TOWARD A GREENER INTERNET

Design and evaluation of green IP and content routing for sustainable communication networks

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Anyone who stops learning is old – whether this happens at twenty or at eighty.
Anyone who keeps on learning not only remains young but becomes constantly more valuable – regardless of physical capacity.

— Henry Ford

ABSTRACT

Green networking is receiving attention to sustainable information and communication technology because it enables more energy-efficient networks and reduces environmental impact. Previous research made strides toward green development for network infrastructure by improving energy efficiency and leveraging renewable energy. In this thesis, we focused on green networking strategies to improve state-of-the-art telecommunication from a green perspective. We especially focused on the Internet protocol (IP) and content networking, which are indispensable core components of the current network designing and planning.

The contributions of this thesis are as follows.

GREEN IP ROUTING. We designed an energy-efficient packet switching framework for green IP networking to reduce energy waste caused by dynamic changes in a network. The network is thereby partitioned into clusters consisting of one *header node* and several *member nodes*. Only the header node within a cluster performs the IP routing, and its member nodes put the routing-related functionality to sleep and conduct packet switching using a tag. We further investigated the performance impact of energy efficiency compared with the existing green solutions through simulations.

GREEN CONTENT ROUTING. To optimize content requests and caching toward green content delivery, we designed a content routing framework for green named data networking. We also introduced a quantitative metric for measuring the network's environmental footprint to define the network node's *greenness* and *green path*. Green paths encourage traffic to aggregate along routes powered by eco-friendly renewable energy. We evaluated the proposed approach's performance through simulations of named data networking and green metrics under real topologies and their meteorological data followed by comparing the existing caching schemes.

The performance of proposed approaches were evaluated through simulations using real Internet topologies, meteorological data, and energy metrics. The results indicated that applying the proposed green approaches to real networks achieves significant energy efficiency and environmental gains.

ZUSAMMENFASSUNG

Green Networking erfährt große Aufmerksamkeit im Sinne nachhaltiger Informations- und Kommunikationstechnologien. Die entsprechende Forschung zielt auf energieeffizientere Computernetzwerke und damit auf Reduktion der Umweltbelastung. Bisherige Forschung erzielte bereits beachtliche Fortschritte in Richtung grüner Netzwerk-Infrastrukturen durch Verbesserung der Energieeffizienz und die Nutzung erneuerbarer Energien. In der vorliegenden Dissertation wurden neue Konzepte und Methoden erforscht und evaluiert, die moderne Computernetzwerke aus einer grünen Perspektive zu verbessern helfen sollen. Wir haben uns besonders auf das Internetprotokoll (IP) konzentriert, das unverzichtbare Kernkomponenten der aktuellen Netzwerkgestaltung und -planung ist, sowie auf modernes *Content Centric Networking* (genauer: *Named Data Networking* (NDN); dieses gewinnt neben klassischem IP-basiertem Internet zunehmend an Bedeutung. Die vorliegende Dissertation leistet kurz zusammengefasst Beiträge wie folgt.

GREEN IP-ROUTING: Wir konzipierten und evaluierten Konzepte und Mechanismen für energieeffizientes Packet-Switching in grünen IP-Netzwerken; diese reduzieren u.a. den Energieverbrauch durch dynamische Veränderungen in entsprechend ausgerüsteten Netzwerksegmenten. Das Netzwerk(-Segment) wird dazu in Cluster partitioniert, die aus einem *Header Node* und mehreren *Member Nodes* bestehen. Nur der *Header Node* innerhalb eines Clusters führt das IP-Routing durch, während die *Member Nodes* die IP-Routing-bezogene Funktionalität in den Ruhezustand versetzen und die Paketvermittlung mithilfe von *Tags* durchführen. Mit Hilfe von Simulationen untersuchten wir die Auswirkungen unserer energieeffizienten Mechanismen auf die Leistung im Vergleich zu bestehenden grünen Lösungen.

GREEN CONTENT-ROUTING: Zur Optimierung von Content-Anfragen und Caching im Hinblick auf eine umweltfreundliche Bereitstellung von Inhalten haben wir ein *Content-Routing-Framework* für grüne *Named Data Netzwerke*. Darüber hinaus haben wir eine quantitative Metrik zur Messung des ökologischen Fußabdrucks des Netzwerks eingeführt, um die Umweltfreundlichkeit eines Netzwerkknotens und somit einen grünen Pfad zu definieren. *Grüne Pfade* veranlassen den Verkehr, sich entlang von Routen zu bewegen, die mit umweltfreundlicher, erneuerbarer Energie betrieben werden. Wir haben die Leistung des vorgeschlagenen

Ansatzes durch Simulationen von Named Data Netzwerken und grünen Metriken unter realen Topologien und deren meteorologischen Daten evaluiert, und präsentieren einen Vergleich mit bestehenden Caching-Verfahren.

Wir haben die Leistung der vorgeschlagenen Ansätze durch Simulationen bewertet, wobei die Netzwerke reale Internet-Weitverkehrs-Topologien, meteorologische Daten und Daten über den realen Energie-Mix an Vermittlungsknoten reflektierten und die konzipierten grünen Metriken evaluierten. Die neuen Ansätze wurden mit Caching Schemata aus verwandten Arbeiten verglichen. Die Ergebnisse weisen auf ein großes Potenzial der in der Arbeit vorgeschlagenen grünen Ansätze hin, die Energieeffizienz und Umweltfreundlichkeit in realen Netzwerken signifikant zu verbessern.

PUBLICATIONS

IN THIS THESIS

Some of the research leading to this thesis has appeared previously in the following publications.

Journal Articles

1. Jo, Seng-Kyoun and Muhammad, Ikram and Jung, Ilgu and Ryu, Won and Kim, Jinsul: **Power efficient clustering for wireless multimedia sensor network**. – *International Journal of Distributed Sensor Networks*, November 2014
2. Jo, Seng-Kyoun and Kim, Young-Min and Lee, Hyun-Woo and Kangasharju, Jussi and Mühlhäuser, Max: **Novel Packet Switching for Green IP Networks**. – *ETRI Journal*, April 2017 ***(Best paper of 2018)***
3. Jo, Seng-Kyoun and Wang, Lin and Kangasharju, Jussi and Mühlhäuser, Max: **Design and Evaluation of Eco-friendly Caching and Forwarding in NDN**. – *IEEE Transactions on Green Communications and Networking* (under review)

Conference Papers

1. Jo, Seng-Kyoun and Kim, Young-Min and Lee, Hyun-Woo and Kangasharju, Jussi and Mühlhäuser, Max: **Minimization of power consumption in IP networks**. – *Proceeding of the 18th International Conference on Advanced Communication Technology (ICACT)*, January 2016, Pyeongchang, Republic of Korea
2. Jo, Seng-Kyoun and Kim, Young-Min and Lee, Hyun-Woo and Kangasharju, Jussi and Mühlhäuser, Max: **Selective Packet Routing for Green Communications**. – *Proceeding of the 1st International Conference on Consumer Electronics(ICCE)-Asia*, October 2016, Seoul, Republic of Korea
3. Jo, Seng-Kyoun and Kim, Young-Min and Wang, Lin and Kangasharju, Jussi and Mühlhäuser, Max: **Green routing using renewable energy for IP networks**. – *Proceeding of the IEEE Inter-*

national Symposium on Local and Metropolitan Area Networks (IEEE LANMAN), June 2017, Osaka, Japan

4. Jo, Seng-Kyoun and Wang, Lin and Kangasharju, Jussi and Mühlhäuser, Max: **Green named data networking using renewable energy**. – *Proceedings of the 9th International Conference on Future Energy Systems (ACM e-Energy)*, June 2018, Karlsruhe, Germany

5. Jo, Seng-Kyoun and Wang, Lin and Kangasharju, Jussi and Mühlhäuser, Max: **Cost-effective and Eco-friendly Green Routing Using Renewable Energy**. – *Proceedings of the 27th International Conference on Computer Communication and Networks (IEEE ICCCN)*, July 2018, Hangzhou, China

6. Jo, Seng-Kyoun and Mühlhäuser, Max and Kim, Se-Han: **Eco-friendly Content Caching for Smart Farm**. – *Proceedings of the IEEE Wireless Communications and Networking Conference (IEEE WCNC) Workshop on Intelligent Computing and Caching at the Network Edge*, May 2020, Seoul, Republic of Korea (Virtual Conference)

7. Jo, Seng-Kyoun and Wang, Lin and Kangasharju, Jussi and Mühlhäuser, Max: **Eco-friendly Caching and Forwarding in Named Data Networking**. – *Proceeding of the IEEE International Symposium on Local and Metropolitan Area Networks (IEEE LANMAN)*, July 2020, Orlando, USA (Virtual Conference)

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Finally, I would like to thank my family: my mother, my wife, and two sons for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

ERKLÄRUNG ZUR DISSERTATION

Hiermit erkläre ich, die vorliegende Dissertation selbständig und ohne Hilfe Dritter nur mit den angegebenen Quellen und Hilfsmitteln angefertigt zu haben. Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen. Ein Promotionsversuch fand bisher nicht statt.

Darmstadt, 25 Februar 2021

Seng-Kyoun Jo

CONTENTS

LIST OF TABLES

ACRONYMS

List of Acronyms and Abbreviations

aGN associated Green Node

ALR Adaptive Link Rate

ARP Address Resolution Protocol

ASIC Application Specific Integrated Circuit

BoE	Bill of Energy
BS	Base Station
CCN	Content Centric Network
CMCF	Capacitiated Multi-Commodity Flow
CMND	Capacitiated Multicommodity Network Design
CO_2	Carbon Dioxide
CORONET	CORe Optical NETwork
DARPA	Defence Advanced Research Projects Agency
DHCP	Dynamic Host Configuration Protocol
EAR	Energy Aware Routing
EB	Eta Byte
ER	Export Router
FIB	Forwarding Information Base
FNSS	Fast Network Simulation Setup
FPGA	Field Programmable Gate Array
GHG	Green House Gas
GN	Green Node
GPT	Green Path Tree
HN	Header Node
ICMP	Internet Control Message Protocol
ICN	Information Centric Network
ICT	Information & Communication Technology
IDC	Internet Data Center
ILP	Interger Linear Programming
IoT	Internet of Thing
IR	Import Router
ISP	Internet Service Provider
IT	Information Technology
LAN	Local Area Network
LCD	Leave Copy Down

LCE Leave Copy Everywhere

LDP Label Distribution Protocol

LER Label Edge Router

LRU Least Recently Used

MANET Mobile Ad hoc NETwork

MILP Mixed Integer Linear Programming

MLU Maximum Link Utilization

MN Member Node

MPLS Multi Protocol Label Switching

NCP Network Connectivity Proxy

NDN Named Data Networking

NFV Network Function Virtualization

NIC Network Interface Card

NIC Network Interface Controller

NLSR Named-data Link State Routing protocol

NR Neutral Router

NS2 Network Simulator 2

NSF National Science Foundation

NSFNET National Science Foundation NETwork

OSI Open System Interconnection

OSPF Open Shortest Path First

OSPFN Open Shortest Path First based routing protocol for NDN

P2P Peer-2-Peer

PARC Palo Alto Research Center

PC Personal Computer

QoS Quality of Service

RWA Routing and Wavelength Assignment

SPT Shortest Path Tree

TCAM Ternary Content Addressable Memory

TCP Transmission Control Protocol

TE Traffic Engineering

TM Traffic Matrix

UDP User Diagram Protocol

VoIP Voice over Internet Protocol

WMSN Wirelss Multimedia Sensor Network

1

INTRODUCTION

The biggest gains, in terms of decreasing the country's energy bill,
the amount of carbon dioxide we put into the atmosphere,
and our dependency on foreign oil,
will come from energy efficiency and conservation in the next 20 years.
Make no doubt about it.
That's where everybody who has really thought about the problem thinks
the biggest gains can be and should be.

— Steven Chu (Novel laureate & professor at Stanford University)

1.1 BACKGROUND AND MOTIVATION

The Internet has revolutionized the computer and communication-related industries. Since the 1950s of point-to-point communications between computers, the Internet represents one of the most successful examples of sustained investment and commitment to the information and communication technology (ICT) industry [45, 104, 159, 164]. The Internet converging with wireless mobile technology has expanded handheld mobile devices and allowed new and various applications opportunities. With the catchphrase "*connecting everything*", the Internet of things (IoTs) as the next step in Internet evolution has appeared as another key driver to promote the creation of new Internet-based mash-up services using data, presentation or functionality from two or more sources to create new services.

By current trends, global Internet protocol (IP) video traffic is expected to comprise 82% of all the IP traffic by 2022 [42]. The paradigm shift of current Internet architecture to correspond with the growing video traffic efficiently has been raised. Therefore, the named data networking (NDN) was born to solve IP's fundamental design limitations [187].

With the advent of these technologies, there is an increase in Internet traffic caused by the evolution of future services. According to the recent Cisco Visual Networking Index 2017 [42], the following are found.

- In 2017, the annual run rate for global IP traffic was 1.5 zettabytes per year or 122 exabytes per month.

- By 2022, the number of devices connected to IP networks will be more than three times the global population. In 2017, there were 2.4 networked devices per capita, and by 2022 it will increase to 3.6 networked devices per capita. Similarly, from 18 billion networked devices in 2017, it will be 28.5 billion by 2022.
- In 2018, PCs accounted for 41% of the total IP traffic. By 2022, PCs will only account the 19% of IP traffic because smartphones will account for 44% of total IP traffic (from 18% in 2017).

Regarding the traffic increase forecast, various ICT equipment's energy consumption is rapidly increasing, resulting in significant economic and environmental problems. Presently, the network infrastructure is becoming a large portion of the energy footprint of the ICT industry. The network infrastructure expects to consume more electricity to support service continuity because of these drastic Internet traffic increases. Consequently, Internet service providers (ISPs) or network providers must consider *energy efficiency* to reduce electricity charges bill. Energy efficiency in this context means the amount of data that could be conveyed from end-to-end per quantum of energy consumed by the network. Previous studies of software and hardware have been carried out to reduce energy cost and consider environmental effects while maintaining other service performances.

There is a need for electricity drives a growing demand for electricity generation, with thousands of new power plants needed globally for the world over the coming decades. Recent studies showed that today's ICT industry generates approximately 2% of global carbon dioxide emissions than the worldwide aviation industry, as illustrated in Fig. 1.1. Further, the sharp growth curve forecast for ICT-based emissions shown in Fig. 1.2 far outpaces aviation.

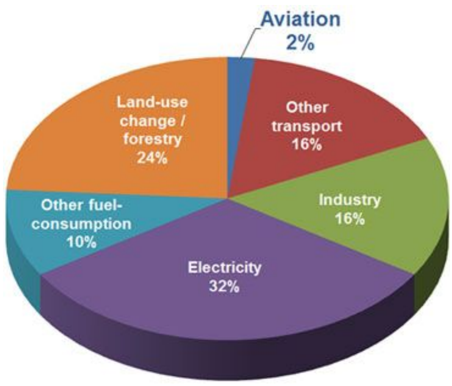


Figure 1.1: The global CO_2 emissions by sector [7, 152]

Globally, the largest sources of energy for electricity generation are fossil fuels. In 2018, fossil fuels (such as petroleum, natural gas, and coal) accounted for at least 80% of energy consumption in the United States [166]. Fossil-fuel power plants burn carbon fuels to generate steam to drive large turbines that produce electricity. These plants can generate electricity reliably over long periods. However, burning carbon fuels produces large amounts of carbon dioxide, causing climate change, and produces other pollutants (such as sulfurous oxides), causing acid rain. The concept of *sustainability* as the ability to continuously exist has become even more important across industry and the environment. Maintenance costs and performance were the major concerns regarding energy consumption in the past, but now it is also important to consider the impact on the environment. Energy collected from renewable resources (such as sunlight, wind, rain, tides, waves, and geothermal heat) is emerging as a future energy source to make our environment sustainable. Renewable energy currently generates a relatively small share of the world's electricity (and that share is growing fast) and produces electricity with no greenhouse gas (GHG) emissions at the point of generation and very low GHG emissions across their entire lifecycle.

