup flows. It is one for all links, except artificial links. The constraints in Equation 5.7 and 5.8 enforce the restrictions that are required for the extended transformation.

$$\sum_j \delta_{ij} = \alpha_i \quad \text{for all } i \in N \tag{5.7}$$

$$\sum_j \delta_{ij} = \beta_j \quad \text{for all } j \in N \tag{5.8}$$

α_i and β_j limit the number of links that emanate and terminate at nodes and enforce constraints that are important for extended network transformation.

5.3.2 Problem (2) - Demands are Protected

This MILP protects all demands, not individual links. It adds another dimension to the backup flow variable y. The new objective function is depicted in

Equation 5.9.

$$\text{Minimize } Z = \sum_{kij} c_{ij}^k x_{ij}^k + \sum_{ij} \delta_{ij} g_{ij} + \epsilon \sum_{ijnm} y_{ij}^{nmk} \tag{5.9}$$

The introduction of the variable y, representing the backup traffic, is the only modification to the scheme. Equations 5.2, 5.4, 5.7 and 5.8 all still apply. Equation 5.10 shows the updated mass balance constraints for backup traffic caused by the failure of link (n, m) for demand k.

$$\mathcal{N}\, y^{mnk} = \delta_{mn}\, b^k \quad \forall\, (n, m) \in A \tag{5.10}$$

Disjointness is enforced by Equation 5.11.

$$y_{i,j}^{m,n,k} \gamma_{i,j} = 0 \;\; \forall\, (i, j) \in A, (n, m) \in A / m = i, n = j \tag{5.11}$$

Equation 5.12 ensures that v_{ij} marks the upper bound for all backup demands. v_{ij} corresponds to the capacity on link (i, j) reserved for backup flows.

$$\sum_k y_{ij}^{mnk} \leq v_{ij} \;\; \forall\, (n, m) \in A \tag{5.12}$$

The key difference between this problem formulation and Problem (1) is the increase in problem size due to the additional dimension introduced by y.

5.4 Evaluation and Analysis of Topologies

This section discusses numerical examples demonstrating how resilience constraints and energy efficiency impact on practical network configurations. Results for different optimisation problems are compared, namely:

(a) *links only* - all nodes are active, only links can be turned off;

(b) *links only (resilient)* - only links can be turned off, the remaining network is resilient to single link failures;

(c) *nodes and links* - both links and nodes can be turned off; and,

(d) *nodes and links (resilient)* - both links and nodes can be turned off, the network can cope with single link failures.

Results for (a) and (c) have been obtained using the optimisation problems introduced in Chapter (3). Results for options (b) and (d) are based on Problem (1) discussed in Section 5.3.1. For option (c) the MILP is used with an untransformed network, while for option (d), the transformed network is used. The mathematical programs were solved using the commercial IBM ILOG CPLEX Optimizer 12.4 [215].

5.4.1 Network and Traffic

As in previous chapters, a network with 8 routers and 24 unidirectional links was chosen to limit computing time. The topology is depicted again in Figure 5.1 to allow comparisons with the following figures. As before, links in this network have nominal capacities of 1 Gbps (dashed lines) and 10 Gbps (full lines), respectively. Nodes in this network have a capacity of 100 Gbps and do not pose a bottleneck. Traffic matrices include 56 demands, i.e. traffic between all routers. The experiment uses 3327 instances of traffic matrices generated randomly. The matrices include traffic demands between origin and destination nodes. More details are discussed in Section 3.7.1.

5.4.2 Resulting Topologies

This section presents a comparison of topologies for one lightly loaded traffic instance. The maximum total load of the network is approximately 10.29 Gbps. The traffic instance used loads the network with 2.64 Gbps, 26% of its maximum load. The examples show how the constraints impact on the

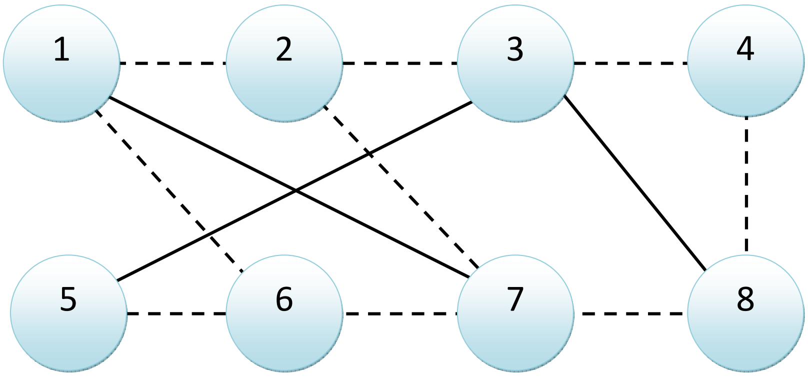


Figure 5.1: Test topology - eight nodes

network topology. The original network is depicted in Figure 5.1, while the topologies for *links only* and *links only (resilient)* are depicted in Figures 5.2 and 5.3, respectively. The arrows in Figure 5.2 indicate that all but one link are unidirectional in this case. The network forms two overlapping rings, and as the links are directional, one disconnected link will impact on a number of nodes. This solution is not fault tolerant. In all other cases, links are bidirectional and arrows have been omitted.

The solution in Figure 5.3 for *links only (resilient)* results in a classic ring network. Without capacity limitations, this is the expected result. Figures 5.4 and 5.5 depict the topologies for cases where both nodes and links can be turned off. The former depicts the energy efficiency, the latter the resilient solution. The dark, orange nodes indicate active routers; lightly shaded nodes indicate inactive routers in standby. Inactive nodes are connected to active nodes via one hop. Inactive links have been omitted from the diagram.

Option (3) results in multiple connected star topologies that do not include meshing links. As this topology does not include any redundant links, it is

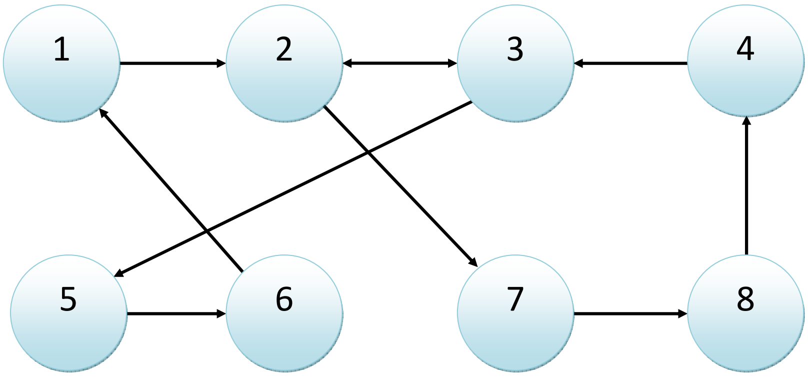


Figure 5.2: Reduced topology - *links only – (1)*.

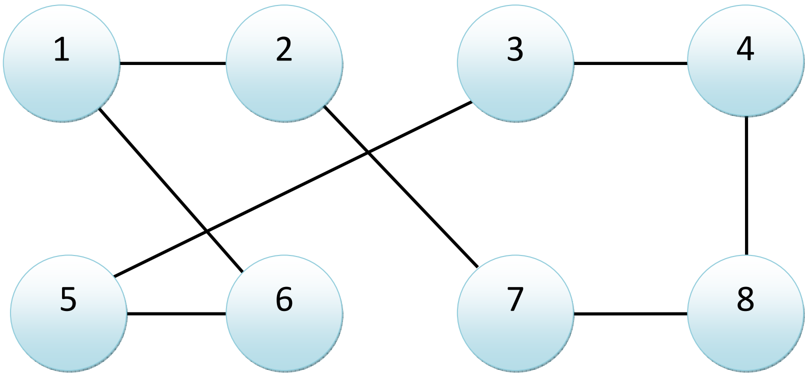


Figure 5.3: Reduced topology - *links only (resilient) – (2)*.

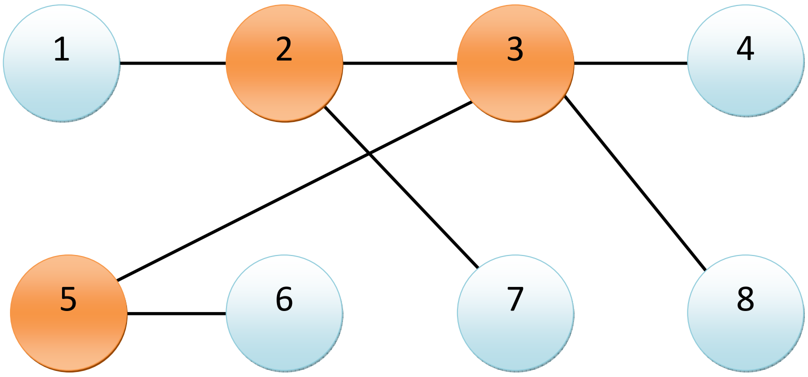


Figure 5.4: Reduced topology - *nodes and links – (3)*.

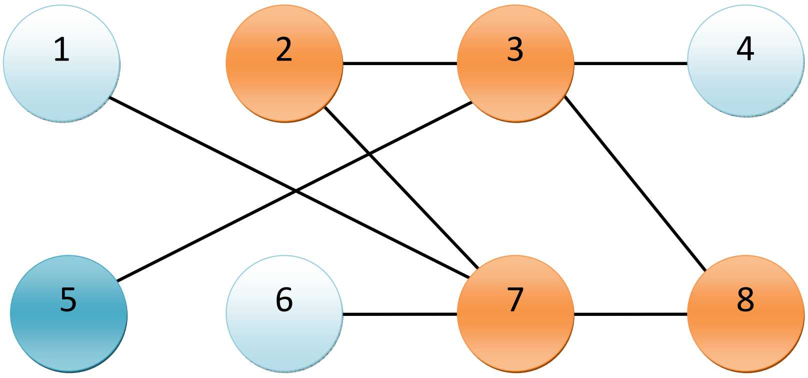


Figure 5.5: Reduced topology - *nodes and links (resilient) - (4)*.

vulnerable to link failure. However, links failures here have a lesser impact than in option (1). For the resilient case, active routers form a ring network, the most efficient, resilient configuration. Related power consumption and the number of active nodes and links are discussed in the next section.

5.5 Network Energy Consumption

This section introduces simulation results for the eight nodes networks to demonstrate the changes in the network power consumption. Network energy consumption has been evaluated using the same assumptions as in the previous chapters.

Figure 5.6 shows the total network power consumption against the total demand for the optimisation problems where only links can be activated or deactivated, as in options (1) and (2). Results for the unmodified network are given by the cloud on top (red) square markers (■); for the reduced topology by the lower cloud (green) triangles (▲) and the cloud in-between indicates the results for the resilient network with (blue) lozenges (◆).

The energy consumption increases linearly as traffic load increase. The small steps are caused by the fixed power component of links that are being activated. The power consumption for the resilient network is less than the unmodified network but more than the reduced topology as the resilient solution requires an intermediate number of active links. Above a total load of 6 Gbps, reduced topology resilient solutions no longer exist.

Figure 5.7 depicts the total network power consumption versus the total traffic demand for options (3) and (4). The unmodified network consumption is indicated by the top cloud of (red) square markers (■), the reduced topology by the lower cloud of (green) triangles (▲) and the cloud in between shows

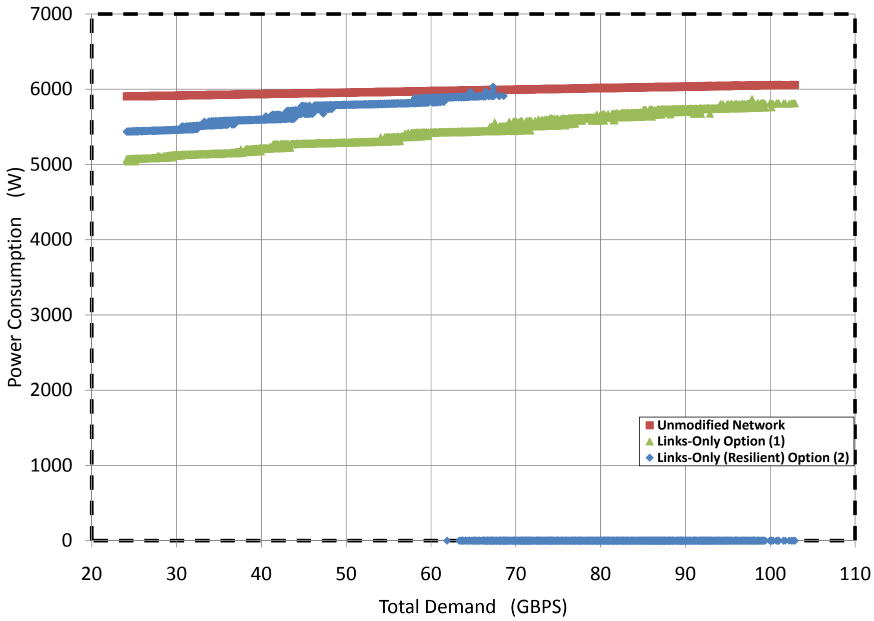


Figure 5.6: Power consumption versus total demand, *links-only* options.

the results for the resilient network with (blue) lozenges (♦). The original network consumes the most energy, increasing linearly with load. Option (4) uses the least amount of energy in case of applying resilient network conditions.

The graph shows distinct steps where the number of nodes change. For higher loads, more active nodes are necessary. The power consumption for the remaining option (3) lies between these two extremes. The graph also exhibits step changes when the number of active nodes change. For most instances above 60 Mbps total traffic, no feasible reduced topology solutions exist: Hence, the optimisation problem (4) no longer yields solutions. This indicates that these traffic matrices result in problems that do not allow for additional backup flows.

Figure 5.8 shows the number of active nodes versus the total traffic demand. Triangle markers (▲) indicate the energy efficient option, lozenges (♦) the resilient option. Instances where the number of active nodes is zero indicate that the instance has no feasible solution for the resilient optimisation

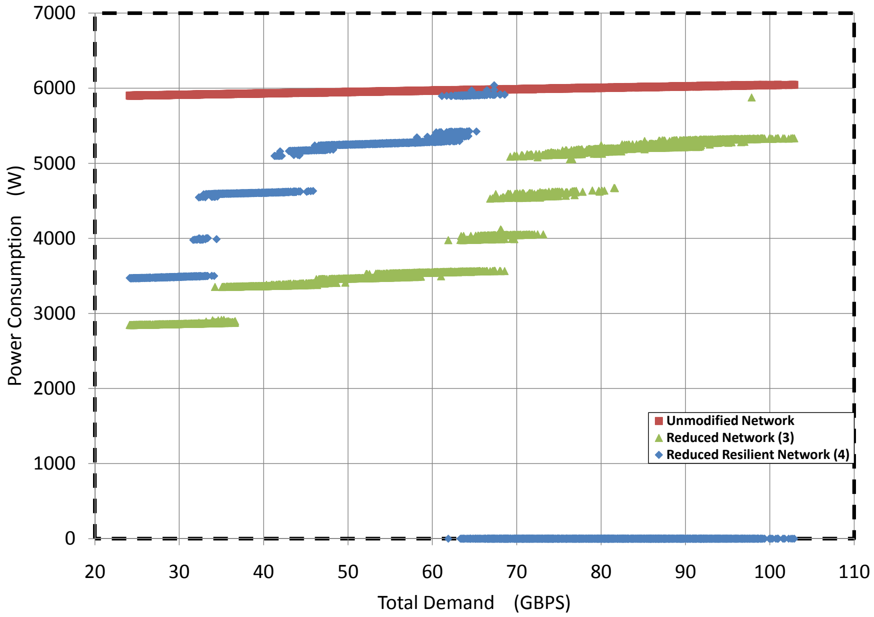


Figure 5.7: Power consumption versus total demand, *nodes and links* options.

problem. For unfeasible solutions, normal traffic demands use the links and sufficient backup capacity is not available. The total load this network can carry is approximately 10.29 Gbps, while the highest load the resilient topology can accommodate is 6.86 Gbps, about 67%. Unfeasible instances begin to occur at about 60% load. This is in accordance with the rule of thumb to reserve 50% of link capacities in case of link failures, as solutions were found for all values below 50% of traffic load. The graph also shows that for reduced topologies, for all but one instance, seven nodes are sufficient. For the resilient case, eight nodes are only necessary in a few instances.

5.6 Discussion

The proposed models for network resilience have been presented and simulated in this chapter to emphasise the ability of dynamic topologies to continue to operate when minimum topologies are applied. Two models of the presented formulations have been implemented for network resilience and shown remarkable results.

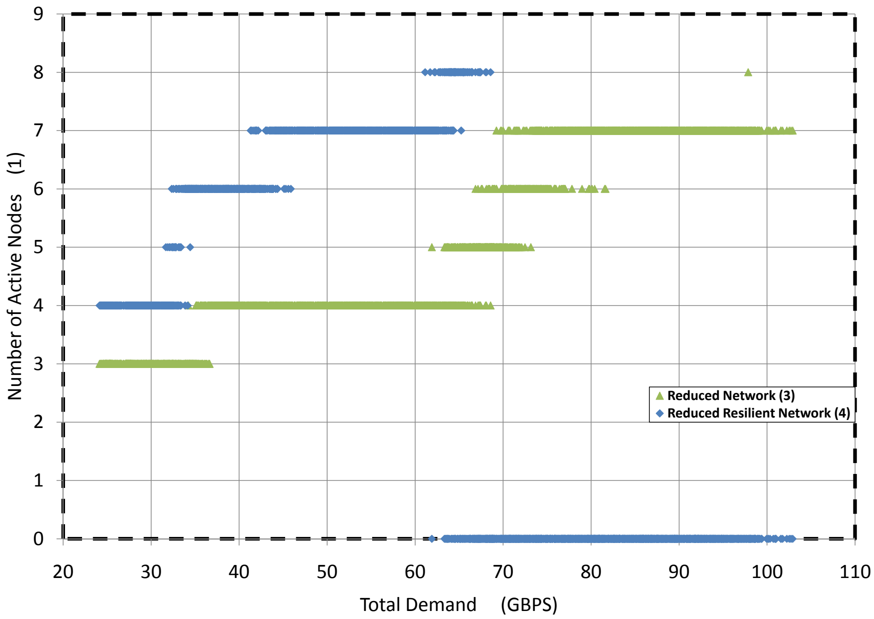


Figure 5.8: Number of active nodes versus total demand.

The proposed model has been tested under two conditions, the links only option and the link and node option. The implementation of the links only option has shown significant power reduction, however, it was outperformed by the implementation of links and nodes option which showed potential for more energy savings. This is to be expected as switching off links and nodes will save more power than the turning off links only, and increasing the power consumption regression in the links and nodes option is more effective than the links only option. This explanation supports this project's hypothesis based on the traffic load and capacity of the links and nodes in the given network.

The simulation for the first problem formulation took less time than that for the second presented problem formulation. The problem size of the second problem is considerably larger than the first formulation. The results suggest that a formulation protecting the links could be a more practical method to examine network resilience for larger given network topologies. The topologies produced from the simulations, as for example those in Figures 5.3 and 5.5, show that the topology forms a loop shape to protect the topology from any failure.

5.7 Conclusion

The work in Chapter 3 has shown that dynamic topologies can lead to considerable energy savings. The work in this chapter has confirmed that this is also possible while a resilient active core of nodes is maintained. There are a number of avenues how further work could explore network resilience in this context. There is potential to develop more efficient mathematical models than the current ILP formulations, while more suitable heuristics could be developed. Increased efficiency formulations would then allow for larger networks to be analysed.