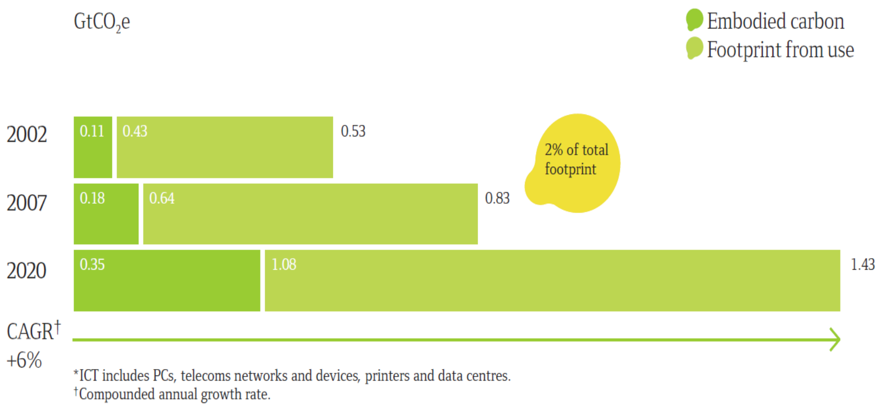


Figure 1.2: The global ICT footprint [153]

1.2 RESEARCH QUESTIONS

Given the aforementioned situation, there are two fundamental challenges.

i) How to increase energy efficiency in the existing communication networks?

ii) How to make and operate communication networks in an eco-friendly manner?

To address these issues, we proposed designing new environmentally friendly network architectures and protocols for supporting the expected traffic growth, new applications, and new services for future communication networks [125].

Previous studies [23, 24, 29, 38, 40, 79, 137] have addressed the first challenge in recent decades. However, this study more focuses on the fact that network elements should always be powered for connectivity regardless of the network volume, status, or other factors. In [106], the network load is proportional to the traffic volume and varies significantly between peak and off-peak times. Therefore, differentiated network operation strategies are strongly encouraged to minimize energy wastage across different periods and maximize energy efficiency. Inspired by these behaviors in current networks, this study tries to sleep selectively corresponding functions of the open systems interconnection (OSI) 7 reference model within a single network entity rather than completely sleep network entities themselves. In short, the IP routing is selectively powered off according to the network situation to save unnecessary power consumption. Consequently, we designed and described a novel network architecture and its corresponding mechanisms.

The second challenge is about using renewable energy for an eco-friendly network. Assuming network entities are equipped with renewable energy enabled, such as solar panels and wind turbines locally; thus, network entities can be powered by combining multiple energy sources. Recently, this assumption is being actualized, especially in mobile network systems [35, 128]. Furthermore, renewable energy is becoming part of the power grid [10], and the proportion of energy sources applies to all domains, including telecommunication. With this rationale, we introduced and analyzed sophisticated strategies to maximize renewable energy's impact on energy efficiency.

1.3 CONTRIBUTIONS

This study offers a novel and innovative approaches toward green communication networks, including green IP routing and eco-friendly content caching and forwarding. Major contributions are summarized in three phases.

Phase I (design of green IP routing)
Discovering the inefficiency of current networks and entities in power consumption, we proposed a novel energy-efficient packet switching method in IP networks. As the first phase toward green networking, the network nodes are classified into header and member nodes. The member nodes then put the routing-related module at layer 3 to sleep under the assumption that the OSI model's layer can operate independently. The entire network node is partitioned into clusters consisting of one header node and multiple member nodes. Only the header node in a cluster conducts IP routing, and its member nodes conduct packet switching using a specially designed identifier, a tag.

Several simulations using well-known real network topologies were conducted to investigate the impact of the proposed scheme.

The research results in this phase have been published in [94–96].

Phase II (design of green IP routing with renewable energy)
With the network architecture and routing schemes described in *phase I*, we investigated the problem of achieving energy efficiency in IP networks by considering the network's energy consumption and the impact of various energy sources, such as renewable energies. Assuming network elements are powered partially by renewable energy and traditional fossil-fuel energy, we designed the extensive routing scheme by considering the generation cost and carbon emission per unit of energy. Various simulations using real-world renewable energy statistics were performed to validate the proposed solution.

The research results in this phase have been published in [98, 101].

Phase III (design of green content routing in NDN)
With the network architecture described in *phase II*, we selected and analyzed the content delivery network, NDN as an extension of target network infrastructure for eco-friendly greener content routing scheme as a new approach for green NDN. The algorithm first defines nodes' greenness, identifies corresponding green paths, and encourages traffic to aggregate green paths powered by more eco-friendly renewable energy than traditional fossil energy. Simulations using realistic network topologies and renewable energy statistics from the USA are performed to validate the solution.

This phase's research results have been published in [97, 99, 100], and one more article is currently submitted.

1.4 OUTLINE

The remainder of this thesis is organized as follow, as shown in Fig. 1.3. Chapter 2 presents state of the art in green networking, including general energy efficiency and using renewable energy in networks. The first part of this chapter surveys the technical trends and works on energy-efficient routing under wired and wireless communication networks. Subsequently, we performed a comprehensive survey of how renewable energy can be deployed in the existing network.

Chapter 3 presents the novel green routing algorithm in IP networks. First, it defines and formulates the minimizing power consumption problem, which is different from other conventional energy minimization problems. Then, it provides design issues of green routing algorithms and network node architecture with reasonable assumptions. The detailed green routing procedures include header node selection,

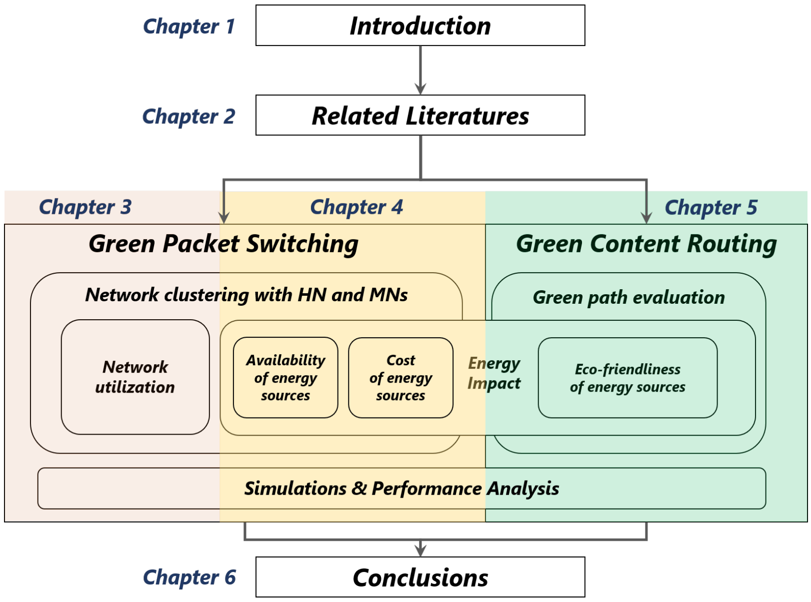


Figure 1.3: The outline of thesis

clustering, tag allocation, and distribution follow. To compare the routing algorithm's complexity, we introduced several existing green IP routing protocols and analyzed their complexity with the proposed green IP routing. Finally, we described the simulation environments and illustrated and discussed the simulation results.

Chapter 4 introduces the renewable energy-based green routing algorithm in IP networks. It defines and formulates the problem of maximizing renewable energy usage in line with green IP routing described in Chapter 3. Considering renewable energy into green routing, we described the impacts and properties of renewable energy. We discussed the performance as a result of simulations using real network topology and renewable energy data.

Chapter 5 extends the green routing scheme into NDN in an eco-friendly manner. First, it defines the problem of minimizing the environmental effects of energy sources by introducing several indices. Then, it provides an eco-friendly content routing algorithm. Green content routing procedure includes selecting green nodes, associated green nodes, establishing a green path, and configuring forwarding information base. To compare NDN and green performance, we introduced several existing NDN protocols. Finally, we described the simulation environments and illustrated and discussed the results.

Chapter 6 summarizes the thesis and highlights the contributions and insights gained and an outlook on future research directions.

2 STATE OF THE ART

An increased push for energy efficiency,
renewable energy technology, electric mobility
along with the growing digitalization movement
and a universal carbon pricing structure
would speed up the carbon
free future and the rise of a global middle class we desperately need.
We can and must all do our part.

— Joe Kaeser (Former CEO of Siemens AG)

The Internet history began in the 1950s with point-to-point communications between computers and flourished to provide various types of services, such as email, voice over internet protocol (VoIP), video conferencing, and social network services in the mid-1990s. Now, the Internet represents a successful example of the benefits of sustained investment and commitment to the information and communication technology (ICT) industry [45, 104, 159, 164].

The Internet converging with wireless mobile technology has expanded the popularity of hand-held mobile devices and allowed opportunities for new applications, such as Facebook, Twitter, and YouTube. Because of the development of mobile devices or the smart phone revolution [108], initiated by iPhone, first launched by Steve Jobs in January 2007, the role of smartphones has changed from calls and text only to the integrated hub of information technology (IT) functions. Users can browse websites like using a desktop computer, spending hours every day on activities ranging from checking email and social medial to streaming video and music to gaming.

As a next step for Internet evolution, the Internet of Thing (IoT) has appeared as another key driver promoting the creation of new internet based mash-up services that use data, presentation, or functionality from two or more sources to create new services. The IoT is a technology connecting all possible objects with which we can interact with and provides up-to-date information and appropriate services to users. The IoT allows objects to be sensed and controlled remotely across existing network infrastructure, further creating opportunities for more integration of the physical world into computer-based systems throughout all industries.

Today's Internet's hourglass architecture centers around a network layer, IP implementing the minimal functionality necessary for global interconnectivity. This thin waist illustrated in Fig. 2.1 enabled the Internet's explosive growth by allowing lower- and upper-layer technologies to innovate independently. However, the current IP was initially designed to create a communication network, where packets were named only communication endpoints. Sustained growth in e-commerce, digital media, social networking, and smartphone applications has led to dominantly using the Internet as a distribution network. Distribution networks are more general than communication networks, and solving distribution problems using a point-to-point communication protocol is becoming increasingly complex. Named data networking (NDN), a new internet architecture, was proposed to solve the fundamental design problem of IP [187]. NDN adopted a data-centric methodology by naming data instead of identifying location-based IP addresses. It enables data packets to be meaningful, independent of where they come from, or are forwarded to.

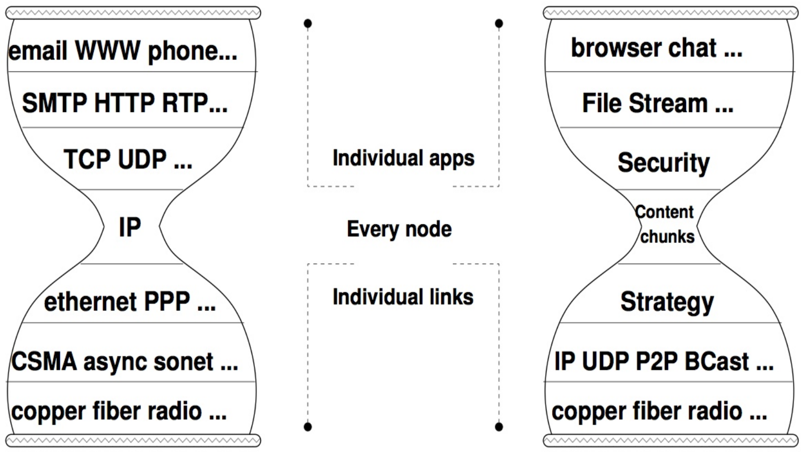


Figure 2.1: Internet and NDN hourglass architecture [188]

Internet traffic caused by the advent and development of these technologies is increasing dramatically, and energy consumption supporting traffic increment is also expected to be a major concern in network perspective. This thesis aims to increase the energy efficiency of the network. This chapter introduces literature regarding green communication networks and structured as follows: Section 2.1 introduces relevant existing works on energy efficiency in communication networks, including both IP and content networking, and Section 2.2 discusses and compares state-of-the-art approaches encouraging using renewable energy for green networking.

2.1 ENERGY EFFICIENCY IN COMMUNICATION NETWORKS

This section provides state-of-the-art energy efficient technologies for IP and content networking.

2.1.1 *Green IP networking*

Energy efficiency is not a new concept and has long been a critical topic in wireless environments, such as sensor networks, IoT, and mobile communication. Much research has been devoted to the extension of battery life in various devices. In [25, 126], the authors defined energy efficiency as a new metric for quantifying the number of bits that can be sent per unit of power consumption, measured in bits per Joule (J) for wireless communication. A general concern in wireless environments is that higher data rates can only be achieved by consuming more energy. If the energy efficiency is constant, 5G's 100 times higher data rate is associated with 100 times greater energy consumption [26]. According to the review in [62], energy consumption in cellular networks, including base stations (BSs), mobile terminals, and the core network, accounts for 80% of the energy required for cellular network operation. Hence, numerous researchers [9, 55, 63, 117, 180, 181] designed simple yet effective BSs with multiple levels of sleep modes, and analyzed the tradeoff between energy consumption and performance. The network lifetime can be prolonged in situations where energy conservation is achieved by sharing the computational load among sensor nodes in wireless multimedia sensor networks. The authors of [93] proposed a resource- and energy-efficient distributed image compression algorithm that dynamically configures clusters. One cluster is used as a header node and others as sensor nodes based on a three-item classification of energy levels by the highest energy level using a forwarding strategy based on the entropy of the image.

This thesis focuses on energy concerns in wired networks, and the following sections will focus on the literature regarding energy efficiency in wired communication environments. Triggered by the recent exponential growth in network traffic volumes [42, 43], the spread of internet access, and the expansion of new ICT services offered by service and network providers, energy efficiency has also become a high-priority for wired networks. To analyze existing green technologies in a wired IP network, the authors of [24] categorized the fundamental approaches as *i*) adaptive link rate, *ii*) interface proxying, *iii*) energy-aware infrastructure, or *iv*) energy-aware applications. Several other works relating to these issues have been published during the last decades. Following the basic classifications presented in [24], this section reviews existing studies on energy efficiency in wired communications.

Significant energy savings can be achieved by developing new silicon devices (e.g., application specific integrated circuits, field programmable gate arrays, network/packet engines, processors) and memory technologies (e.g.,ternary content-addressable memory) for packet processing engines [29]. However, this thesis focuses primarily on green strategies from a software viewpoint, and hardware-dependent approaches are not discussed.

2.1.1.1 *Adaptive link rate*

According to the measurement studies in [84, 123], the energy consumption of a network link largely depends on its use. In practice, even during idle intervals when no frame is transmitted, links are used to continuously send special sequences of symbols to preserve synchronization and avoid the time required to send a long frame preamble. Therefore, a link's energy consumption depends on the negotiated link capacity rather than the actual traffic load.

To improve these situations, several studies have proposed modifying the link rate by either *i*) turning off unnecessary links during idle periods, referred to as *sleep mode*, or by *ii*) reducing the line rate during low usage periods, referred to as *rate switching*.

1) Sleep mode: The sleep mode is founded on power management primitives, allowing all or part of the device to turn itself off completely or partially, entering a low energy state in which most of its functions are disabled. In a pioneering study of link rate adaptation, the authors of [79] presented an approach in which the packet inter-arrival times are measured to calculate whether the average interval between two consecutive frames is long enough to save energy. The routers then set the activity and energy state of the interface accordingly. Efficiency is, thus, directly affected by the inter-arrival distributions. The approach was evaluated using recorded traffic traces to investigate the practicality of the proposed energy saving scheme. Since this initial work, many studies have proposed several types of sleep modes for interfaces. Consequently, the interface could be in either a fully or partially idle state for energy saving. In a fully idle state, the interface drops arriving packets during sleep [80]. Hence, although this state is effective in saving energy during the sleep period, the packets received are lost. This drawback can be overcome using a buffer to store the packets that arrive during sleep so that the interface can process them when it wakes up. Any type of fully sleeping state requires additional energy (wake-up power) to transition from an idle to an active state when the sleep period ends. To avoid packet loss and delays of a fully idle state, in a partially idle state the interface can sleep temporarily and be awakened by every packet reception. This state can process the arriving packet more dynamically than a fully idle state. However, it might consume more wake-up power because the packets arrive more frequently resulting in reduced energy saving.

The author of [78] investigated the possibility of placing various local area network (LAN) switch components into a sleep state during idle periods and proposed a two-state sleep mode model of regular operation and energy-saving mode. The first transition, from energy-saving mode to operational mode takes time (with state-of-the-art technology, the wake-up time is approximately 0.1 *ms*) and generates a spike in energy consumption. The second transition, from the normal working mode to the energy-saving mode, should be instantaneous and spike-free. Their results show that this approach is feasible for some LAN switches. They suggest additional hardware to support the sleeping state. In [80], the authors described the limitations of low-power modes in existing switches and proposed methods for detecting such idle or underused periods to achieve energy saving with little impact on performance indexes. Through various real-time traffic monitoring techniques, they demonstrated that Ethernet interfaces at both ends could be placed in extremely low-power modes for 40%-98% of the time observed. Furthermore, approximately 37% of the interfaces used in the experiment on the same device could be in low-power modes simultaneously, opening the potential for further energy savings in the switching fabric within the switch.

2) Rate switching: Sleep mode functionality supports the choice between an idle and a working mode, and is limited by its inability to manage variations in the status of network traffic and switches. In contrast, rate switching offers a more dynamic approach to realizing adaptive link rate (ALR) and can respond to various situations by changing the transmission rate. Ethernet is a good example of rate switching and defines several transmission rates from 10Mb/s to greater than 10Gb/s.

In [76], the authors revealed a non-negligible difference in energy consumed by interfaces across different data rates. For instance, increasing the data rate of a PC end-system network interface card (NIC) from 10 Mb/s to 1Gb/s resulted in an energy consumption increase of approximately 3W, representing approximately 5% of the overall system energy consumption. For regular switches, the same throughput shift resulted in a per-interface energy consumption increase of approximately 1.5W per link.

In the US alone, Ethernet NICs consumed 400 million US dollars' worth of electricity per year in 2011 [11]. Most Ethernet links are typically underused, such that link energy consumption can be reduced by operating at a lower data rate. To reduce the energy consumption of a typical Ethernet link, the authors of [77] proposed the ALR algorithm for dynamically controlling the data rate in response to network use. ALR determines when to change the link data rate. The results show that one can operate at 100Mbps for more than 80% of the time with an additional delay of less than 0.5ms when the average link use is 5% or less of the highest data rate. Figure 2.2 illustrates a simple ALR algorithm using output buffer queue length thresholds. To eliminate rate oscillations, the authors developed and evaluated using utilization-threshold and time-out-threshold policies, demonstrating them to be effective for smooth traffic. Simulation experiments using real and synthetic traffic traces showed that an Ethernet link with ALR could operate at a lower data rate for more than 80% of the time, yielding significant energy savings with only a small increase in packet delay. In summary, the utilization-threshold policy should be used only if the effort of counting packet arrivals is acceptable. Otherwise, the time-out-threshold policy should be used. In no case should the dual-threshold policy be used because of its inherent oscillation with smooth traffic.

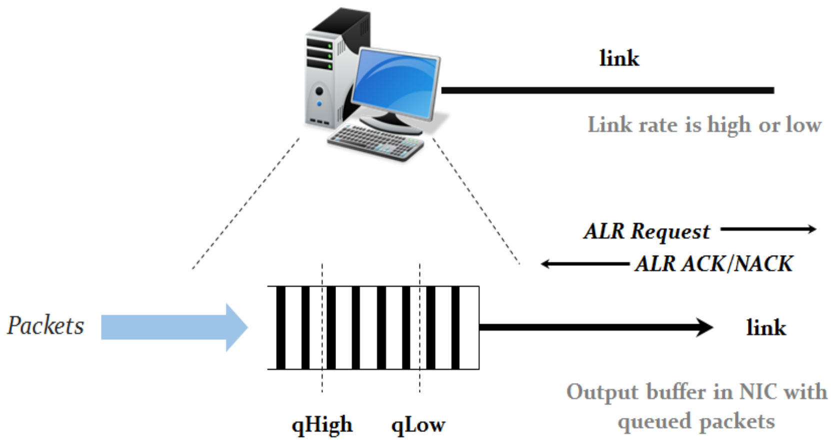


Figure 2.2: Example NIC output buffer with thresholds (adapted from [77])

3) Comparison of sleep mode and rate switching: In [137], the authors presented the design and evaluation of sleep mode and rate switching schemes for reduced energy consumption at the network infrastructure level. Both algorithms were compared for Quality of Service (QoS). More precisely, they were evaluated based on end-to-end packet delay and loss rate and energy savings achieved. In the sleep mode case, the percentage of time in which network elements may sleep was evaluated, and in the rate switching case, the average rate reduction was evaluated. Regarding energy saving, the comparison highlighted a network utilization threshold beyond which the sleep mode demonstrated better performance than rate switching. Moreover, the authors compared two types of rate sets, distributed exponentially (10Mb/s, 100Mb/s, and 1,000Mb/s) in the first case, and uniformly (330Mb/s, 660Mb/s, and 1,000Mb/s) in the second case. Finally, the authors concluded that both sleep and rate switching adaptation can be valuable, depending primarily on the power profile of the network equipment and the use of the network itself.

The authors of [179] also compared two schemes applied to processors and servers. Rate adaptation is critical for reducing power consumption, involving a tradeoff between mean response time and mean power consumption rate. The work presented in [179] provides insight into this tradeoff by comparing stochastic and worst-case analysis of sleep mode in processor-sharing systems. Here, the results favored sleep mode strategies because they offer lower management complexity for a comparable performance level. The lower complexity arises from the simpler optimization goals of minimizing idle energy and transition time. Comparable results were presented in [131]. However, dynamic rate switching is more robust in the presence of more realistic burst traffic, such as in the case of misestimation of workload parameters.

2.1.1.2 *Proxying*

The previous section introduced energy-saving mechanisms based on placing interfaces into idle or low energy modes, with greater periods spent in the respective modes, resulting in greater energy savings. As an extension of these mechanisms, a similar type of sleeping mode can be applied to users' end devices, such as PCs. Here, however, the device cannot sleep completely because some functionality must be delegated. For example, when a device enters sleep mode, its applications stop working and lose their network connectivity. Consequently, the device loses its network presence because it cannot maintain network connectivity, or respond to application/service-specific messages. Moreover, when the device wakes up, it must reinitialize its applications by sending a non-negligible amount of control traffic.

With recent advances in the PC industry, most modern PCs are equipped with power management features allowing them to quickly enter sleep or low-power mode while retaining their network presence (transmission control protocol (TCP) connections and LAN broadcasting). Even though the PC appears to be idle, it can process incoming network traffic in the background. This power management functionality is included in most modern internet-connected devices and servers.

In a previous study on power management for interface proxying [40], the authors highlighted problems with current Ethernet adapters in desktop computers, which lack the functionality needed to enable existing system power management features. Therefore, they proposed a proxying Ethernet adapter to manage routine network tasks for desktop computers in a low-power sleep mode. This proxying adapter supports using existing power management features in desktop computers, enabling the computer to always retain its network presence, with a reported energy saving of 0.8-2.7 billion US dollars per year. In [40], the same authors developed and evaluated several new methods for improving the IT equipment power management schemes presented in [76]. Proxying, application-specific wake-up, and split TCP connections can all increase the low-power sleep time of PCs. Their solution for maintaining a continuous network presence uses a network host to transfer the PC's network presence to a proxy, denoted as the network connectivity proxy (NCP), when entering sleep mode.

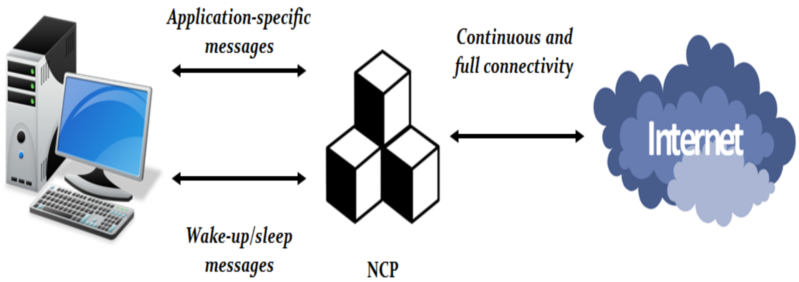


Figure 2.3: Example of network connection proxy (adapted from [29])

Figure 2.3 shows that an NCP should manage address resolution protocol, internet control message protocol, dynamic host configuration protocol, and other low-level network presence tasks for a network host. It should also maintain TCP connections and user datagram protocol (UDP) data flow, and respond to application messages. Thus, the principal objective of such a proxy is to respond to routine network traffic as the device sleeps, and wake the device only when necessary. In more detail, an NCP and the sleeping device must exchange two types of messages:

- Application-specific: These messages are needed to register the sleeping host's applications and services with the NCP. They contain descriptions of application connections and application routine messages.
- Wake-up/sleep: These messages are needed to trigger the NCP when the host enters sleep or wake the host when the NCP receives a message that the host must process.

The authors in [177] investigated using an NCP, enabling significant energy saving by allowing idle hosts to enter a low-power sleep state while maintaining a full network presence. Here, an NCP is implemented and deployed as an additional functional block in a network interface, Ethernet switch, third-party server or device near sleeping hosts.

2.1.1.3 *Energy-aware routing*

The mechanisms discussed in Section 2.1.1.1 and Section 2.1.1.2 only involve local decisions in a single device or a limited set of collaborative devices. While these techniques alone offer non-negligible energy savings, further improvements can be expected from a reasonable amount of collaboration between individual devices at an infrastructure level. Green routing and switching in networks as the major focus of this thesis are the key drivers of energy-aware infrastructure. Routing and switching are basic functions of network communication operating in layers 2 and 3 of the OSI model, respectively. Both functions require a wider knowledge of the network infrastructure to determine where to route and switch packets. To facilitate green network infrastructures, various packet delivery approaches have been proposed, involving either new architectures or modification of existing infrastructures.

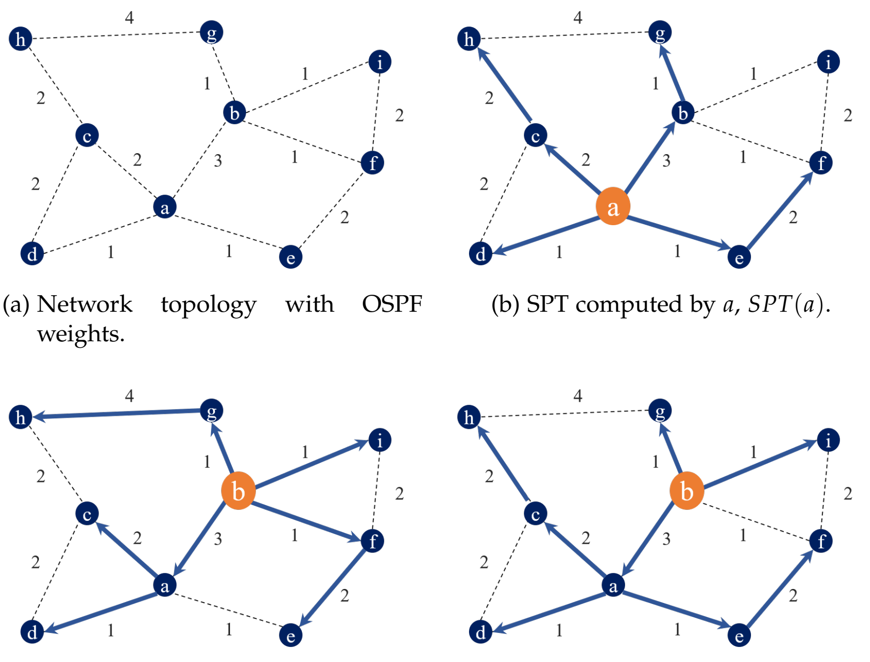
From 2010, much effort has been applied to reducing the energy consumption of core networks. In an initial investigation into the feasibility of energy-aware routing in IP networks [23], the authors analyzed green routing algorithms and evaluated their energy saving potential in several realistic network scenarios. The authors of [69] presented a joint formulation of energy and QoS problems in packet networks using the control capabilities inherent in G-network [68], including control-traffic overheads. G-network is an open network of G-queues, first introduced in [67] as a model for queueing systems with specific control functions, such as traffic re-routing or traffic destruction. Additionally, the authors of [70] extended their work to focus on network routing control to reduce energy consumption while retaining the awareness of QoS considerations. They proposed approaches based on network analysis and modeling used to distribute traffic within the network to reduce an overall cost function, including energy and QoS. As an implementation case study, the authors of [151] built an energy-efficient routing protocol on top of the open shortest path first (OSPF) implementation of Quagga [145], a popular software router used in operational networks. The authors showed that their prototype could outstretch a more energy-efficient network topology while preserving network stability and reconfiguration capabilities and compatibility between green and legacy routers.

The authors of [169] proposed an extension of the OSPF-Traffic Engineering (TE) (OSPF-TE) protocol and a green-aware routing and wavelength assignment algorithm based on routing connection requests through green network elements. Network behavior and algorithm performance were analyzed using simulations under different scenarios. The results showed that one could reduce GHG emissions at the expense of increased path length and, in some cases, blocking probability. The tradeoff between emissions and performance were studied previously, but according to the authors of [169], theirs was the first work to provide a detailed study of a green-aware OSPF protocol.

Significant energy savings can be obtained by switching redundant or unused network components to an inactive mode. Therefore, green IP routing protocols should aggregate traffic flows over a subset of network routers and their links, allowing other components or functions to be switched off. Two widely deployed green IP routing protocols, comparing their performance will be introduced and analyzed as reported in the literature.