From a topology perspective, energy efficiency and resilient dynamic topologies are feasible, and could potentially enable significant energy savings. Where these techniques could be used in live networks will largely depend on implementation and operational factors. Potential methods of implementing dynamic topologies in practical networks is discussed in the following chapters.

Chapter 6

Potential Dynamic Topology Implementations

The dynamic topologies concept involves networks adjusting their topology according to the dynamic traffic load. Conventional routing protocols are not suitable to implement such networks as re-routing would cause major disruptions to active traffic. Based on existing protocols [216], [217], two approaches appear to be feasible: extensions to OSPF or MPLS. This chapter briefly summarises how OSPF could be used, but largely focuses on an MPLS based implementation and addressing operational considerations in the context of dynamic topologies. The aim is to enable IP networks to switch between original and reduced topologies without impacting on the performance of individual flows. The proposed mechanisms involve minor changes to MPLS to maintain the transaction states at the network egress, and include a power control for routers. The previous chapters have proposed methods to generate reduced topologies; this chapter will discuss their practical implementation in a real IP network environment.

6.1 Introduction

Dynamic topologies aim to change the number of active routers and links in a network according to traffic load. It is advantageous if unused routers and links enter low power states. Chapter 3 has previously established that dynamic topologies can greatly improve network energy consumption if they are implemented in computer networks. This chapter focuses on how the concept can be implemented in an IP backbone network. The key challenges include maintaining accurate forwarding information in the active devices, detection of changes in traffic loads and the timing of topology changes. The former is addressed in this chapter; the latter will be left to future research.

In principle, traditional routing protocols such as Open Shortest Path First (OSPF) support dynamic reconfiguration. However, it is not feasible to rely on these mechanisms as a means to implement dynamic topologies (DTs), due to the time delay in routing protocols detecting changes in the network and propagating this information. For instance, routing protocols may take several minutes to converge once changes in topologies have been detected. This typically leads to packet loss and packet reordering, disrupting active connections. If topologies change dynamically and rely on existing routing protocols, any changes in topology will directly impact active traffic flows. To implement DTs it is therefore necessary to suggest a mechanism to overcome these issues.

MPLS is an obvious choice as it has been widely used for traffic management and traffic engineering [218]. There has been a lot of work in relation to node and link protection in MPLS networks [219]. Fast rerouting for protected label switched paths have been discussed previously [220], [221]. This method allows networks to respond in case of congestion and link failure by introducing predefined alternative LSPs.

To enable dynamic changes, the proposal in this chapter depends on predefined LSPs for multiple topologies. The concept of multiple MPLS paths and the ability to redirect traffic has also been used in [202]. Dynamic Topology Reconfiguration for energy conservation has been discussed and is a proposed mechanism that conducts traffic engineering in order to dynamically aggregate traffic on particular links, and turn off unused links [222].

Using different label sets, MPLS can support a multitude of topologies where only minor modification to ingress Label Switched Routers (LSRs) are necessary for MPLS to support packet forwarding for dynamic topologies. This chapter proposes the implementation of Dynamic Topologies using MPLS (DTM) and introduces a mechanism that builds on native MPLS forwarding. It adds a network management function, a topology and flow tracker at each ingress label switching router; and a router function that is able to change router power states. It is assumed that routers in this proposal support at least two power states, active power-on state and a standby low power state. In the standby state the router operates a bridge between the access link that accommodates local demands and one core link. The MPLS related modules also remain active to maintain labels and forwarding tables. Details of the low power mode however are outside the scope of this chapter.

Dynamic topologies can potentially be implemented using OSPF or MPLS protocols. The protocols have to be able to maintain multiple topologies in parallel. Extensions to OSPF have been proposed that support multi-topology routing [223] while MPLS natively supports multiple topologies. The next section will describe the OSPF protocol and the multi-topology approach in more detail.

6.2 Topology Management Using Open Shortest Path First (OSPF)

OSPF is widely used as an intra-domain routing protocol [224] in IP networks. Its current version, v2 [148] is defined in RFC2328, and includes several extensions to the initial version. OSPF is a layer 3 link state routing protocol where link state protocols rely on a distributed map concept. Each router maintains an identical database describing the area topology. On this basis, each router calculates and constructs individually the shortest path(s) from itself to any destination in the area. The distribution of the topology information is performed via Link State Advertisement (LSA) and Link State Update (LSU) messages which are flooded to the whole network area when there is a change in the state of the neighbours [225].

Failure detection is based on lower layers using the *Hello* protocol or alarm escalation [226]. Periodically, router sends *Hello* messages on all outgoing interfaces of the router. The neighbouring routers detect these messages. In the case of a router not receiving the *Hello* message from neighbouring routers, the link between the interfaces of the two routers will considered as down until two *Hello* message are received again.

With an ECMP extension of OSPF (Equal Cost Multi-Path), a router evenly distributes the load over the fan of all available shortest paths with equal lowest cost [227]. The main advantages of this approach are to allow better load distribution and a faster reaction to failure. For the routing of the packets either flow-based distribution or round robin based is possible. Flow-based routing avoids the problems of packet reordering. In the case of a link failure the preceding router automatically switches the flows to one of the remaining links of the multi-path fan. This scheme is relatively fast because the reaction is local.

One of the significant advantages of OSPF is that it is completely autonomous [228], [229]. Once the network administrator has set up the output interface costs for the routers, the protocol which is active in each router of the system will discover the topology, and react to changes on its own. The network recovery is ensured with this protocol as long as some physical connectivity exists.

OSPF supports several routes to a destination with a different costing associated with each route and rapid convergence when a topology changes. This allows backup routes to be available if a main route goes down. Another advantage is the hierarchical nature of the protocol, which allows OSPF networks to scale very well with little impact upon overall routing overhead [230].

The disadvantage of this protocol is that the detection and signalling of failures is slow when the *Hello* mechanism is used [231]. Moreover, the path computation and update of the forwarding information bases (FIB) take an additional hundreds of milliseconds [232]. Another problem with the OSPF protocol is the difficulty in managing and configuring network topology areas, this adds more complexity to the protocol [233].

Extensions to OSPF have been previously proposed to improve traffic engineering and resilience mechanisms by supporting multi-topology routing [234]. This combines the notion of pre-planned backup structure with the connection-less approach of link-state-based routing. Packets are routed along a shortest-path tree that is calculated at each network router.

MPLS protection mechanisms like *Local Link Protection* can be emulated with multi-topology routing when using one resilient routing topology per failure pattern. However, the number of topologies and routing table quantity can be reduced when a topology is used for multiple failure patterns.

Doyle [235] discusses extentions to OSPF to assign a multi-topology identifier to each logical topology where each OSPF interface is assigned one or more multi-topology identifiers to designate what topologies run on that particular interface. Adjacency is established with all neighbours as per usual methods, LSAs and LSPs are tagged with the appropriate multi-topology identifiers, a separate SPF algorithm is run for each topology and then the route entries resulting from the topology-specific SPF calculations are stored in separate routing information databases (RIBs). These extensions make OSPF a feasible implementation for dynamic topologies in IP networks.

OSPF could be implemented to apply the proposed mechanisms in DTs, where routes are calculated for the given topology to find the shortest paths based on the weight setting on active links. This operation is not suitable with DTs because the topology is changing frequently, causing OSPF to calculate the routes after every change. However, the extensions in [235] suggest use of multiple logical topology identifiers. These multi-topology identifiers can then be assigned by transmitting a number to each OSPF interface. That means that the OSPF should identify the topologies frequently to match the proposed changes in the dynamic topologies.

The OSPF method could be implemented in dynamic topologies by computing the shortest path for every node in the network function management and consider the timers for the topology and flow tracker to apply the new topology because OSPF is unable to quickly adapt to short term load variations. In OSPF the router's packet-forwarding decision is based only on the destination address specified in the packet header, then the packet forwarding information should be managed by the network management function.

However, MPLS allows the specification of explicit routes through the network, where the incoming IP packets are classified at the ingress nodes, with labels attached to their headers. Routers within the network then base their forwarding decisions on these labels. This way, the routes through the network topology do not depend on the underlying routing protocol, but rather on the classification and labelling process commenced at the ingress nodes with forwarding information stored in the label switching routers along the way. As a result, MPLS could implement the proposed mechanisms without any extensions as opposed to OSPF, which requires extensive modification.

6.3 Topology Management using MPLS

The key to using dynamic topologies in communication networks is a routing methodology that is able to support multiple topologies simultaneously. This section introduces an approach that relies on Multiprotocol Label Switching (MPLS). MPLS networks feature three basic types of router functions including ingress, egress and transit label switch routers. To support dynamic topologies in MPLS networks only additions to the ingress router function are required. Flow and topology trackers are added while transit and egress LSR functions remain unchanged.

Dynamic Topologies using MPLS (DTM) consist of three components: a central Network Management Function (NMF), a Topology and Flow Tracker (TFT) located at ingress LSRs, and a router Power Management Function (PMF) component in all LSRs.

6.3.1 Network Management Function (NMF)

The NMF is the central management function that controls the other DTM components. It stores a complete representation of all network nodes and links and calculates reduced topologies as well as the corresponding optimal paths. Each topology has its own set of labels that are managed using existing label management mechanisms. Each LSP has an associated topology identification (ID). Optimal topologies are calculated offline.

The NMF tracks network utilisation online and signals topology changes to the TFT and PMF by broadcasting the topology ID to all nodes. On receiving the message the nodes start their relevant switch over functions.