GreenOSPF, presented in [41] and widely referenced as a green routing protocol, extends the existing OSPF protocol slightly to share the shortest path tree (SPT) of a specific node with neighboring nodes. It solves the above problem by switching off network elements that are excluded by shared shortest paths. As a network level strategy, i.e., a solution based on coordination between routers, GreenOSPF is designed to reduce power consumption during low traffic periods. This protocol first designates some nodes with a high nodal degree (the number of edges connected to the node) as the export router (ER) nodes. The ER nodes compute their SPT via the classical Dijkstra algorithm and disseminate that information to their neighboring nodes, designated as import router (IR) nodes. The IR nodes then re-calculate their SPT by sharing the disseminated information. Note that with the OSPF protocol, each node can have full knowledge of the network because of the link state advertisement (LSA) database, such that each node can share network knowledge in a distributed manner. Energy saving can be achieved by switching off the network elements excluded by the SPTs. Figure 2.4 illustrates the GreenOSPF procedure. Only a subset of routers evaluates their SPTs, whereas the others use these SPTs to determine their routing paths. In this manner, it is possible to re-route network traffic and power off some network links. Furthermore, it is fully compliant with the existing OSPF protocol. Results presented in [41] show that more than 50% of links can be switched off in a real IP network scenario. This green routing protocol is used in Chapters 3 and 4 for a comparative analysis of the proposed green IP routing scheme.

Another widely referenced green routing approach [38] for reducing overall ISP power consumption involves turning off network nodes and links while guaranteeing full connectivity and maximum link utilization constraints. This solution first provides an integer linear programming (ILP) formulation to precisely define the network power



(a) Network topology with OSPF weights.

(b) SPT computed by a, $SPT(a)$.

(c) SPT computed by b, $SPT(b)$.

(d) EAR algorithm performed by b.

Figure 2.4: GreenOSPF procedure in [41]

minimization problem. This approach results in an NP-hard problem impractical to solve optimally, even for small networks. To solve this NP-hard problem, the heuristic approaches summarized in Fig. 2.5 must be adopted. The nodes consider several sorting rules (i.e., random, least-link, least-flow, and most-power) to determine which links to turn off. The random heuristic sorts the nodes randomly, whereas the least-link heuristic sorts the nodes according to the number of links that are sourced/sunk at each node. Therefore, nodes with a small number of links are considered first. The least-flow heuristic first accounts for the nodes with the smallest amount of information flowing through them, and the most-power heuristic tries to switch off the nodes with the highest power consumption first. Results from a real-world test case show that significant power savings can be obtained, greater than 35%.

To solve the problem of minimizing network power consumption, known as NP-hard as per the approach proposed in [38], the authors of [105] proposed an interesting framework for energy-saving routing shown in Fig. 2.6, using an ant colony optimization technique [52, 53]. The proposed algorithm also heuristically solves the reformulated problem without any supervised control by allowing the incoming flows to be autonomously aggregated on specific heavily loaded links and switching off lightly loaded links. Furthermore, the routing scheme modifies energy consumption by adjusting the amount of traffic to be aggregated, which can dramatically reduce energy con-

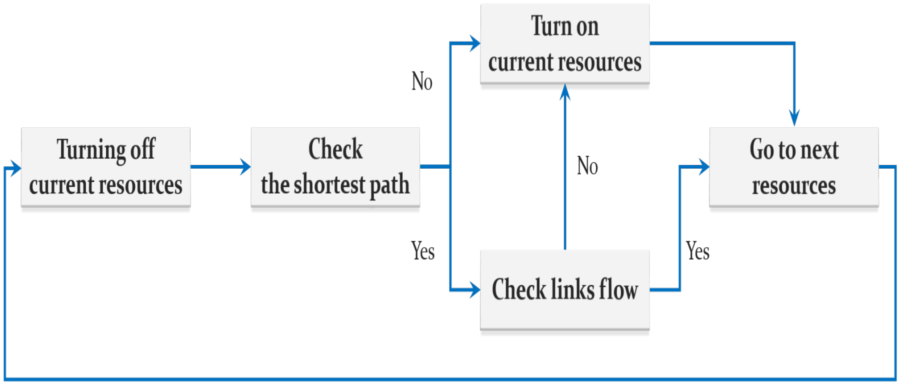


Figure 2.5: A schematic description of the heuristics for the turning off technique (adapted from [38])

sumption during nighttime. This scheme also provides a high degree of self-organization, using the significant advantages of swarm intelligence in artificial ants. Results obtained using this approach achieved 20% higher energy efficiency than other green routing algorithms because it gathers online information about the current network status using several artificial ants in real-time, and all incoming flows are autonomously aggregated to obtain best-fit for the accumulated current networks.

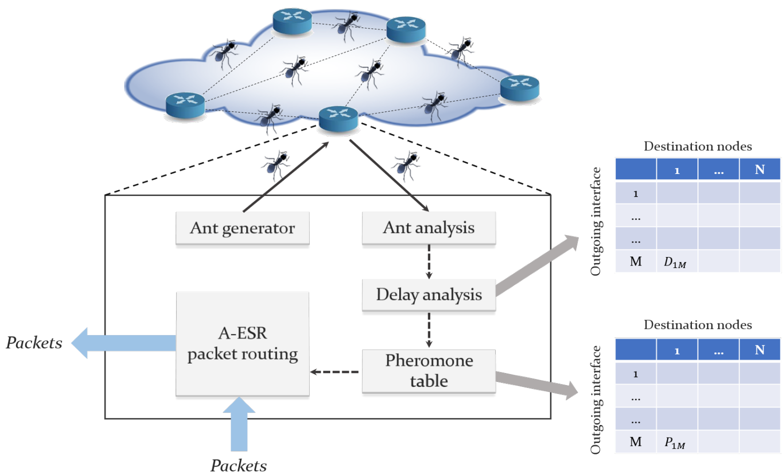


Figure 2.6: The logic for energy-saving framework using ant colony optimization (adapted from [105])

Recently, the authors of [191] targeted the problem of network-wide energy conservation, leveraging speed scaling as an energy-saving strategy. Their work is an extension of [87], which was limited by long convergence times and routing instability. To improve network energy efficiency in a distributed manner (as in [38, 105]) without significantly compromising traffic delay, the authors proposed a hop-by-hop distributed energy-efficient routing (HDEER) scheme. In this scheme, the traffic destined for each node is divided into multiple paths in a directed acyclic graph generated for the node. The traffic injected into each node will be distributed among these loop-free paths, and optimal routing of both energy consumption and traffic delay can be achieved. As a fully distributed green routing scheme, *HDEER* does not need to know the traffic matrix beforehand. Instead, each node only needs periodically updated knowledge of its traffic, easily obtained by monitoring the traffic of adjacent links.

2.1.1.4 *Energy-aware software and applications*

Besides energy-aware networks and system infrastructures, several studies exist on avoiding unnecessary energy waste at the application level. For instance, Green Telnet [27] modified the existing Telnet protocol from a green perspective, allowing the client to enter sleep after a given time and recover later.

Using peer-to-peer (P2P) technologies, such as BitTorrent, to distribute legal content to consumers is actively being explored as a way to reduce both file download times and data center energy consumption. However, the current BitTorrent protocol requires clients to be fully powered to participate in a swarm. Green BitTorrent, presented in [28], verified the possibility of making simple changes to the BitTorrent protocol, including long-lived knowledge of sleeping peers and a new wake-up semantic to enable clients to sleep when not actively downloading or uploading, yet, still be responsive swarm members. According to the results, this approach achieved significant energy savings achievable with only a small performance penalty in increased file download time.

More generally, tools such as those proposed in [12, 85, 102], designed for application energy profiling and energy-aware programming, could aid the development of energy-aware software. The authors of [12] created an energy-aware tool for mobile application development because applications with higher battery power consumption are unpopular with mobile users. Unfortunately, software developers lack the knowledge and tools needed to create energy-efficient applications. To rectify this, the authors introduced *EnSights*, a tool that provides developers with critical energy change information using the structural properties of the software application. The performance of the *EnSights* tool was verified with different versions of three open-source android applications (BeHe ExploreR, PDFCreator, and QKSMS), and the results estimated the change in energy consumption across versions of these applications with F-scores of up to 86%. The authors of [85] presented *PEEK*, a systems approach to proactive energy-aware programming. *PEEK* fully automates energy measurement tasks and suggests program-code improvements at development time by providing automatically generated energy optimization hints.

The authors designed a lightweight yet powerful electronic measuring device capable of taking automated, analog energy measurements. Results show an up to an 8.4-fold increase in energy analysis speed when using *PEEK*, while the energy consumption of the analyzed code improved by 25.3%.

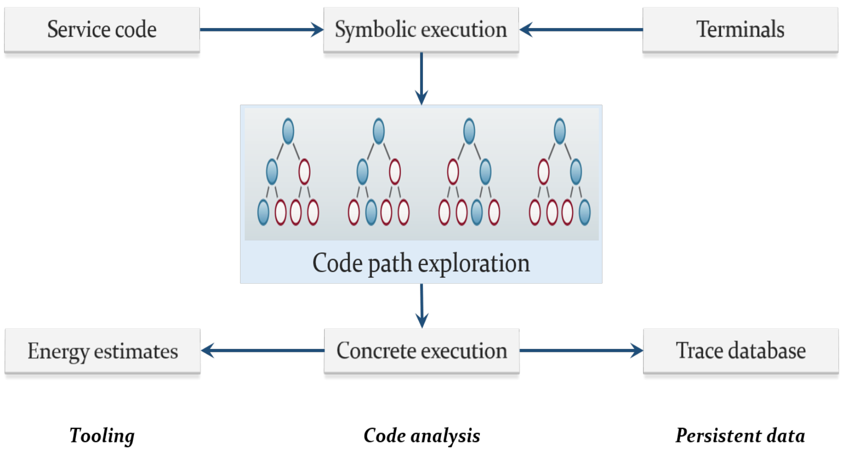


Figure 2.7: Overview of the PEEK architecture (adapted from [85])

The authors of [102] proposed the development of automated tools for guiding design choices by profiling the energy usage of various resource components used by an application. Using an early version of a tool they developed, they could demonstrate how automated energy profiling could help a developer choose between alternative designs in the energy performance trade-off space.

Summary

Green IP networking solutions that can save the power consumption of wired networks are introduced in Section 2.1.1 with several categorizations.

The energy consumption of a network link largely depends on the negotiated link capacity rather than on the actual traffic load. To improve this situation, the first approach, referred to as *ALR* in Section 2.1.1.1 was designed to adapt the link rate by either turning off unnecessary links or reducing the line transmission rate. Energy saving can be achieved by controlling the network link only. However, it requires additional functions (state management and buffering) and power consumption when the link changes its status (either active or idle) according to environments.

As an extension of link adaptation dedicated to putting interfaces in idle or low energy mode, a similar sleep mode could be applied to devices such as PCs. In this approach, when a device goes to sleep, the applications running on the device stop working and lose their network connectivity. Moreover, when the device wakes up, it must reinitialize its applications by sending a non-negligible amount of control traffic. To overcome this problem, an additional functionality called *proxying* was introduced in Section 2.1.1.2. NCP in [29] maintains network connectivity to the Internet and performs application-specific control to the device. Table 2.1 summarizes the comparison between the two approaches.

Table 2.1: Comparison between ALR and proxying approaches

Category	**Adaptive link rate**	**Proxying**
Target component	Links	Nodes
Type of modes	Active, idle (fully or partially)	Active, idle (fully only)
Decision basis	inter-arrival time [79, 80], different power consumption per interface [76], low link rate [77]	PC's low-power mode [76]
Implementation cases	ALR [77], LAN interface [78, 80]	Ethernet adapter [40], NCP [29, 76]
Decisions	Locally (within a single device or limited set of collaborative devices)	Locally (within a single device)
Deficiencies	Need additional power (e.g., wake-up power), limited power saving	Need additional power and proxy components, local solutions

While these approaches alone offer non-negligible energy saving because of their limitations, more energy saving can be obtained by a reasonable amount of collaboration between individual devices. *Energy-aware routing* described in Section 2.1.1.3 provides a network-level approach to save power consumption in the network by considering network nodes and their connectivity. This approach is realized either to modify existing infrastructures or to design a new architecture regarding packet delivery (i.e., routing and switching). Most energy-aware routings in Section 2.1.1.3 adopted a heuristic manner by aggregating traffic to the specific links and achieved more energy saving as much as the number of power-off links. Table 2.2 summarizes the comparison among existing green routing protocols.

Lastly, several energy-aware softwares and applications were introduced in Section 2.1.1.4 and provide special software (e.g., Green

Table 2.2: Comparison of energy-aware routings

Category	**GreenOSPF[38]**	**ILP[41]**	**Ant [105]**
Type	Link state		
Target component	Links and nodes	Links	Links
Metric	Link cost	Link cost, flow, power consumption	Link delay
Algorithm	Heuristic (Dijkstra)	Heuristic	Heuristic (Dijkstra)
Remarks	Enhanced OSPF algorithm for energy saving	Turning off links according to policies (random, least-flow, most-power)	Ant colony optimization for energy saving

Telnet [27], Green BitTorrent [28], InSight [12]) to monitor and analyze the energy consumption of applications.

In a nutshell, Section 2.1.1 provides general insights into existing green IP networking solutions and the key lessons are summarized as follows:

- *ALR* and *proxying* approaches are limited and energy-aware approaches, reducing power consumption within a single device. More collaboration among individual devices must be considered.
- *The energy-aware routing* approach considering network nodes and links together should gain more energy efficiency in networks than other approaches described in Section 2.1.1.
- Existing energy-aware routing protocols focus on how to reduce the power consumption of network links by either putting on the sleep or adjust the transmission rate according to network conditions.
- There has been no approach to consider the selective sleeping of several functions in a router.

With these learnings, this thesis provides a novel energy-aware routing with active collaboration among devices in networks. Furthermore, the energy-aware routing manages functions in the network node independently to sleep them selectively according to network conditions to achieve more energy saving. This energy-aware routing will be described in Section 3.

2.1.2 *Green content networking*

With the explosive increase in global video traffic, the issue of energy efficiency in content networking is an increasingly major concern for ISPs.

Information centric networking (ICN) [8, 183], a paradigm shift from host-centric to information-centric networking, first appeared around 2010, inspired by Van Jacobson's 2006 Google Tech Talk "A New Way to look at Networking" [1]. This talk presented a novel approach aimed at moving the Internet toward a content distribution architecture. ICN represents a broad field of research involving a content/information/data-centric approach to network architecture. Under a common ICN banner, several architectural designs have emerged recently. Content centric networking (CCN) and NDN are specific architectures, existing as different implementations under the broad ICN umbrella. More information on CCN and NDN is provided below:

CCN [143] refers to an architecture project started by Van Jacobson at the Palo Alto Research Center (PARC) [142], where he led the development of the software codebase forming the baseline implementation of this architecture.

NDN [135] refers to the NSF-funded Future Internet Architecture project, a 12-campus collaboration that began in 2010 and included PARC. The NDN project originally used CCN as its codebase, but as of 2013, forked a version to support the specific needs of NSF-funded architecture research and development.

CCN and NDN are two prominent ICN architectures based on similar principles but with some differences in implementation. In a CCN network, two types of packets at the network level exist, namely *interest* and *data*. The consumer requests content by sending an interest packet that carries the name of the data. One difference to note between CCN and NDN is that in later versions of CCN, the interest packet must carry a full name, while in NDN, it could carry a name prefix and receive any data with a name matching this prefix.