6.3.2 Topology and Flow Tracker (TFT)

This is the key addition in the forwarding path and its purpose is to maintain flow-state for label assignments. Each topology has its own set of labels and topologies are changed by switching the set of label switched paths. To avoid traffic disruptions for short-lived flows during a switch over period, only new flows will be assigned to the new label sets, maintaining the routing of existing flows. Once a change over timer expires, all flows are forced onto the new set of paths.

The scheme relies on two timers to determine the actions that are taken by individual components. The first timer identifies how long a state is maintained for existing flow when the topology is decreased in size; the second timer determines the time before a state is erased in the flow tracker once the topology is increased. If the network size is increased, the flow assignment has to be delayed to give the nodes sufficient time to wake up. This can be managed by the central NMF delaying the topology ID broadcast. Figure 6.1 depicts a flow chart of the flow and topology tracking mechanism that is used in the forwarding path of the router. Once a packet is received, the NMF messages will be identified as a wakeup message or not. If the message is a wakeup message and the node is in standby, then the nodes will power up and send an active node message to the NMF. When the node is not in standby, then active node message will send to the NMF in response to the wakeup message and will continue to monitor NMF messages. Where the NMF message is not a wakeup message, the node will test if it is already powering down through the sleep branch method. If it is already powering down,

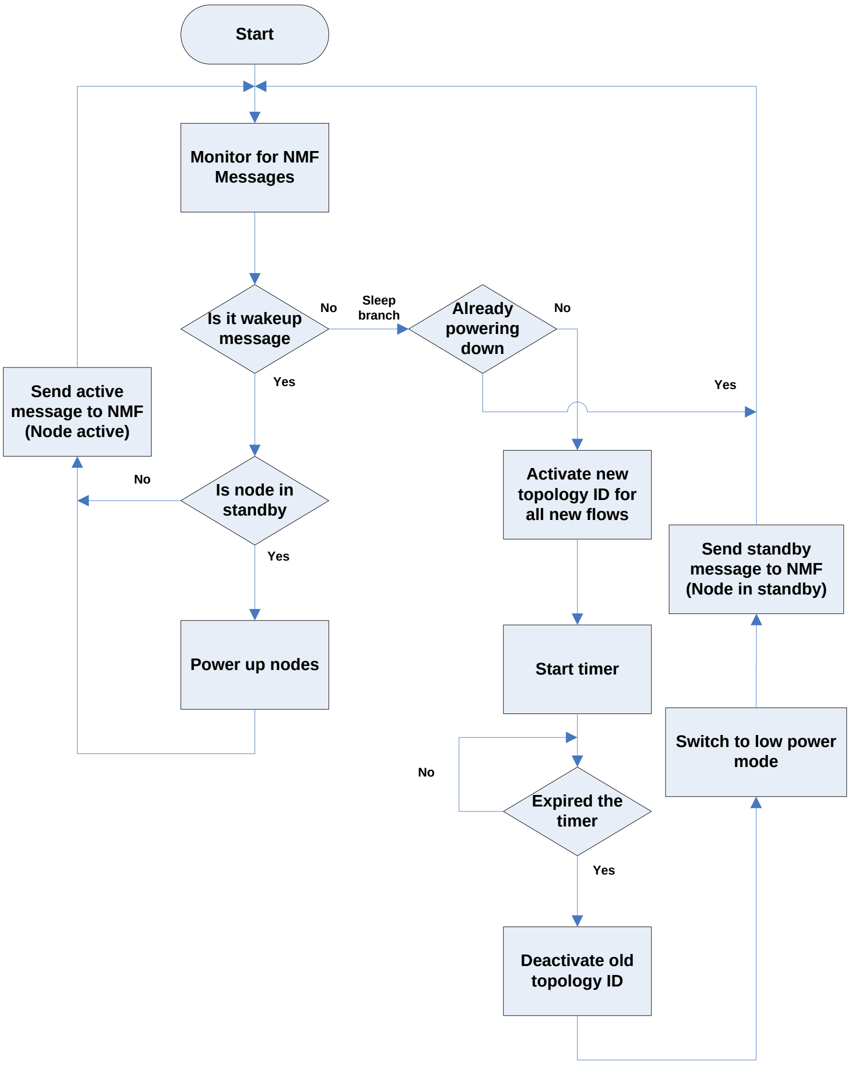


Figure 6.1: NMF flow chart of flow and topology tracker.

then the algorithm will continue to monitor for NMF messages. If it is not already powering down, then the new topology ID will activate for all new flows. After that, the timer will start to apply the new topology. After expiration of the timer, old topology will deactivate, and the low power mode will apply with standby node messages sent to the NMF.

6.3.3 Power Management Function (PMF)

The power management function (PMF) is aware of topology changes through broadcast messages. If the network is downsized, the function waits for the traffic to subside and after all flows have been assigned to the new topology, nodes and links are powered down into a standby mode. If the topology size is increased, nodes and links are immediately powered up.

A flow chart of the operation of the PMF is depicted in Figure 6.2. In the illustrated chart, the NMF monitors traffic compared to the threshold. Depending on this comparison, the traffic will be low or high or unchanged. In case of low traffic, the NMF will broadcast a sleep message in the next step in the flow chart and adjust the threshold. After that, the NMF will continue to monitor the traffic. In case of high traffic, the NMF will broadcast a wakeup message with node IDs then adjust the threshold and continue to monitor the traffic. In case of medium traffic flow, the NMF will make no change to the network topology and continue to monitor the traffic.

6.3.4 Operation

The operation of the DTM can be divided into four phases: an offline configuration phase, an online monitoring phase and two online topology change phases; downsize and upsize. Each of these will be discussed in the next pages.

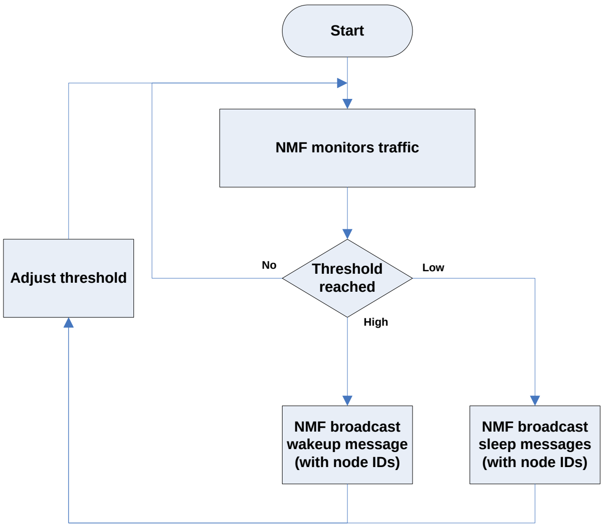


Figure 6.2: DTM flow chart of NMF

Offline Configuration Phase

It is assumed that the NMF has knowledge of the network topology as well as network traffic levels. Based on the existing network topology, the NMF solves the optimisation problem for a set of different network load levels. This determines active nodes, links and routing for all topologies. The process is dependent on the size of the network and can be done by using an ILP solver such as the commercial IBM ILOG CPLEX Optimizer. As these network problems belong to the class of NP-hard problems [186], larger networks may require specific heuristics to find optimal or near-optimal solutions as discussed in Chapter 4. The results of these offline calculations include a set of reduced topologies, corresponding routes and labels for each traffic level. Based on this information, LSP paths can be pre-computed and configured in the network. Details of the label distribution process are outside the scope of this project, but it is assumed that it relies on native MPLS methodologies.

Online Monitoring Phase

The NMF monitors the traffic load in the network. It gathers details from the individual routers using simple network management protocol (SNMP). When trigger levels for topologies are reached, topology changes are initiated. The producers for each type of change, downsizing and upsizing, are different.

Online Topology Changes (Downsize)

For this transition it is important that nodes are no longer used by traffic before they are shut down. The duration of the topology transition timer is critical as it determines how long it will take before nodes can power down. The following steps are necessary:

- The NMF signals all TFTs the new topology ID and the time out value.
- The TFT immediately routes all new flows via the LSP that correspond to the new topology. Established flows are routed via the original LSP sets. The NMF sets the switch over timer.
- Once the transition timer has expired, all flows are routed via the new set of LSP. At this point established flows will be forced onto new paths.
- Once the unused routers in the topology are no longer handling traffic, the PMF will transition the routers into standby mode.
- The topology transition is complete.

Online Topology Changes (Upsize)

For this transition direction, it is important that routers are powered up before the new label set is activated. The topology transition timer is less critical in this situation. As it does not trigger any further actions, two label sets can be maintained for a longer period. The following steps have to be completed:

- The NMF sends a wake-up signal to all PMF that are attached to routers that are required for the new topology.
- Once the routers are operational, they signal the NMF.
- Once all necessary routers are active, the NMF signals all TFT functions the new topology ID.
- The NMF uses the new topology immediately for all new flows, established flows remain on the old paths. The NMF sets the topology transition timer.
- Once the topology transition timer expires, the TFT routes all traffic via the new paths.
- The topology transition is complete.

The advantage of this approach is that the routing for all topologies is already known by all nodes and the labels are active. Therefore exact synchronisation of the switch over is not necessary.

6.4 Performance of Real Time and Non-Real Time Flows

In broad terms, traffic can be divided into two categories: Elastic TCP traffic and real-time UDP traffic. In the former, the limiting factor is available bandwidth while in the latter, the main limiting factors are delay, jitter and packet loss. This is reflected in different traffic flows such as video on demand and downloads. Both real time and non-real time traffic are relevant in this context, two performance aspects are relevant: link load and disruptions to active flows that are forced onto new links. For the former it is assumed that as long as the link load is below a given threshold, performance is acceptable; an assumption that is widely used in other studies [236]. The latter is further discussed in this section.

Disruptions during changes in topology occur if flows last longer than the timeout period and path latency once the new path changes. If traffic is routed to longer paths, packets are not reordered and no disruptions occur; however, if active flows are routed on a longer path, packet reordering may occur and some subsequent packets might have to be discarded. Figure 6.3 depicts and example of a four node network with an unproblematic change from Path P2 to Path P1 and the switch in the other direction that potentially leads to disruptions for active flows. The associated packet loss is not problematic for non-real time flows as either the transport protocol, (TCP) or the application layer protocol retransmits the lost packets.