In certain instances, a content delivery network (CDN) could refer to content networking. To be exact, however, it is an example of a service implemented as an overlay on today's TCP/IP architecture to meet the demand for scalable content distribution when many users request the same content. CDN operates in the application layer, whereas CCN and NDN work directly in the network layer. In this thesis, NDN, as an enhanced version of the CCN architecture is used to refer to content networking, in line with recent technology trends.

To analyze existing green technologies in content networking, the author of [58, 59] categorized the fundamental approaches as being hardware optimization, shutdown, slowdown, cache, or routing strategies. The following section reorganizes that categorization based on [59] and surveys existing works regarding energy efficiency in content networking.

2.1.2.1 *Shutdown and slowdown*

Applying shutdown or sleep strategies to redundant network elements to optimize energy consumption has been widely studied in the telecommunication industry (Section 2.1.1.1). For example, the authors of [60, 113] suggested that energy saving could be achieved by switching the ICN components (routers and links) on or off according to network traffic requirements. An energy-aware router architecture was introduced in [113], ranging from core routers to home gateways. By comparing different content distribution platforms, the authors demonstrated the validity of incorporating energy-proportional computing and networking features into CCN designs. Furthermore, the power consumption of content router components, such as memory and disks must be considered when configuring energy-efficient content routers.

Shutdown approaches temporarily power-off some links by transferring their traffic to other links. However, this increases using remaining links (except in some special cases), roughly in proportion to the amount of traffic being rerouted.

To investigate this trade-off between the number of sleeping links and link utilization under a caching scheme, the authors of [162] proposed an NDN power-aware solution, able to cache and retrieve contents in routers with infinite storage attached to simplify the network model. This approach facilitates power-aware traffic engineering, reducing network energy consumption in the NDN because some traffic does not need to travel through the core network anymore, only arriving at the edge routers, which have already cached the required content. The results showed that by combining power-aware traffic engineering with an NDN architecture, the link utilization could be reduced while enabling many links to enter sleep and remain asleep for a longer time compared to conventional IP networking.

A novel content-centric node architecture for mesh networks, named COCONET was developed in [15] for improving energy efficiency in multi-hop communications. Leveraging the emerging content-centric paradigm, COCONET represents a new energy-aware routing protocol that could coexist with both the classical power saving model and shutdown approaches, while outperforming the IP-based approach regarding energy efficiency, scalability, latency, and control overheads.

A more elaborate control of network elements than those employed in the shutdown, or rate adaptation approaches, and their implementation issues, were discussed in [31]. Two types of energy consumption were considered in energy analysis, namely, *i*) the energy required to manufacture the network devices and *ii*) the energy required for operation. Simulation results based on a tree topology showed that CCN networks require only slightly more energy for manufacture and operation than IP- based networks without applying any additional rate adaptation techniques. A simple rate adaptation implementation can make CCN an energy-efficient architecture, leading to energy savings of between 10% ans 20% over the network's lifetime.

To reduce power consumption in CDN as a content networking service, the energy management scheme in [66] provisioned the minimum number of active servers needed to serve content requests and puts the rest into the sleep mode to save energy when content demand is low. CDN QoS is assured by honoring constraints on the load capacities of the servers and virtual links in the CDN network, as well as restricting interdomain content traffic to avoid increased end-to-end delays. Meanwhile, the reliability and lifetime of CDN hardware is addressed by avoiding frequent on/off state transitions in servers. In their evaluation, the authors demonstrated that the proposed scheme could achieve an energy reduction of up to 45.9% without compromising CDN performance regarding the end-to-end delay.

2.1.2.2 *Energy-aware cache management*

Where to locate content has been a critical problem facing the CDN community and several researchers have proposed content distribution strategies. The objective of such strategies is to find the number of content copies and their locations within networks to minimize network delay and bandwidth and storage costs under limited cache capacity [17, 30, 49, 122]. However, ICN cache strategies differ from the CDN-based service level approaches because they exclude functionality for in-network caching. In an ICN, content is dynamically created and requested, and can be cached as it travels toward end users, providing per-request granularity, responsiveness, and adaptation [118]. As an in-network cache management strategy, an analytical framework for performance evaluation of content delivery with limited-capacity network and caching resources was proposed in [133]. An analytical tool was proposed in [115] for the approximation of cache content distribution and hit ratio for any multi-cache topology and Least Recently/Frequently Used caching policies.

Although most previous studies have exploited the in-network caching capabilities of CCN, energy issues regarding caching have received less attention. In the following subsection, a review of energy-efficient cache techniques in ICN is presented from the perspectives of content and router placement.

1) Content placement: A content placement strategy minimizes the overall energy consumption by finding the optimal network configuration regarding the content objects being cached and delivered over the network to satisfy the user's requests while accounting for resource capacities [118]. Figure 2.8 shows an example of content replacement in a router with one server and three content routers labeled S, R_1, R_2, and R_3, respectively. The yellow rectangles denote object replicas. Figure 2.8a is the initial network configuration. For some content, when the transport energy that is needed to request it is much higher than its caching energy, each node will cache content (Fig. 2.8b). However, when caching energy is predominant, only remote router R_2 opts to replicate the content (Fig. 2.8c). However, neither case ensures minimal global network energy consumption. Therefore, an efficient content placement policy must to be developed for CCN to make the trade-off between the transport and caching energy.

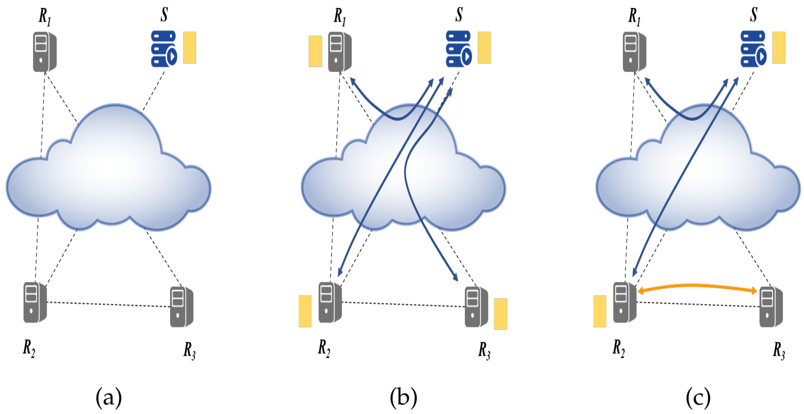


Figure 2.8: An example depicting the self-interested behavior of the content routers (adapted from [118])

Energy-efficient content placement strategies have been widely studied in [39, 57, 75, 90, 114, 119, 147]. In [39], energy saving in CCN was achieved by optimal cache policies that considered different caching hardware technologies, number of downloads per hour, and content popularity. The authors first defined an energy consumption model, including caching and transport energy, and formulated linear and nonlinear programming problems to minimize the total energy consumption of content networks. Furthermore, a genetic algorithm approach to find a near-optimal cache location was proposed and evaluated based on existing energy efficiency reports for computational hardware and network equipment. Numerical results showed that energy-proportional caching with sufficient caching capacity is needed to achieve further energy efficiency in CCN. Furthermore, when distributing caches, trade-off between energy and delay should be carefully revised because transport delay requirements could significantly increase in energy consumption.

The authors of [75] proposed energy models based on the energy consumption of current equipment and devices in CCN networks, and further analyzed the energy trade-off in key networking resources. Content popularity as a key performance index in CCN was chosen to optimize the placement of content objects, and the CCN network achieved good scalability regarding energy consumption, i.e., the per-bit energy decreased with an increase in the content download rate. Given the energy consumption levels of current network equipment and devices, these results demonstrate CCN to be more energy-efficient in delivering popular content, whereas the optical bypass approach, which is a physical layer approach for managing transport energy [18, 19], is more energy-efficient when delivering infrequently accessed content. Besides content popularity, equipment energy efficiency and network topology also affect the relative energy benefits of CCN. The relative energy benefits of CCN versus conventional CDN are more complicated because energy performance also depends on factors such as content popularity and catalog size. The authors of [75] concluded by suggesting a combination of server-based CDN and dynamic optical bypass architectures to maximize energy efficiency.

A comprehensive comparison of caching strategies in CCN was presented in [21, 61]. Although many studies have proposed new caching strategies to improve CCN performance, it remains unclear which one provides the best performance because of lacking a common environment in which to compare different strategies. The authors of [21] compared the performance of five CCN caching strategies (*Leave Copy Everywhere*(LCE) [92], *Leave Copy Down* (LCD) [186], *ProbCache* [144], *Cache "Less For More"* [34], and *MAGIC* [148]) in terms of the cache hit, path stretch, diversity, and complexity. They determined the most appropriate cache strategy for each scenario. These caching strategies are described in detail later in this work and are used to analyze caching performance in Section 5.

The NDN paradigm shift toward name-based forwarding and caching brought improved data delivery performance by introducing an in-network caching scheme. From an energy perspective, however, these characteristics impose new challenges.

To provide higher cache performance and improve the energy efficiency of CCN, an energy efficiency-based in-network caching scheme was proposed in [16]. Based on the energy consumption analysis of content distribution, the authors first designed judging criteria to reduce the total energy consumption associated with content access. Combining this with content popularity and node importance, they proposed a cache placement strategy to select optimal caching nodes. The schema also performs a neighbor cooperation-based cache replacement, which uses the cache resource of neighboring nodes to increase the chances of content being cached, improving resource utilization and caching service quality. The authors of [147] reviewed the main features of NDN and the principal challenges in naming schemes, routing and forwarding, security and privacy, and mobility, focusing on solutions related to caching strategy to improve energy efficiency.

One fundamental challenge in content networking is optimizing the overall energy consumption associated with content transmission and caching. Furthermore, designing an appropriate caching strategy that considers both energy consumption and QoS is a major goal in green content networking. Being aware of QoS regarding an imposed delay, the authors of [50] observed that less popular content is cached near the origin server. In delay-sensitive applications with less popularity, this could lead to dropping delayed chunks, increased energy waste, and QoS degradation. The authors then performed minimization using ILP by considering most of the energy-consuming components. However, since this is known as NP-hard problem, they proposed a quantized Hopfield neural network with an augmented Lagrange multiplier method (MEDCCN-QHN) as a novel approach for deriving the solution. Considering the same energy minimization problem, the authors of [51] used the Markov approximation method in an energy-delay aware caching strategy (MAEDC) using a log-sum-exp function to find a near-optimal solution in a distributed manner. Their results showed that the MAEDC strategy achieves near-optimal energy consumption with a better delay profile than the optimal solution.

2) Cache placement: Although content router placement is less attractive than the content placement approach previously discussed, it can significantly affect reducing the power consumption in CCN. Caching strategies for deciding where to locate content routers from an energy perspective have been studied in the literature [89, 90, 109]. In [109], the impact of content caching on CCN was investigated regarding the energy efficiency of the caching strategy. The authors analyzed the thresholds at which content caching becomes beneficial based on two metrics, namely by considering the energy efficiency of content caching and the storage technologies and the location of the CCN routers.

An energy-efficient cache management scheme was proposed by the authors of [89, 90] to select content caching locations that minimize the power consumption of storage devices used for content caching and network devices used for content delivery. In the proposed scheme, appropriate cache locations are managed to balance traffic volumes for delivering each content and memory used for storing content replicas. Content caching is then controlled by maintaining an autonomous distributed framework in the CCN network.

Recently, work in [190] has focused on cache placement and network performance in ICN, proposing a cache placement strategy with energy consumption optimization. To optimize ICN energy consumption, the best cache placement node is selected from the user's perspective. First, the distance sequence of different nodes arriving at each user is obtained based on detection results from network distribution channels. The corresponding energy consumption of information distribution is obtained from that distance sequence. Second, the reward function of the cache node is derived using two factors, namely, the additional energy consumed by changing the cache node, and the energy consumption of the content distribution. Finally, a problem is constructed using optimal stopping rule to solve the maximum expected energy saving. Table 2.3 shows the corresponding relationship between the elements of the problem and the optimal stopping problem. Results from [190] showed that the proposed strategy offers a higher delivery success rate and lower energy consumption than other strategies.

Table 2.3: Optimal stopping elements in cache node selection

Optimal stopping elements	**ICN**
Decision maker	Network node
Observation	Decision
Random variable	Distance
Income function	Energy saving
Taking action	Caching content

Furthermore, the authors of [116] proposed an effective design for edge content cache and dissemination from the perspective of energy efficiency in mobile environments.

2.1.2.3 *Other approaches*

This subsection describes some other ICN techniques for reducing network energy consumption. In a mobile environment such as a sensor network, battery life is critical for maintaining services. However, more specific methods for reducing the energy of mobile nodes must also be considered regarding routing and forwarding content requests. To reduce energy consumption in ICN with content caching, requests must be forwarded to the nodes that temporarily host (cache) the required content.

In mobile networks, nodes with limited battery power are likely to shut down because of a lack of power if higher popular content is transferred repeatedly using the same routing path [146]. To solve these problems, the authors of [112] used added residual energy and node usage frequency as routing parameters, proposing an energy-efficient routing protocol for CCN-based mobile ad hoc networks (MANETs), prolonging the service life of network nodes. The benefits of extending the CCN to MANETs have been demonstrated in [130, 141, 167]. However, these approaches require modifications to effectively cope with mobile environments such as MANETs. For example, the proactive flooding of content announcements to populate FIBs is unsuitable for MANETs with high mobility because of the large control overhead. Also, the broadcast wireless channel enables packet overhearing; thus, helping to identify neighbor nodes and cache data, but it causes a broadcast storm [165] and scalability problems.

A content-centric MANET architecture called content centric fasHion mANET (CHANET) designed to extend the battery's lifetime was presented in [13, 14] to provide energy-efficient content delivery. CHANET is designed to achieve content discovery, delivery, and caching over IEEE 802.11 MANETs and Fig. 2.9 shows its reference protocol stacks. It relies on identifying the content and uses broadcast for the transmission of both interest packets and data. For content discovery, delivery, and caching over IEEE 802.11 MANETs, CHANET defines four message types, *Interest* used to request the first content chunk, *Int-Ack* used to request subsequent chunks and acknowledge previously received packets, *Data-Object* containing data chunks, and *Content Advertisement* used by fixed providers to advertise the availability of contents. For content caching, CHANET nodes maintain a content store with cached downloaded contents and become providers of that content. It benefits all involved parties, namely users by allowing fast and low power access to the requested content, and content or network providers by reducing operational costs of the provided sources and infrastructure. Other interesting techniques implemented in CHANET to increase the effectiveness in the wireless environment are the overhearing of nearby nodes transmissions and local decision-making processes regarding packet-forwarding. The experimental results show that their approach performs better than traditional TCP/IP-based solutions regarding network overhead and download time.

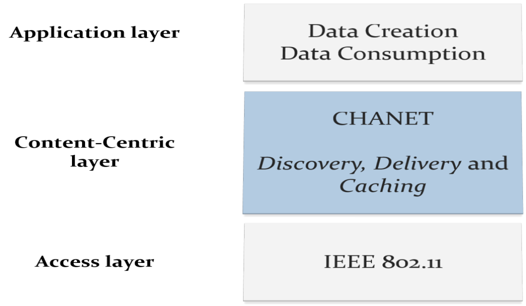


Figure 2.9: CHANET protocol stack (adapted from [13])

The authors of [163] proposed cache-aware routing mechanisms to manage routing processes by influencing the forwarding of interest/-subscription packets and make caching decisions about where and what item to cache. This routing improves the operations and overall utility of the ICN architectures through extensive usage of caching as an inherent architectural function. In [161], an energy-aware routing algorithm was proposed. It formulated a model for energy saving in traffic routing to achieve a link rate adaption and predicted traffic to preserve network stability, in which the contents were placed at the edge routers to decrease traffic going through the backbone.

Recently, an energy-efficient QoS-routing mechanism for ICN, known as EQRI was [178]. First, it evaluates the link state regarding the user's QoS requirements using the Cauchy distribution model, and link energy efficiency is obtained by monitoring the corresponding traffic. Second, it employs a priority determination strategy based on QoS and energy efficiency, a color management strategy to assign a color to the outgoing interface, and a backtracking strategy to cope with the failed interest packet. This strategy is adapted to FIB with red, yellow, or green, and when a FIB entry is unavailable, the corresponding color of the outgoing interface is modified as red, instead of deleting this entry from FIB. Third, it proposes a link selection algorithm based on color management, priority determination, and backtracking strategies. The experimental results showed that EQRI not only retrieves the content effectively but also outperforms existent mechanisms.

Summary

Section 2.1.2 with several categories introduces green content networking solutions that can reduce the power consumption of content networking.

Shutdown and slowdown in Section 2.1.2.1 are basic green approaches for energy-efficient content networking by switching the components on or off and controlling the transmission rates. This approach usually applies to aggregate traffic to specific links according to traffic conditions. However, more aspects regarding the characteristics of content networking must to be considered. Unlike IP networking, content networking is based on in-network caching where all the nodes have storage, and a content request can be served by any node holding a copy of the content in its storage. This difference introduces additional considerations, such as content requests [66], caching policy [162], and caching node architecture [15, 113] to reduce power consumption in content networking.

Where to locate content is a critical concern in content networking for an energy efficiency. The *energy-aware cache management* approach described in Section 2.1.2.2 minimizes the power consumption by controlling caches and contents from the router placement and content placement perspectives. Cache placement [89, 90, 109] finds the cache locations of content that minimizes the sum of the power consumption of storage devices for caching and power consumption of network devices for content delivery. Furthermore, content placement [16, 57, 75, 114, 119, 147] reduces the overall energy consumption by finding the optimal network configuration regarding the content objects being cached. Table 2.4 summarizes and compares several energy-aware management strategies.

The above studies shows that most of the works investigated shutdown, slowdown, and cache management issues while caching contents. Although extensive research has been done on reducing power consumption in content networking, only a few have considered these issues jointly with environmental aspects. This thesis on the green content networking perspective provides a novel cache management strategy with renewable energy concerns. Further discussion will be described in Section 2.2.2 for summative assessment.

2.2 GREEN COMMUNICATIONS USING RENEWABLE ENERGY

energy efficiency and reduction in global warming are becoming critical considerations for all industries involving ICT. Not only is a scope for energy efficiency in ICT itself, but it can also help other sectors to become smart, energy efficient. Smart buildings, smart motors, smart logistics, and smart grids are being realized by incorporating ICT. The ICT industry is equally aware of the potential benefits of renewable energy making future systems greener and more sustainable [9, 83, 110, 140]. According to a recent survey [71], renewable energy should supply two-thirds of the total global energy demand and contribute to the bulk of GHG emission reduction that must be achieved between now and 2050 to limit the increase in the average global surface temperature to below 2 °C. The efficient consumption of renewable

Table 2.4: Comparison of several energy-aware cache management strategies

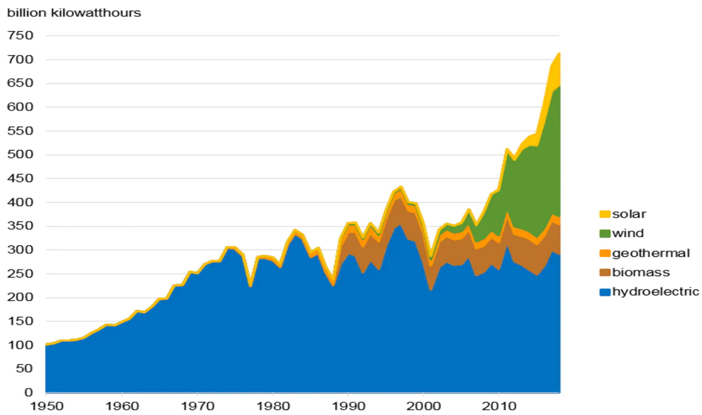
Category	Lafond *et al.* [109]	Guan *et al.* [75]	An *et al.* [16]
Approach	Cache placement	Content placement	Content placement
Caching decision basis	threshold (considering memory technologies and location)	Content popularity	content popularity, node importance
Performance metrics	Minimum access rate	Energy consumption	Cache hit ratio, average response hops, energy saving rate
Remarks	Analyzing the thresholds from which caching content starts to be beneficial by considering storage and location of the CCN router	Optimizing CCN content caching problem according to content popularity	Optimizing the selection of caches according to judging condition to reduce the total energy consumption

energy, therefore, is strongly recommended. Figure 2.10 illustrates the electricity production in the US and Germany.

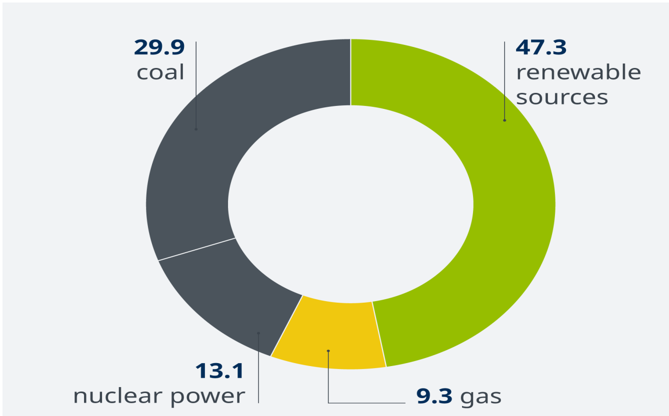
Increased use of renewable energy is necessary to transition toward a more sustainable society. This new landscape has shifted ICT research toward minimizing CO_2 emissions and improving energy consumption in communication networks. The following subsection provides an overview of the existing literature on using renewable energy in communication networks.

2.2.1 *Green routing with renewable energy*

As described in Section 2.1, several researchers have been seeking greener solutions for reducing power consumption in network infrastructures. Despite recent achievements in reducing energy consumption in networks, solutions leveraging available sources of renewable energy remain limited. For example, wind power was used in [20] to



(a) U.S. electricity generation from renewable energy sources, 1950-2018 [6]



(b) Net electricity production in Germany (January-July 2019) [160]

Figure 2.10: Renewable energy production in the US and Germany

improve the energy efficiency of a data center where energy is crucial for operation and maintenance.

In the first study to combine renewable energy concerns with routing protocols, the authors of [132] introduced a novel gradient-based routing protocol using hybrid renewable energy for application in large ISP networks. The routing protocol is aware of the distributed and hybrid renewable energy (the combination of wind and solar power) infrastructure in a realistic ISP network and can self-adapt to dynamic network loads and weather pattern changes. Additionally, the routing protocol allows unused routers to be placed in sleep mode minimizing fossil-fuel use. The results demonstrated this energy-aware routing protocol to be effective in decreasing the amount of brown energy consumed by the intra-domain network (by up to 72%) without generating topological instability.

Similarly, the authors of [184] proposed green internet routing using renewable energy sources by clarifying the model of how routers can distinguish renewable from nonrenewable energies. They then reformulated an energy consumption problem, constructed unusual cases based on the clarification, and proposed optimal and sub-optimal algorithms while guaranteeing QoS requirements. Compared to algorithms for minimizing total energy, the results show that this approach could reduce the consumption of nonrenewable energy by more than 20%.

To investigate network management costs regarding renewable energy, the authors of [22] considered temporal variations in traffic demands and energy prices, as well as constraints between different periods, to determine where to install a renewable energy plant.

The supply of renewable energy is inherently random and intermittent, which could lead to problems, such as energy outage, energy overflow, and QoS degradation. Accordingly, the enhancement of renewable energy stability is a critical issue in green networking. The authors of [189] proposed an energy-sustainable traffic-steering framework for 5G, in which the traffic load is dynamically adjusted to match energy distributions in both the spatial and temporal domains by inter- and intra-tier steering, caching, and pushing. Case studies show that the proposed framework could reduce on-grid energy demand while satisfying QoS requirements.

Data centers are another promising target for reducing the carbon footprint and energy costs using renewable energy. The authors of [175] proposed an energy efficiency model for data center networks by scheduling and routing deadline-constrained flows where the transmission of every flow must be completed before a rigorous deadline. In [174], the authors proposed a combination of virtual machine assignment and traffic engineering to reduce power consumption in data center networks, providing a general framework for achieving network energy efficiency in data centers based on this combined approach in [173]. However, none of these studies consider using renewable energy. The authors of [72] focused on a hardware framework using solar energy. They proposed a scheduler named *GreenSlot* for parallel batch jobs in a data center powered by a photovoltaic solar array with backup from the electric grid. GreenSlot predicts the amount of solar energy that will be available in the future and schedules the workload to maximize the consumption of green energy while meeting job deadlines. Based on real-world power trace experiments, the authors of [65] presented the case of an internet data center system exploiting the geographical and temporal diversity of wind power to implement a green cloud service. The idea was to leverage the front-end load dispatching server to send work to a location with available wind power. The authors then proposed a wind-power-aware (WPA) algorithm to route jobs based on both the current states of workloads and wind power availability in data centers.

Summary

Despite recent progress in green IP routing, several green solutions trying to use eco-friendly energy sources are limited. Table 2.5 summarizes the comparisons of the existing green routing using renewable energy described in Section 2.2.1. The key lessons from this chapter are as follows:

Table 2.5: Comparison of existing green routing using renewable energy

Category	**Hybrid green routing[132]**	**Green internet [184]**	***GreenSlot*[72]**	**WPA routing [65]**
Target	Network node and link		Data center	
Renewable energy type	Wind, solar	Wind, solar	Solar	Wind
Renewable energy consideration	Amount of renewable energy available			
Goal	Routing to reduce the usage of fossil-fuel energy	Routing to reduce the usage of fossil-fuel energy	Job scheduling to maximize the usage of solar power	Job load balancing according to wind power
Algorithm	Gradient-based next hop selection	minimum non-renewable energy routing	Solar energy first job allocation	Wind power aware job mapping policy
Evaluation metrics	Brown energy saving ratio	Brown energy saving ratio	Green energy increase, cost saving	Brown energy utilization, brownout probability

- Like initial approaches, which consider routing protocols jointly with renewable energy, most existing solutions intend to replace existing fossil-fuel power with renewable energy as much as possible because the generation of electricity from renewable energy strongly depends on both geographical location and the time of the day.

- Many types of renewable energy exist, each having advantages and disadvantages regarding generation cost, environmental impact, and other factors. However, existing works hardly consider any other dependency on renewable energy sources.
- The metric that can measure the amount of renewable energy replaced with existing fossil-fuel power is used to estimate the effect of existing green routing. To address the impact of power consumption from multiple energy sources, a new metric is necessary.

With these learnings and implications discussed in Section 2.1.1.4, this thesis provides a novel green routing by considering the characteristics of different energy sources. More specifically, the impact of renewable energy, such as generation cost and environmental cost per energy source, is used to manages functions in the network node independently to sleep them selectively. This energy-aware routing will be described in Section 4.

2.2.2 *Green content routing with renewable energy*

Although Section 2.1.2 includes some proposals for reducing energy consumption in NDN, few studies have considered renewable energy for caching and forwarding. The authors of [103] envisioned future internet devices equipped with renewable energy sources, and proposed heuristic green solutions employing efficient cache and route selection to exploit the readily available solar and wind power.

The concept of powering data storage units with renewable energy aligns with the overall goal of energy reduction. The authors in [185] introduced a proactive caching strategy that caches content in helper nodes cooperatively, accounting for intermittent renewable energy supply and variable content load for various hours of the day. Assuming the amount of renewable energy available to the various helper nodes varies depending on the node location and time of day. The content load across helper nodes will also vary with time. As such, if the helper nodes work cooperatively by considering the available renewable energy and content load at each helper node, the aggregate nonrenewable energy consumption for content caching can be further reduced. The results show that the proposed scheme achieves a significant 23% reduction in nonrenewable energy consumption compared to the existing green solution.

Motivated by the emergence of energy harvesting in mobile communications, the authors of [192] proposed a caching framework at the access edge called *GreenDelivery*, using solar-powered small cells. In [73], the authors designed a joint caching and push mechanism

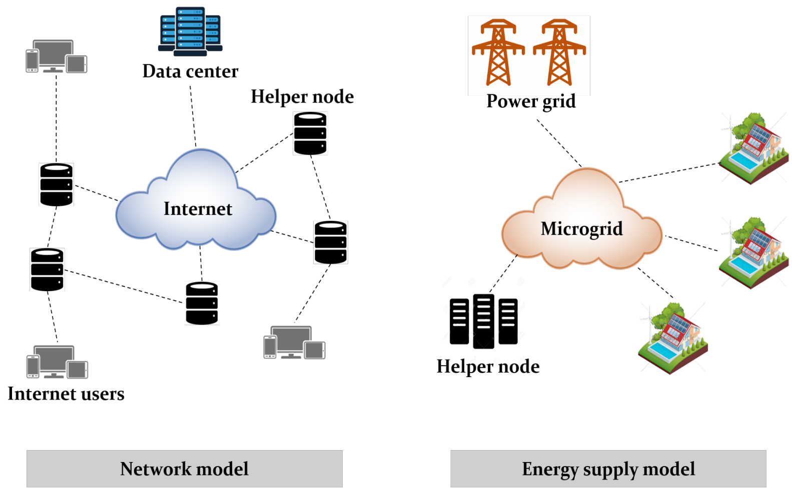


Figure 2.11: The system architecture for cooperative green content caching (adapted from [185])

for small-cell base stations (SBSs) powered by renewable energy. The minimization problem is formulated as a Markov decision process by exploring the features of content popularity and renewal and considering the energy consumption of fetching content from the core network and pushing it to users. The objective is to minimize the number of requests that the SBSs cannot meet. The results show that performance gain with large SBS cache sizes is marginal because of the limited energy. Furthermore, simulations showed a trade-off between the number of cached content in the SBS and the energy available for content push.

Similarly, the authors of [74] designed a framework for optimizing energy costs and user's perceived quality of experience (QoE) within a CDN. Their proposed algorithm was developed to minimize the total operational cost using real-time electricity pricing and the integration of available green energy resources from the smart grid. To define the joint optimization problem, the authors used an ILP and a differential evolution algorithm to provide a trade-off between operational cost saving and computational complexity. The joint problem is formulated as a noncooperative game in which the CDN providers function as players. They defined a group utility function for the players and demonstrated the existence of a Nash equilibrium for the joint quality and energy cost-saving when each CDN provider has a single cluster or multiple clusters. The results showed significant operational and energy cost reductions while optimizing the user's perceived QoE for a CDN or multiple CDN providers.