The shortest possible path in a network with n nodes is one hop; the longest possible path without loops is $(n-1)$ hops. An example of this is depicted in Figure 6.3. If the path is changed from Path P1 to Path P2, all packets in flight on all but the last hop will be received out of order. The number of packets that belong to a particular flow and traverse the network at one time depends on packet inter-arrival times and network latency. The example in Figure 6.3

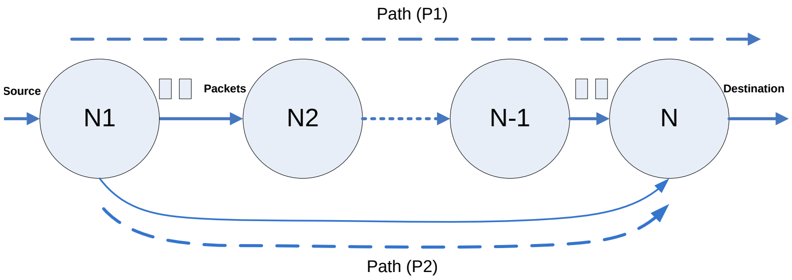


Figure 6.3: Shortest and longest possible path

depicts the worst case topology for this scenario. To estimate the impact of changes to topologies, it is assumed that propagation and transmission delays are the same for all links.

It is possible to calculate a simple relationship between the number of nodes n and the average of lost packets n_p based on the calculation presented in [237]. With an average inter-arrival time of t_i, link latencies t_L, and average node latencies of t_N; on average, n_p packets are lost during the switch over in the worst case (Equation (6.1)).

$$n_p = \frac{(n-2)(t_N + t_L)}{t_i} \tag{6.1}$$

As shown in examples from [238] and [237], for an IP telephone call with a packet inter-arrival time of one 120 byte frame every 20ms and a gigabit core network with 10 nodes, about 25 packets are lost in the worst case. In practical networks, changes in path length will only be in the order of several hops. Therefore, if the path is changed to three hops in this example, the impact will be lower and approximately five packets will be lost.

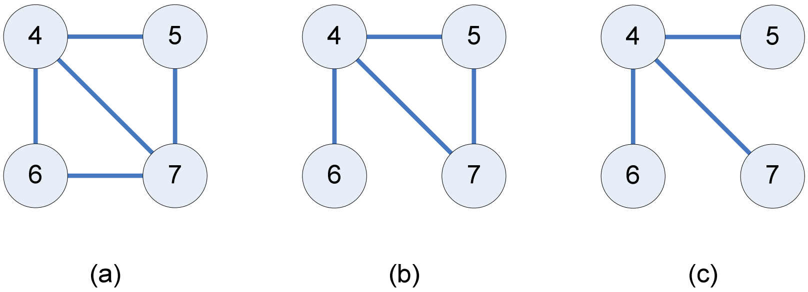


Figure 6.4: Test topology – original(a), reduced(b) and minimal (c).

6.5 Simulation Environment

The well-known network simulator NS-2.34 [239] has been used to demonstrate the operation of network and show the potential impact of topology changes on individual flows. The simulation uses the native MPLS implementation and a custom module to enable flow-aware routing and to switch between topologies. To evaluate DTM performance in MPLS networks and visualise the operation, a core network topology that consists of 4 nodes and 5 bidirectional links is used. This network size is sufficient to investigate the impact on the network protocols. Figure 6.4 depicts the original (a), the reduced (b) and the minimal topology (c). In this example it is assumed that all links have the same capacity and that all traffic is symmetrical. There are 4 variations of topology (b) with the same features. A direct transition from topology (a) to topology (c) is simulated as an example.

Figure 6.5 depicts the overall network topology that was used by the simulator. Link (i, j) exists if Link (j, i) exists. Nodes 8 to 11 represent the core network, i.e. MPLS nodes. The dashed core links are switched off for the reduced topology. Nodes 0 to 7 are traffic sources and traffic sinks; and Nodes 12 to 15 are *DelayBox* nodes that emulate the WAN environment. It is the NS2 equivalent of NetEm [240] and NistNet [241] the well-known WAN emulator.

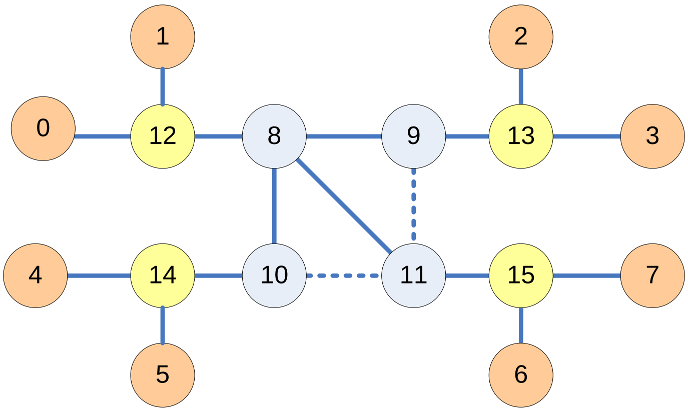


Figure 6.5: Simulation network toplogy with four core MPLS nodes.

The PackMime Model [242] was used to generate realistic backbone application traffic. The network is loaded via the access Nodes 0, 3, 4 and 7 with background traffic. The traffic model has no direct impact on the operation of the scheme, but it impacts on how many flows are still active when traffic is forced off links. To emulate a complete traffic matrix, twelve source-sink pairs are required. The traffic generators were configured with the default model parameters. In this experiment, all of the traffic generators produce the same amount of traffic and all stub nodes are sources as well as sinks. As a consequence, the traffic is symmetrical and network links have the same traffic profiles in both directions.

UDP traffic was generated as a real-time Voice over IP (VoIP) call using an interval time of 10ms and packet size of 80 bytes [243]. TCP traffic emulates elastic traffic such as downloads. UDP and TCP sources and sinks are connected via Nodes 1, 2, 5 and 6. The capacity of these four access links is 512kbps; all remaining links have a capacity of 10Mbps. This is not representative of the current backbone network, however results can be scaled by a factor of 100/1000 to represent current networks. The reduced capacities allow for practical simulation run times.

To enable flow and topology tracking, additional functions were implemented as part of the MPLS classifier in NS2. For each flow the active topology ID is stored in a hash table, using the flow ID as the key. Before packets are assigned to LSPs, the applicable topology ID is retrieved from the hash table. Since NS2 maintains a flow ID, no special flow identification was necessary, and a hash over port number and IP addresses.

6.6 Simulation Results – DTM Operations

This simulation focuses on the packet forwarding aspect and not the dynamics of the MPLS network. Simulation results were validated empirically by comparing average flow rates obtained by the simulation with simple models that estimate average flow sizes on links based on fluid models. The key parameter impacting on the network performance during changes in topology is the duration of the traffic flows. If a flow finishes before the forced switchover occurs, there are no performance impacts at the flow level at all.

Figure 6.6 depicts link loads versus simulation time for Link (6,7) and Link (6, 4). In this example, the timeout period has not been set. Imitially, Link (6,7) accommodates traffic between nodes 6 and 7 and Link (6,4) accommodates traffic between nodes 6 and 4. At $50\ s$ topologies are changed and new flows originally routed on Link (6,4) are now routed on Link (6,7). The traffic gradually migrates to the new links over the following $35\ s$, with Link (6,7) evantually no longer carrying any traffic. Practical networks will feature long-lived flows that last much longer and would remain on the links. Therefore it is necessary to introduce a timer to force remaining traffic onto new links. For the remainder of the simulations the topology switchover timer was set to $14\ s$.

To demonstrate the operation of DTM, a switch over between topology (a) and topology (c) as illustrated in Figure 6.4 was simulated.

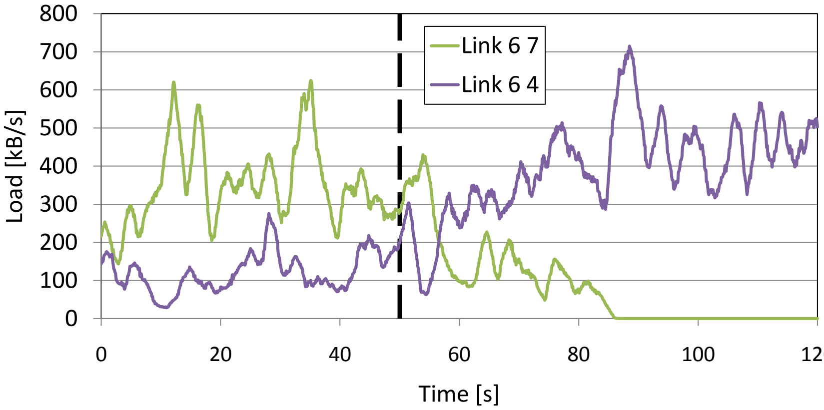


Figure 6.6: Load - Link (6,7) and (6,4)

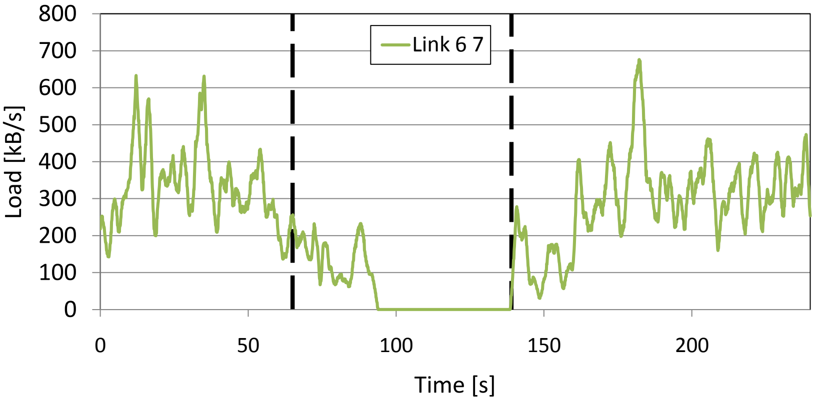


Figure 6.7: Load - Link (6,7).