The authors in [176] investigated a cooperative transmission and power management problem for a set of off-grid BSs in a cellular network hierarchy, powered solely by on-site renewable energy sources. They formulated the network throughput maximization problem as a mixed-integer nonlinear programming problem. In the proposed formulation, a base station can adjust its transmission power in a coordinated multipoint communication scheme and switch to sleep mode for energy saving. Based on the Lyapunov optimization theory, an efficient near-optimal solution method was proposed with a provable bound for the optimality gap. Experimental results obtained from a realistic setup showed that the proposed algorithm could achieve up to 2.96 times download throughput per user compared to some existing algorithms.

As in the most recent work, the authors in [81] have formulated a mixed ILP (MILP) model to optimize delivery from cloud or fog data centers. Their focus was on reducing of brown power consumption in network and data centers by caching video contents in intermediate fog data centers with energy storage devices. The results revealed that brown-powered cloud and fog data centers could achieve an energy-saving rate of up to 77% regarding network power consumption.

Summary

As an extension of green communications, several energy-aware approaches aiming to reduce power consumption for in content networking were discussed in Section 2.2.2. Although excellent works exploit an energy efficiency in content networking, a green approach considering in-network caching capabilities jointly with environmental aspects is hardly introduced.

Table 2.6 summarizes the comparison of the discussed green caching strategies using renewable energy. The key lessons from this chapter are as follows:

- Few approaches considering caching schemes jointly with renewable energy intended to replace existing fossil-fuel power with renewable energy as much as possible without significant service degradation.
- No existing work considers an environmental impact (e.g., CO_2 emission per energy source) from renewable energy for content caching and forwarding.
- The metric to measure how much fossil-fuel power is reduced is used to estimate the effect of existing green caching strategies. More elaborate metrics to illustrate caching performance along with the environmental aspect from multiple energy sources are necessary.

With these learnings and implication discussed in Section 2.1.2, Section 5 of this thesis provides a novel content routing strategy,

Table 2.6: Comparison of existing green caching using renewable energy

Category	Zahed *et al.*[185]	Goudarzi *et al.*[74]	Halim *et al.*[81]
Target	CCN	CDN	Data center
Renewable energy type	All possible renewable energy	Solar	Solar
Energy consideration	Amount of renewable energy available	Amount of renewable energy available, energy billing cost	Amount of renewable energy available
Goal	Caching to minimize using fossil-fuel energy while maintaining a minimum E2E delay	Caching to minimize the total operational energy cost and consider QoE	Caching to minimize using fossil-fuel energy in data center
Algorithm	Proactive caching that caches content in helper nodes in cooperative way considering renewable energy and content load	Linear programming & differential evolution algorithms to analyze trade-off between operational cost and computational complexity	MILP algorithm to reduce the brown energy of transport networks when delivering VoD by maximizing solar energy
Evaluation metrics	Brown energy saving ratio, E2E delay, cache hit ratio	Brown energy saving ratio, payoff (QoE loss)	Brown energy saving

maximizing the impact of renewable energy from an eco-friendly perspective. Furthermore, a new metric to evaluate the performance of environmental aspects is defined and discussed.

3 GREEN ROUTING FOR IP NETWORKS

We simply must balance our demand for energy
with our rapidly shrinking resources.
By acting now we can control our future
instead of letting the future control us.

— Jimmy Carter (Former U.S. President)

As a first step toward green networking, this chapter introduces a novel energy-efficient packet switching in IP networks. Specifically, assuming that the functions of each layer in a network node can be independently controlled, a routing algorithm tries sleeping the routing-related functions selectively within a single network node rather than completely sleep the network nodes themselves.

This chapter is structured as follows: Section 3.1 motivates this chapter and Section 3.2 establishes the relevant terminology and general technical preliminaries before the details of packet switching. Section 3.3 presents the problem formulation and Section 3.4 describes an energy-efficient packet switching algorithm. A performance analysis using simulation is developed, and Section 3.5 presents the results and conclusion.

3.1 MOTIVATION

According to the forecast from the Cisco Visual Networking Index 2019 [43], global IP traffic in 2017 stood at 122 EB per month and will triple by 2022 to reach 366 EB per month. Consumer IP traffic will reach 333 EB per month and business IP traffic will be 63 EB per month by 2022. Accordingly, efficient networking strategies to cope with this traffic explosion are required. Energy concerns to reduce power consumption in the elements of networking infrastructure have a higher priority in the list for future networks. However, most network elements should always be powered for connectivity, regardless of the network volume, status, or other factors and are not usually optimized for power efficiency, as described in [36].

According to [106], the network load is proportional to the traffic volume and varies significantly between peak and off-peak periods as shown in Fig. 3.1. To minimize energy waste across different periods,

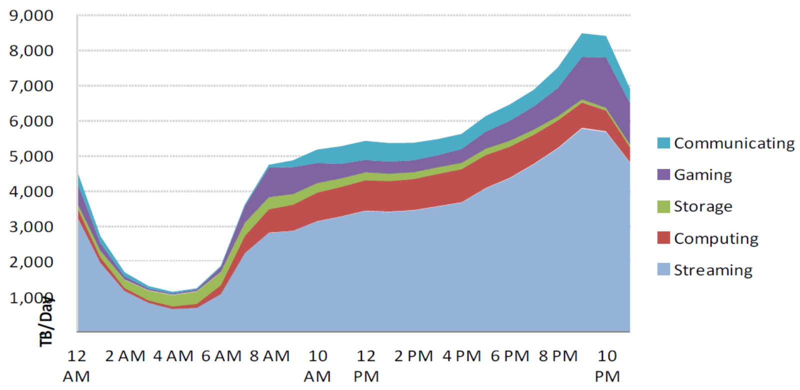


Figure 3.1: Daily traffic in Western Europe [121]

differentiated network operation strategies are strongly encouraged to maximize energy efficiency, and several strategies are summarized and discussed in Section 2.1.1. However, these approaches occasionally require additional components such as a proxy and can consume more power when the nodes toggle from power-on to power-off and back.

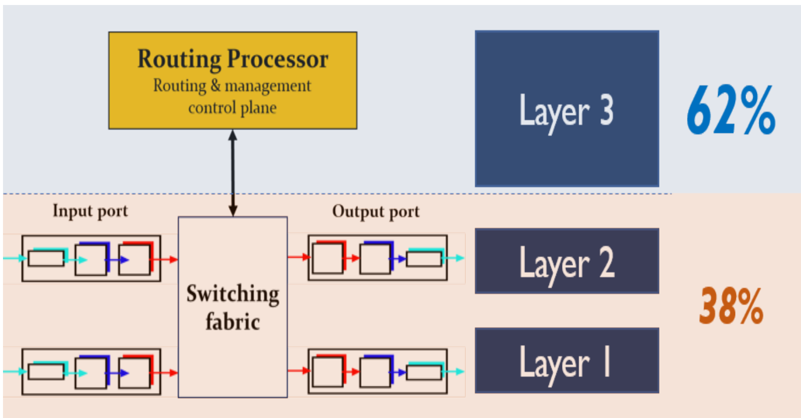


Figure 3.2: Core router power consumption by layer [120]

It is challenging to measure exactly how much power will be consumed by each component of the router architecture because any estimate depends on the vendor and manufacturer. However, according to measurement studies in [4, 54, 111, 120, 182], the power consumption at layer 3, which is used in a routing engine, and packet-forwarding engine can be estimated to occupy 32% - 62% of the total power consumption in the current IP router architecture shown in Fig. 3.2.

From this estimation, a reasonable question, "what if only routing-related functions in a router can be powered off?" is asked to reduce the power consumption of the router. Since most green routing solutions in IP networks described in Section 2.1.1 focused on how to sleep or awake the entire network entity, no green strategy discussed the way to sleep a specific target within a network entity. Accordingly, more elaborated energy-saving than existing solutions cab be achieved if this question is answered. To answer this question, each layer in the OSI model must be operated independently (i.e., sleep or awake layer 3 selectively and independently of operation in other layer) according to the network conditions during peak and off-peak periods. Now, this question has become valid through the development of cloud (or virtualization) related technologies such as Network Function Virtualization (NFV) [129]. NSF uses IT virtualization-related technologies to virtualize entire classes of network node functions into building blocks that might be connected to create a communication service.

Motivated by *i*) traffic volume variation between peak and off-peak time and *ii*) the feasibility of control routing-related function independently, this chapter provides a novel energy-efficient packet switching in IP networks.

3.2 preliminaries

This section provides a brief overview of the general idea for a green packet switching algorithm and corresponding terminologies to describe a green packet switching, referred to as GreenPS, in this chapter.

3.2.1 *Terminology*

Several terminologies necessary to describe a GreenPS are defined as follows.

Header Node (HN)
: An HN is a network node (or IP router) for IP packet processing.

Member Node (MN)
: An MN is a network node (or IP router) that can perform IP packet switching using a tag when its function at layer 3 is in sleep mode. A network node can be either HN or MN according to the HN selection algorithm.

Cluster
: A cluster is a set of one HN and more than zero MNs. In a special case, a cluster can comprise one HN without an MN.

Tag
: A tag is a specially designed identifier within a cluster for packet switching instead of IP routing, and includes the outgoing network node interface.

Packet switching

A packet switching is a special procedure for forwarding IP packets in MNs by determining the outgoing interface using tags instead of general IP lookups.

3.2.2 *General idea*

Motivated to achieve more energy saving in network nodes by putting only routing-related functions on sleep, an idea starts for HNs to manage general IP packet processing and subordinate MNs. According to the HN selection procedure (Section 3.4.1), the network nodes are classified into either HNs or MNs. The entire set of network nodes is then partitioned into clusters consisting of one HN and more than zero MNs according to the clustering algorithm (Section 3.4.2). When clusters are configured, MNs send its routing information to their HNs and HNs update the routing table. Later this routing information of MNs is used to define a tag. After network node clustering, only the HN in a cluster conducts IP routing and their MNs put the routing-related module at layer 3 to sleep and conduct packet switching using a tag. The links between MNs are on sleep. Accordingly, energy-saving in MNs and some link switched off is achieved.

Figure 3.3 illustrates the logic for energy-efficient packet switching, including the node architecture of the HNs and MNs.

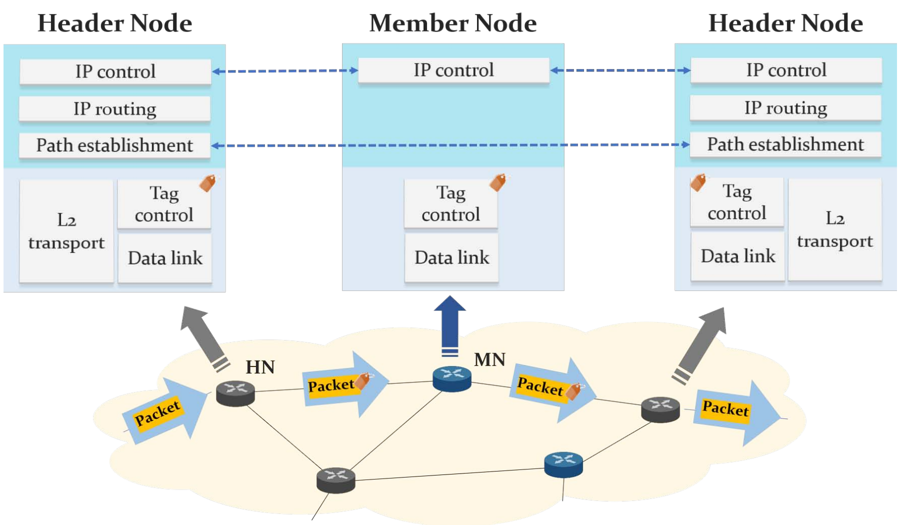
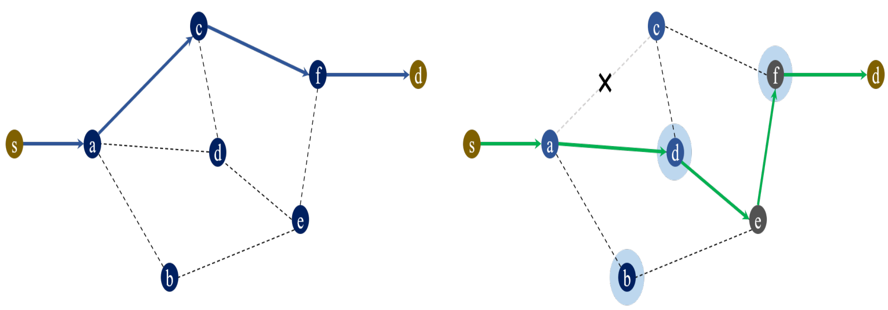


Figure 3.3: Logic for green IP packet switching

3.2.3 *Initial discussions*

GreenPS must reduce more power consumption in the network. Compared to other existing green solutions in Section 2.1, a GreenPS should have more energy savings by letting MNs put routing-related functions occupying major power consumption of network nodes on sleep. Even though this GreenPS seems to have much gain in energy saving, it is critical to investigate whether this green routing could affect any service degradation in network performance.

This section discusses an expected service degradation of the GreenPS by applying it to a simple network topology shown in Fig. 3.4. The conventional shortest path is configured toward a minimum link cost between source and destination as shown in Fig. 3.4a. However, a path of GreenPS is established according to HN selection and clustering procedure as shown in Fig. 3.4b with three clusters: $\{a, c, \boldsymbol{d}\}$, $\{\boldsymbol{b}\}$, and $\{e, \boldsymbol{f}\}$, where each HN of a cluster is expressed in bold.



(a) Shortest path. (b) GreenPS path.

Figure 3.4: Path comparison.

Table 3.1: Comparison between shortest path vs packet switching path

Type	Path	# of hops
Shortest path	(a) → (c) → (d)	2
Packet switching path	(a) → (d) → (e) → (d)	3

Energy-saving GreenPS is a major concern and should reduce power consumption in MNs (node a, c, e) and some switched off links between nodes a and c. Even though more energy in networks can be achieved according to the increase in the number of MNs, some degradation of network performance can also be expected. Table 3.1 shows the path and the corresponding number of hops between two paths. The packet switching path has more than one hop because of GreenPS procedures. Furthermore, if the source sends packets to node c, the shortest path is established as (s) → (a) → (b). However, GreenPS establishes the path as (s) $\rightarrow$ (a) $\rightarrow$ (d) $\rightarrow$ (c) with one more hop than the shortest path.

Compared to a conventional shortest path, GreenPS seems to cause a re-routing problem, resulting in a longer network delay and traffic load increment. It is challenging to evaluate the network performance caused by topological reasons and network conditions and more analysis will be discussed in Section 3.5.3.

3.3 PROBLEM DEFINITION AND FORMULATION

The problem of minimizing power consumption in a network while satisfying a given traffic matrix can be usually formulated with ILP. As briefly explained in Section 3.1, however, the guiding idea of this chapter is different from other energy-saving approaches because we must decide what nodes must be selected as HN and what links must be switched off accordingly. Given this, this section defines and formulates the problem of this chapter.