Figures 6.7 to 6.11 depict link loads as a function of simulation time for the 5 core links. A $30\ s$ warm-up period preceded the data gathering. The simulation begins with connected topology. At $70\ s$ the reduced topology is activated, at $85\ s$ all remaining traffic is forced onto the new links, at $145\ s$ the topology is switched back to the original network and at $160\ s$ all traffic is forced back onto the original links. The graphs show how the traffic migrates from the links that will be deactivated to the links that remain active. In the reduced topology, Link (4,6) has to carry the additional traffic from Link (6,7) Link (4,5) has to carry the additional traffic from Link (5,7) and Link (4,7) has to carry the additional load from both Link (6,7) and Link (5,7). If traffic on the bottleneck link [here Link (4,7)] remains below maximum utilisation,

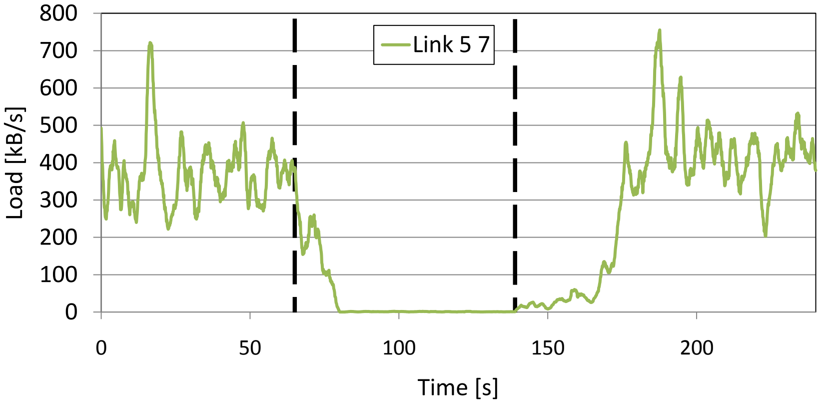


Figure 6.8: Load - Link(5,7).

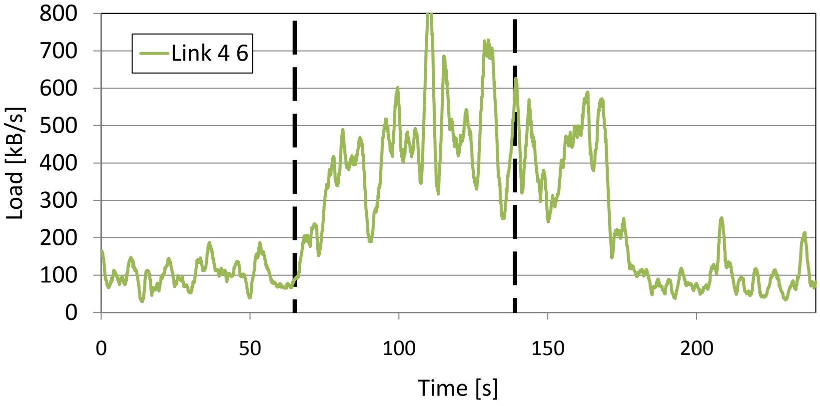


Figure 6.9: Load - Link(4,6).

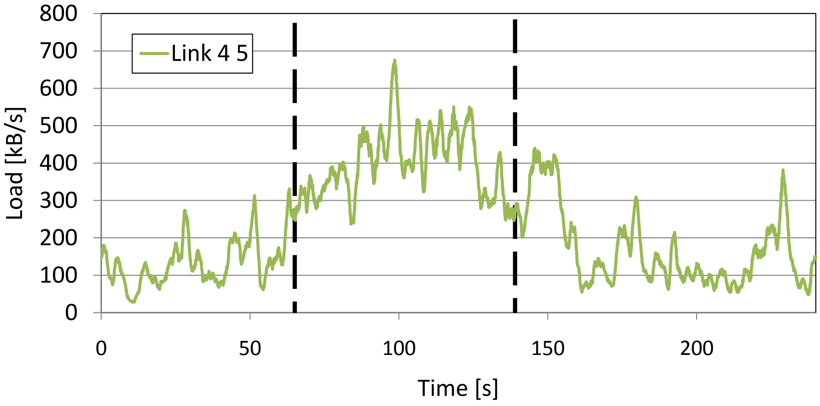


Figure 6.10: Load - Link(4,5).

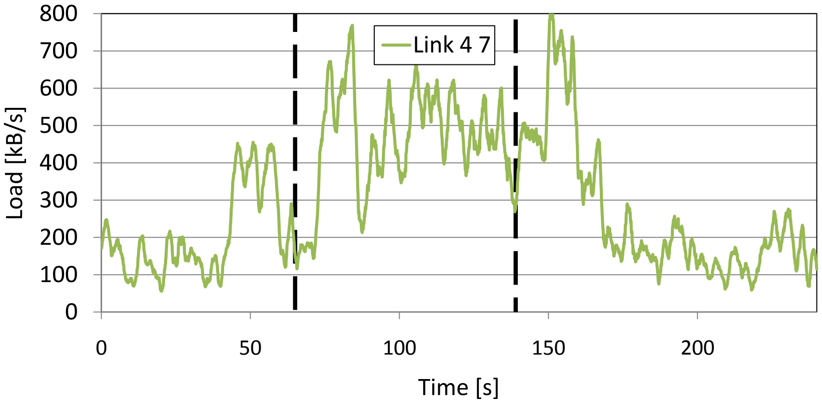


Figure 6.11: Load - Link(4,7).

the topology changes do not impact on the performance of short lived flows. Flows that are active for longer periods still have to be rerouted.

6.7 Simulation Results – Performance

The previous section has demonstrated how DTM reroutes traffic when topologies are changed; in this section the impact of these changes on the performance of traffic flows is discussed. The impact of the topology changes and the related rerouting will be evaluated by three types of traffic including web requests, real-time traffic and non-real-time traffic. The loaded web traffic uses the details from [244] and [245], packet loss/reordering for real-time traffic (UDP) and throughput for real-time traffic (UDP) and non-real-time traffic (TCP).

6.7.1 Background Web Traffic

To simulate a realistic backbone network scenario, the network is loaded with web traffic. Figure 6.12 and 6.13 depict the link utilisation for two core links, Link (11,10) and Link (8,11), versus the simulation time. The transition be-

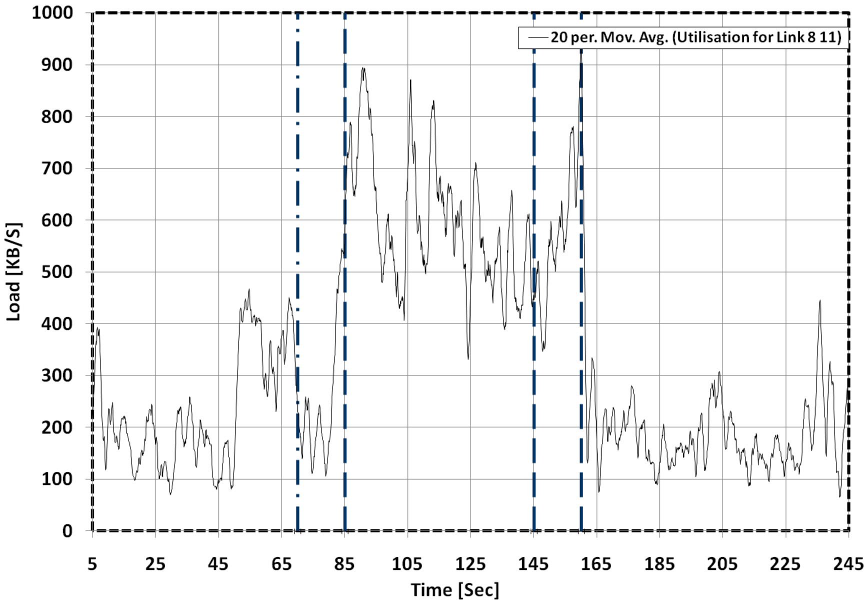


Figure 6.12: Link utilisation (8,11)

tween topologies is evident. At 70 seconds the topology is changed from the default to the reduced topology, indicated by the dot-dashed line. All flows that arrive after this time are routed via the reduced topology. The traffic gradually migrates to the new path set. During this period, the previous path set that presents the old network topology is still active and the new path set of the new topology is activate at the same time.

As long as the utilisation remains below the link threshold, there is no performance impact. Established flows remain on their original paths during this period. At $85\ s$, shown by the second dashed line in Figures 6.12 and 6.13, all remaining flows are forced onto the new paths. Link (10,11) is no longer used. At $145\ s$, shown by the third dashed line, the reduced topology will change back to the full topology and the remaining traffic flows will be forced onto the new topology. In this simulation most web related flows are completed before the timer expires. Therefore, there is no noticeable impact on performance to web users.

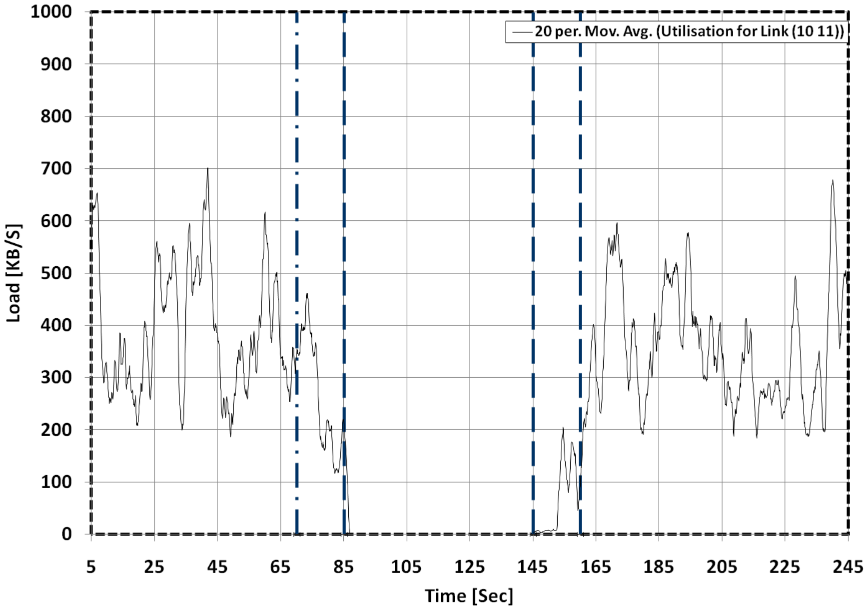


Figure 6.13: Link utilisation (10,11)

6.7.2 UDP Traffic

Figure 6.14 depicts the packet loss for a single UDP flow between Nodes 1 and 6 traversing Link (8, 11) for the same simulation. As discussed above, the topology changes at 70 seconds to use the new label set of the new topology and at $85\ s$ the traffic flows are forced to use the new label set. The figure does not show any explicit impact of these changes to the network topology. Changes between the two network topologies at $145\ s$ and $160\ s$ are also not identifiable through increased packet loss.

Figure 6.15 shows the throughput of the same UDP flow. The average throughput is around 8kBps (64kbps) as expected. The distinct steps in the graph are caused by variations in the number of packets arriving within the sampling period. Packets are generated at 8kBps. If one additional queued packet arrives in the sampling period; the rate rises to 8.8kBps, and for two packets to 9.6kBps. There are no recognisable changes to the throughput in response to the changes of the network topologies; the UPD flow is not obviously affected.

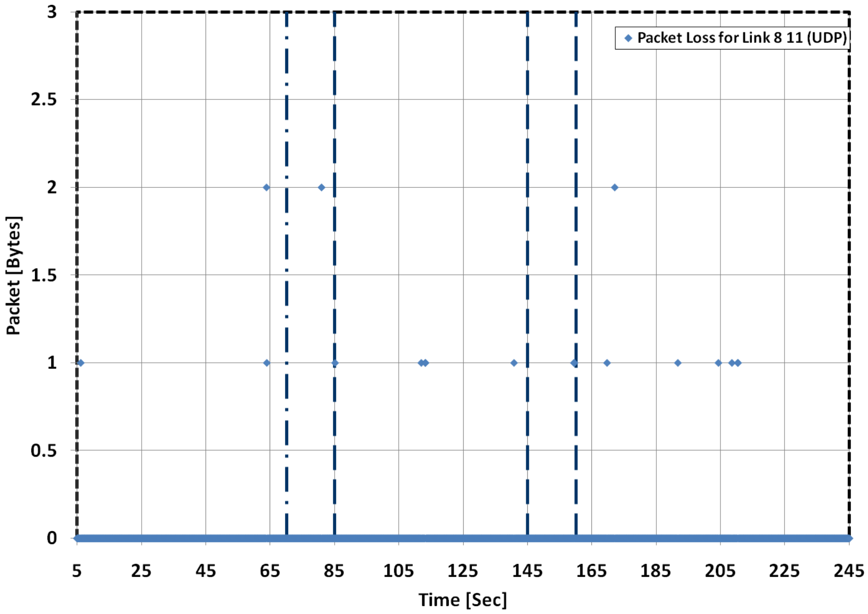


Figure 6.14: UDP packet loss for the flow between Nodes 1 and 6.

6.7.3 Elastic TCP Traffic

Figure 6.16 depicts the throughput of a TCP connection between Nodes 1 and 6 versus simulation time. The flow traverses Link (8,11). The lines indicate the changes of the network topology. There is no apparent impact on the throughput as a result of the changes in network topology. The throughput largely remains unaffected. Results for other flows in the network, for example, traversing Link (10,11) are very similar in nature and do not show any changes.

6.7.4 Power Savings and Flow State Timers

This section discusses the impact of the length of the timer t on the overall power saving in the network topology. Two aspects are relevant: how long is the timer and how often is the topology changed to a low power state.

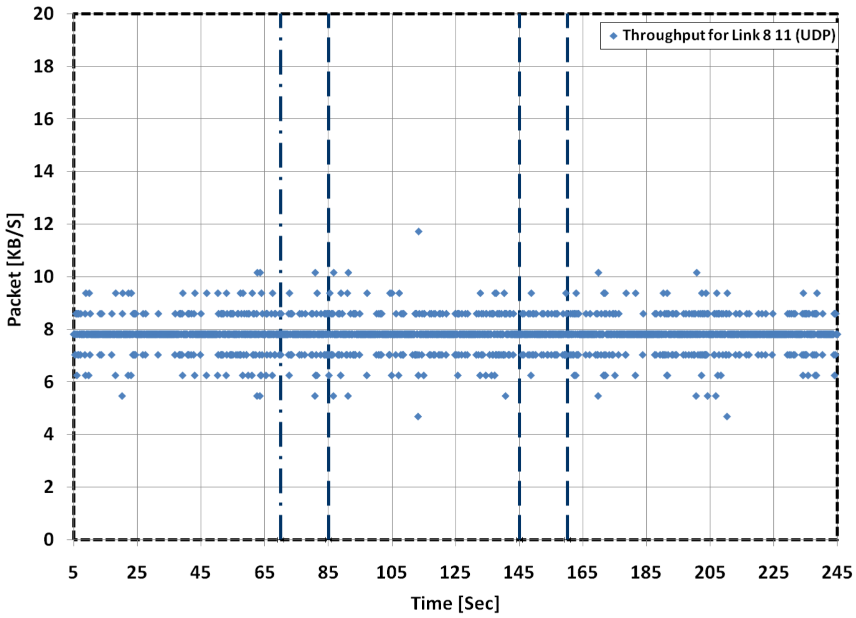


Figure 6.15: UDP throughput for the flow between Nodes 1 and 6.

The calculations focus on the fixed power consumption as the network load does not change between topology switches. Therefore it is assumed that the proportional power use remains fairly constant between topologies. Minor changes are possible due to changes in path length.

The maximum power consumption in this network can be calculated using the fixed power consumption of 4 nodes (4*540W= 2160 W) and the 5 links (5 * 64 W = 320 W), resulting in a maximum power consumption for the fully loaded network of 2160 W + 320 W = 2480 W.

In the simulated case, the reduced topology consists of one active node and three standby nodes. The power consumption of the routers includes one active router at 540W and three routers in standby 3*60 W = 180 W. The three active links consume 3*64 W = 192 W and so the total minimum power consumption for the reduced topology is 912 W.

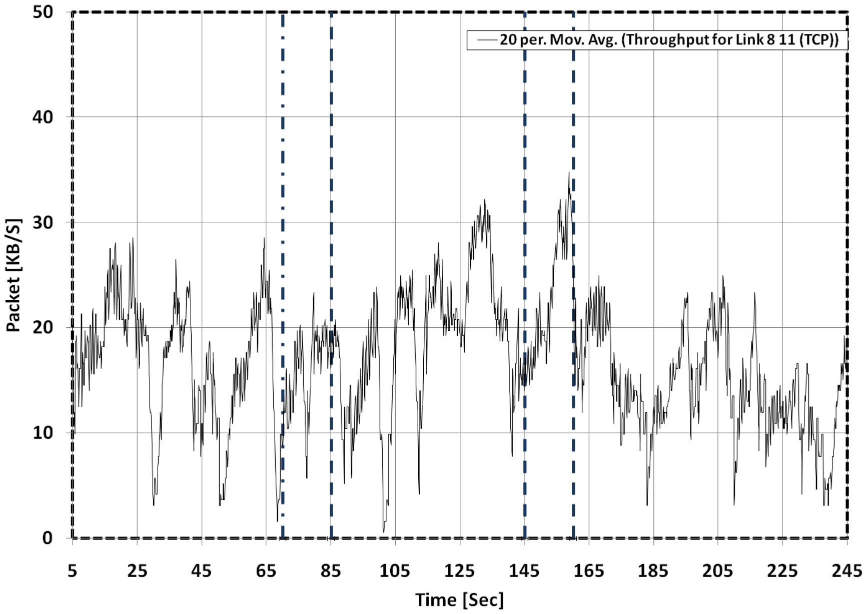


Figure 6.16: TCP throughput for the flow between Nodes 1 and 6.

The following model is used to evaluate power savings for different timer settings. Relative energy savings, S, are shown in Equation (6.2) for a network with two topologies: a fully active topology, fa and a reduced topology, rd.

$$S = 1 - \frac{t_{fa}.P_{fa} + t_{rd}.P_{rd} + n_s.t(P_{fa} - P_{rd})}{(t_{fa} + t_{rd}).P_{fa}} \tag{6.2}$$

where t_{fa} (s) is the length of the time to apply the fully loaded and reduced topology, t_{rd} (s) is the length of the time to apply the reduced topology, P_{fa} (W) is the power consumption for the fully loaded topology, P_{rd} (W) is the power consumption for the reduced topology, n_s is the number of the changing times, and t (s) is the length of the timer to switch between the topologies. These estimates only account for fixed power consumption and not the load dependent components such as traffic volume. It is assumed that traffic dependent energy use is comparable in both topologies.

Assuming that a network consumes $P_{fa} = 25\ KW$ in the fully active state and $P_{fa} = 15\ KW$ in the reduced state, that a topology is switched to the low power state 5 times, and that the network operates for 12 hours in each state and timer $t = 0$, energy saving are 20%.

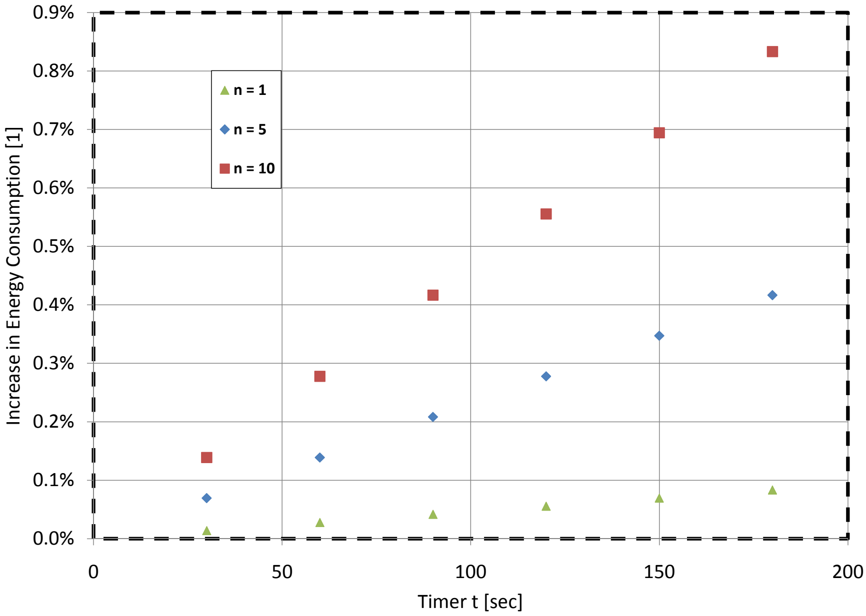


Figure 6.17: Relative energy increase

Figure 6.17 depicts the increase in energy consumption versus duration of timer t. The number of changes to reduced topologies in the observed period of 24 hours is the parameter for the curves. The dependencies are linear; however, the impact of the timer on energy saving is minimal, i.e. below 1% for all values in this example.

6.8 Operational Considerations

The previous chapters have shown that, particularly for lightly loaded networks, there is a good chance to find feasible solutions with smaller energy footprints. Optimal solutions for given networks have been discussed in Chapter 3 and it has been shown that multi-commodity flow problems can be readily solved for small and medium size networks. Chapter 4 has demonstrated how reduced topology schemes can be implemented in IP networks. The aspect that has not been addressed yet is how traffic data can be collected and how shifts in load are detected to trigger topology changes. Operational considerations are briefly discussed in this section; in particular how decisions are made to upsize or downsize the network topology.

Link load can be used as a basic information to identify the network load. Network traffic fluctuates over time. Traffic matrices are a concise description of end-to-end traffic demands, but cannot be directly measured in a backbone network. Network optimisation algorithms rely on accurate knowledge of traffic information. Traffic matrix estimation has been an active research area as this data is required by network planning and network management algorithms.

As direct measurement of traffic matrices is not feasible for the large IP networks, most of the traffic matrix measurements are based on the accessible network information that can be gathered by existing network measurement infrastructure. This includes SNMP link loads, sampled NetFlow data and periodic snapshots of network routing configuration.

Different methods have been proposed to generate traffic matrices form available measurements and these can be classified by the data that is used for the estimation. For example, methods using SNMP link loads are proposed in [246–249]. The number of SNMP link loads is usually far less than traffic matrix elements and the accuracy of these approaches is limited to around 10 per cent error. This might pose problems for network management tasks such as fault diagnosis.

The second type of approach, included in [250–252], is to estimate traffic matrices directly from flow measurement sample data gathered on routers. Besides, The traffic matrix has been investigated in [253] to develop an approach to monitoring origin-destination flow in a given network.

Therefore, the link load could be helpful to take the right decision to upsize or downsize the given topology. For each network traffic load, there are number of topologies those can manage the traffic load. By sorting out the number of topologies based on the link load, the network management can switch between the suitable topologies (upsize or downsize) to manage the traffic load.

6.9 Conclusion

The work discussed in the chapters 3,4,5 has demonstrated that energy savings are possible if the network topology is adapted to traffic load. This chapter has demonstrated how the concept of dynamic topologies can be implemented in practice, and has proposed a mechanism to implement dynamic topologies in IP networks. This method largely relies on native MPLS including an additional network management function requiring a topology and flow tracker and a router power management function.

Relying on multiple active label sets for the various topologies allows the change over not to be time critical. This enables timers that allow most flows to complete before the actual switch over is enforced. The impact on individual TCP and UDP flows having to be rerouted has been investigated. The investigation showed no noticeable impact on either throughput or packet loss for affected flows. In addition, it has been shown that the length of the switching timer has only a minimal impact on overall energy savings.

Future work needs to address the remaining issue of how changes in topology are triggered based on traffic measurements. Similar issues have been widely discussed in the context of network planning and management. If the concept is to be applied to commercial networks, survivability and resilience also need to be incorporated as was alluded to in Chapter 5.

Chapter 7

Conclusions

The previous chapters discussed the concept of dynamic topologies as method of reducing network power consumption. They have shown that dynamic topologies are feasible and have also demonstrated how these could be implemented in IP networks. It provides a summary of the thesis and highlights the main contributions and also discusses further work.

7.1 Summary

The generic router and link power model and the network transformation model have been discussed in detail and a multi-commodity flow problem formulation has been presented to evaluate these. Router, links loads and capacity have been used to formulate the network problem. Linear programming (LP) has been used to find the feasible reduced topology solutions for a given network topology with a set of traffic demands. Also, node bypass transformation has been implemented to evaluate the problem formulation. The energy consumption model has been applied to compute the power saving in the communication networks. As a result, the proposed model has the potential to reduce the number of active devices and consequently is reducing the power consumption.

To address performance limitations of the MILP approach, heuristics were proposed to find reduced topologies for particular networks. Two algorithms were discussed, both relying on link utilisation as a measure to detect overloaded topologies. The algorithms identify optimal topologies and reduce the power consumption for the given network. Shortest path routing has been used to reconfigure routing tables accordingly after redundant links and nodes are removed. Node gravity or node load were used to select candidate nodes for removal. Also, weight setting techniques were employed by the proposed algorithms to prevent link overloads. Evaluation of the algorithms has shown that power savings are possible using these algorithms, in particular for lightly loaded networks.

Network resilience is an important part of communication networks and is a requirement of network operators. Therefore, an enhanced model in chapter 5 was proposed that accounts for resilience constraints for dynamic topologies. The model is based on the generic problem formulation that forms the basis for this project. Two alternative formulations were introduced, one that protected single links and one that protected demands. Both were solved for a sample network using MILP. The results have demonstrated that network topologies can be reduced while maintaining resilience requirements that allow recovery from link failures. The resilient reduced topologies still result in lower energy footprints. The proposed methods were implemented in MPLS to demonstrate the feasibility of the scheme impact on network performance and the performance of individual flows analysed. The study has demonstrated that with minimal changes at the network ingress, MPLS can support dynamic topologies. Traffic shifts occur as anticipated and has minimal impact on existing sessions. The final step was to identify ways to trigger topology changes to either reduce or increase the network size.

7.2 Contributions to this field

The contributions of this thesis are given below:

- Power consumption model have been proposed to measure power usage and then compute power saving in networks.
- A node bypass transformation model was developed to reduce the number of nodes in the networks.
- A problem optimisation formulation for the multi-commodity flow problem was determined and Mixed Integer Linear Programming (MIP) was used to evaluate and reduce the active routers and links.
- Two network topologies have been studied numerically to determine the feasible solutions of the proposed models and the power saving in networks.
- Heuristics have been developed to find the optimal topologies for given networks.
- The power savings of the proposed optimal topologies was estimated.
- OSPF weight settings were introduced to enhance the implementation of the presented heuristics.
- The algorithm performance was analysed by implementing a network emulator.
- Problem formulations have been developed to address the network resilience issues.
- The performance of the network topology under the network resilience conditions was studied.

- Numerical results have been discussed to evaluate the power consumption of networks with and without the resilience conditions.
- A mechanism has been proposed to implement dynamic topologies in MPLS networks by considering minimal changes to the current forwarding mechanisms.
- Network topology performance in MPLS conditions was investigated by studying the performance of the network on UDP, TCP, real time and non-real time traffic while applying the network changes.
- Network management functions have been designed to change router power states.

7.3 Further Work

The intent of this project was to develop multi-commodity flow problem formulations to minimise network power consumption. Through this thesis, methods have been proposed and the mathematical formulations have been validated using sample topologies. A more comprehensive sample set of topologies will need to be studied to potentially identify patterns that could be exploited by heuristics to find optimal topologies.

Resilience in the dynamic topologies has been covered by protecting demands or by protecting links in given topologies. Other alternative formulations are also possible. Problem sizes of the current formulations are large and can only be solved in practical time frames for small networks. Therefore, it is important to find more efficient problem formulations or heuristics so that larger networks may benefit from dynamic topologies.

Evaluation results in this thesis are based on simulations through this project. The next step is to verify these results and develop a prototype test bed implementation with the key goal to assess the effects of dynamically changing topologies. The test bed could be setup using Linux-based routers and could be used to evaluate the impact of dynamic aspects on performance and power consumption. The power consumption of full-scale routers and interfaces could be extrapolated from dynamic data such as link utilisation and node uptime. Data about sleep modes and power down of routers could be used as parameters. The test bed could then be used to benchmark hardware-level power savings options.

This study has proposed a generic router power model; more specific models require further investigations to evaluate realistic hardware options. Router architectures differ based on capacity and size, results in various power models. The power models in this project will have to be adopted to generate results based on specific hardware.

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