3.3.1 *Network energy consumption problem*

An energy consumption minimization network problem can be formulated using ILP [38], a commonly used technique to analyze network. Let us consider a communication network that is modeled as a directed graph $G(V, L)$, where V is the set of network nodes and L is the set of directed network links. A link that connects node $i \in V$ to another node $j \in V$ is denoted by l_{ij}. The set of neighbors of node i is denoted by $\{N_i \in V, l_{ij} \in L\}$. Each node $i \in V$ and link $l \in L$ are characterized by the energy consumption $e^v : V \rightarrow \mathbb{R}^+$ and $e^l : L \rightarrow \mathbb{R}^+$, respectively. Furthermore, all nodes and links in the network are assumed to have the same capacity and energy consumption, respectively. The power consumption of network, P_N can be represented by

$$P_N = \sum_{i \in V} e^v + \frac{1}{2} \sum_{i \in V} \sum_{j \in N_i} e^l \tag{3.1}$$

Given the traffic matrix $\mathbf{TM} = [f^{sd}]_{N*N}$, such that f^{sd} is the amount of traffic from source s to destination d, the problem can be solved as follows.

$$\begin{aligned}
&\textit{Minimize} \quad P_N \\
&\textit{subject to}
\end{aligned}$$

$$\sum_{j \in N_i} f_{ij}^{sd} - \sum_{\{j \in V | i \in N_j\}} f_{ji}^{sd} = \begin{cases} f^{sd}, & \forall s, d, i = s \\ -f^{sd}, & \forall s, d, i = d \\ 0, & \forall s, d, i \neq s, d \end{cases} \tag{3.2}$$

$$\sum_{s \in V} \sum_{d \in V} f_{ij}^{sd} \leq C_{ij} \qquad \forall i, j, l_{ij} \in L \tag{3.3}$$

where f_{ij}^{sd} is the amount of traffic from s to d that is routed through link l_{ij}. Constraint 3.2 refers to the classical flow conservation constraints, whereas constraint 3.3 requires the total offered load transmitted on link l_{ij} to be less than the link capacity C_{ij}. The above network energy consumption is a capacitated multicommodity network design (CMND) problem [48, 168], i.e., the network problem when multiple commodities must be routed over a graph with capacity constraints. CMND problem is a well-known to be NP-hard problem [168], and accordingly, solving this is impractical even for small networks. Thus, it is only possible to solve this problem for trivial cases and finding optimal solutions is unfeasible.

To solve this problem, the authors in [36, 37] proposed heuristic approaches. Initially, all network elements start in the on-state. Then, they try temporarily switching off either a node or a link, and evaluate the network connectivity constraint 3.2 and maximum using constraint 3.3. If no violation occurs, the network element can be switched off. In this manner, the authors iteratively try switching off all other network elements. Although the authors contributed significantly to reducing the computational complexity of the original ILP problem, it takes much time to decide and calculate solutions as described in Table 3.2, which makes this method intractable for large scale networks. This intractability is caused by the computational complexity of the problem, which the number of considered internet nodes. As another approach, the authors of [38] provided several cases, such as flow aggregation and additional constraints for solving CMND by reducing the problem size.

Thus, it is challenging to find the optimal and actual solution to the original problem without any additional effort. Figure 3.4 shows

Table 3.2: Comparison of calculation time under various topologies.

Network topology			Calculation time [36, 37]
Name	# of nodes	# of links	
NSFNET	14	42	1.44(s)
Exodus	79	294	2,395.69 (s)
Ebone	87	322	3,339.03 (s)

the difference between network graphs before and after GreenPS. We now introduce several primitives regarding the proposed algorithm to reformulate the original problem using Fig. 3.4. However, the solution process was not enough to explain how to simply reformulate the original problem. Therefore, we additionally present several primitives regarding the GreenPS algorithm to explain the reformulation in the following section.

3.3.2 *Reformulation of network energy consumption problem*

We reformulate the original network energy consumption minimization problem to be feasible by introducing several primitives related to network clustering and a definition. We minimize the total power consumption of a network. We start by comparing the power consumption computed without and with packet switching. All nodes and links as shown in Fig. 3.4a should be turned on, and in this case, the power consumption of network denoted as P_N is represented in Eq. 3.1.

However, several nodes and links can be switched off after clustering, as shown in Fig. 3.4b and the power consumption denoted as $P_N^\diamond$ can be less than P_N. Consequently, we can reduce power consumption by increasing the amount of difference between the power consumption before and after clustering. Therefore, our goal can be referred to as maximize the power consumption reduced by clustering, which is defined as,

$$\mathit{Maximize} \quad \left(P_N - P_N^\diamond\right) \tag{3.4}$$

Let us now assume that the network consists of K clusters and V^k is a set consisting of one HN and more than zero MNs. The number HNs in the network is denoted as n^{HN}, and the number of MNs in cluster V^k is given as n_k^{MN}.

$$V^1 \cup V^2 \cup \cdots \cup V^K = V$$

Then, the number of HNs and the total power consumption of cluster k (denoted as P_N^k) is

$$n^{HN} = N - \sum n_k^{MN} \tag{3.5}$$

$$P_N^k = e^{HN} + n_k^{MN} e^{MN} + \frac{1}{2} \sum_{i \in V^k} \sum_{j \in N_i} \gamma(l_{ij}) e^l \tag{3.6}$$

where N is the number of nodes in the network and equal to $n^{HN} + n^{MN}$; $e^{MN} : V \to \mathbb{R}^+$ is the power consumption of an MN as a constant where the IP routing-related operation at layer 3 is temporarily put to sleep; n^{HN}, n_k^{MN} is the sum of the number of HNs in the network and MNs in cluster k, respectively; and, $\gamma(l_{ij})$ is a function with a binary value {0, 1} if the link from node i to node j is connected, which is set to 1, is powered on.

To calculate the effect of clustering, we divide the power consumption of the network into the power consumption of the nodes and links. First, from the node energy perspective, the power consumption of nodes (denoted as P_N^n) before clustering is

$$P_N^n = \sum_{i \in V} e^{HN} = N e^{HN} \tag{3.7}$$

The power consumption of the nodes after clustering (denoted as $P_N^{\diamond n}$) is

$$\begin{aligned} P_N^{\diamond n} &= \sum_{k \in K} \left(e^{HN} + n_k^{MN} e^{MN} \right) \\ &= n^{HN} e^{HN} + n^{MN} e^{MN} \end{aligned} \tag{3.8}$$

Accordingly, the amount of power consumption of the nodes reduced by clustering can be obtained using Eqs 3.5, 3.7 and 3.8.

$$
\begin{aligned}
&Ne^{HN} - \left(n^{HN}e^{v} + n^{MN}e^{MN}\right) \\
&= n^{MN}\left(e^{HN} - e^{MN}\right)
\end{aligned}
\tag{3.9}
$$

Now, from the link energy perspective, we investigate the difference between the power consumption before and after clustering. The total power consumption of the links before clustering is

$$
P_N^l = \frac{1}{2}\sum_{i\in V}\sum_{j\in N_i} e^l \tag{3.10}
$$

Using Eq.3.6, the total power consumption of links within cluster k after clustering is

$$
P_N^{lk} = \frac{1}{2}\sum_{i\in V^K}\sum_{j\in N_i} \gamma\left(l_{ij}\right)e^l \tag{3.11}
$$

where $\gamma(l_{ij})$ is a function specifying whether the link between node i and node j is powered on or off and has binary value {0, 1}. Note that Eq.3.11 includes only links within the cluster. To consider the power consumption of links after clustering, we must consider the links that connect the clusters, expressed as

$$
P_N^{l\diamond} = \sum_{k\in K}\left(P_N^{lk} + \frac{1}{2}\sum_{i\in V^k}\sum_{j\in N_i}\delta(l_{ij})e^l\right) \tag{3.12}
$$

where $\delta(l_{ij})$ is a function of l_{ij} having binary value {0, 1}, and sets to 1 if nodes i and j belong to different clusters and l_{ij} is powered on. The amount of power consumption of the links reduced by clustering can be defined using Eq.3.10 through 3.12.

$$
\sum_{i\in V}\sum_{j\in N_i} e^l(l_{ij}) - \sum_{k\in K}\left(P_N^{lk} + \sum_{i\in V^k}\sum_{j\in N_i}\delta(l_{ij})e^l\right) \tag{3.13}
$$

Note that all links between the MNs within the cluster are switched off except the link connected to each HN after clustering. Thus, the number of links can be obtained as

$$\sum_{i \in V^K} \sum_{j \in N_i} \gamma(l_{ij}) = n_k^{MN}, \qquad \sum_{k \in K} \left(\sum_{i \in V^k} \sum_{j \in N_i} \gamma(l_{ij}) \right) = n^{MN} \tag{3.14}$$

Then, Eq. 3.13 can be rewritten using Eq.3.14 as

$$\sum_{i \in V} \sum_{j \in N_i} e^l - \left(n^{MN} e^l + \sum_{k \in K} \left(\sum_{i \in V^k} \sum_{j \in N_i} \delta(l_{ij}) e^l \right) \right) \tag{3.15}$$

In conclusion, our goal is to maximize Eq. 3.9 and Eq. 3.15 from the viewpoint of the total power consumption of nodes and links, respectively. According to the measurement study in [120],

$$e^{HN} - e^{MN} \geq 0$$

Thus, maximizing Eq. 3.9 is the same as maximizing the number of MNs (that is, minimizing the number of HNs) in the network, which is the purpose of our proposed algorithm. Accordingly, we focus on maximizing Eq. 3.15 (that is, minimizing the links among clusters). To solve Eq. 3.15, we introduce a new concept referred to as *link centrality among clusters*.

Definition 1 *(**link centrality among clusters**). If φ_{ij} is a measured traffic volume in bytes on link l_{ij} connecting node i in cluster k to its neighbor node j within another cluster, then the link centrality among the cluster of node i is defined as*

$$C^k(i) = \frac{\varphi_{it}}{\sum_{i \in V^K} \sum_{j \in N_i} \varphi_{ij}}$$

where $\varphi_{it} = \max_{i \in v^K} \varphi_{ij}$ and $C^k(i) (\leq 1)$ defines how densely the traffic of node i centralizes on a specific link l_{ij} to other clusters.

As $C^k(i) \to 1$ (maximized), the energy consumption of links among clusters is minimized and the number of active links among clusters (that is, the number of active links among clusters, $\sum_{i \in V^K} \sum_{j \in N_i} \delta$ in Eq. 3.15 can also be minimized.

For $C^k(i) \to 1$, $\varphi_{it} \approx \sum_{i \in V^K} \sum_{j \in N_i} \varphi_{ij}$ must be satisfied. This implies l_{ij} $(j \in N_i,\ j \notin V^K) \to 0$ holds except for the link with the highest traffic volume; that is, there exists little traffic on the links $l_{ij}(\neq l_(it))$. Accordingly, node i in cluster k can minimize the energy consumption by allowing the traffic carried on $l_{ij}(\neq l_{it})$ to be aggregated on the link l_{it} $(t \in V^t)$ first, and then switching off the other links, $l_{ij}(\neq l_{it})$. The number of links among the clusters can then be reduced by switching off $l_{ij}(\neq l_{it})$.

Accordingly, our goal to minimize the original problem in Eq. 3.1 is to reduce the number of active links among clusters that maximizes Eq. 3.15, while satisfying the flow conservation described in constraints Eq. 3.2 and Eq. 3.3.

3.4 DESIGN OF GREEN PACKET SWITCHING

As an objective of green routing for IP networks, this section presents a GreenPS algorithm along with several detailed procedures.

3.4.1 *HN selections*

We start with a simple method for selecting HNs and configure clusters using the selected HNs and MNs. For selecting HNs, various criteria can be considered for the selection policies, such as the power consumption of the network node, the network nodality, and end-to-end delay. In this chapter, we assume that the utilization of network nodes is applied to the HN selection and node clustering, as shown in Fig. 3.5 and described in Algorithm 1.

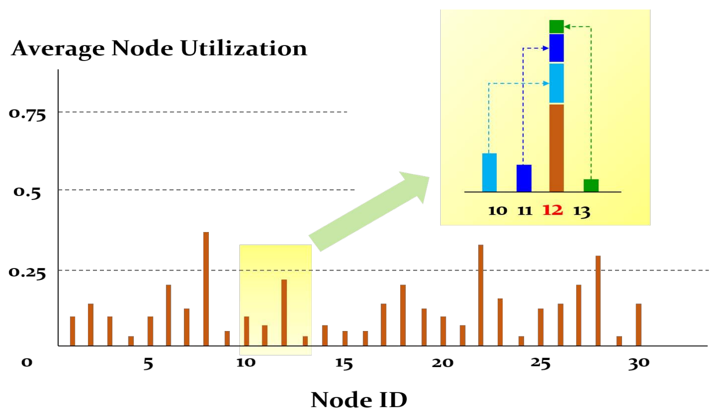


Figure 3.5: Motivation of HNs selection

According to Algorithm 1, first, each node sends a message including the utilization of a node and link to its neighbor nodes. Upon receiving this message, each recipient node inserts the neighbor information into the neighbor table. After sending and receiving a message, each node calculates the difference in utilization between nodes. Finally, nodes are selected to be either HNs or MNs by comparison with the threshold. The threshold is a predefined value calculated by the network operator and used as the basis for an HN decision. A lower value of the threshold would result in a greater number of HNs that are candidates for selection.

Algorithm 1: HN selection procedure

u_i	network utilization of node i
$u_{i,j}$	network utilization of link from node i to node j
node_j	adjacent node of node i
k	the number of adjacent nodes of node i
u_{th}	the predefined threshold value by network provider
$\text{node}_{i \to j}$	node i sends a message to node j

forall *node* $i = 1$ *to* $i = N$ **do**
  sendToNeighbor ($\text{node}_{i \to j}$, u_i, $u_{i,j}$) ;
  receiveFromNeighbor ($\text{node}_{j \to i}$, u_j, $u_{j,i}$) ;
  insertNeighborTable (node_j, $u_i + u_{i,j} - u_j + u_{j,i}$) ;
end
CalUtilGap(i) = $\sum_i^k (u_i + u_{i,j} - u_j + u_{j,i})$;
if CalUtilGap$(i) \geq u_{th}$ **then**
  node i is selected to be a HN
else
  node i is selected to be a MN)
end

Along with selecting HNs, the ratio of HNs (R_{HN}) can also affect the performance. For instance, if more nodes are designated as HNs (i.e. $R_{HN} \to 1$) according to the HN selection procedure and accordingly, few nodes are working as MNs and less energy efficiency is expected. Ideally, HNs should be chosen for the network to maximize the benefit from the sleep of the L3 functionality in MNs under the constraint of the property of network conditions. In this thesis, we assume that the value of R_{HN} is fixed, a priori given by internet or network operator, whereas main focus is to define a strategy to determine how to select HNs.

3.4.2 *Network clustering*

After the HN selection procedure, the nodes selected as HNs send advertising messages to the adjacent nodes as described in Algorithm 2. If HNs receive an advertising message from other HNs, they discard the advertising message. On receiving a join message from MNs, HN allows them as their MNs and configures a cluster.

Algorithm 2: Clustering procedure in HNs

forall *header node* $i = 1$ *to* $i = N$ **do**
  HNsendToMN (node$_{i \to j}$, u_i, $u_{i,j}$) ;
end
discardFromHN(node k) ; /* Advertising message from other header node k is discarded */
HNallowMN(node i, node j) ; /* Header node i receives a join message from member node j and allows to join cluster */

Algorithm 3 describes the clustering procedure in MN. Once neighbor nodes, MNs receive a message from the HNs. The MNs first collect all adverting messages and look for the utilization of HNs. Then, MNs select the HN that is the least utilized among multiple HNs and send a join message to HN selected.

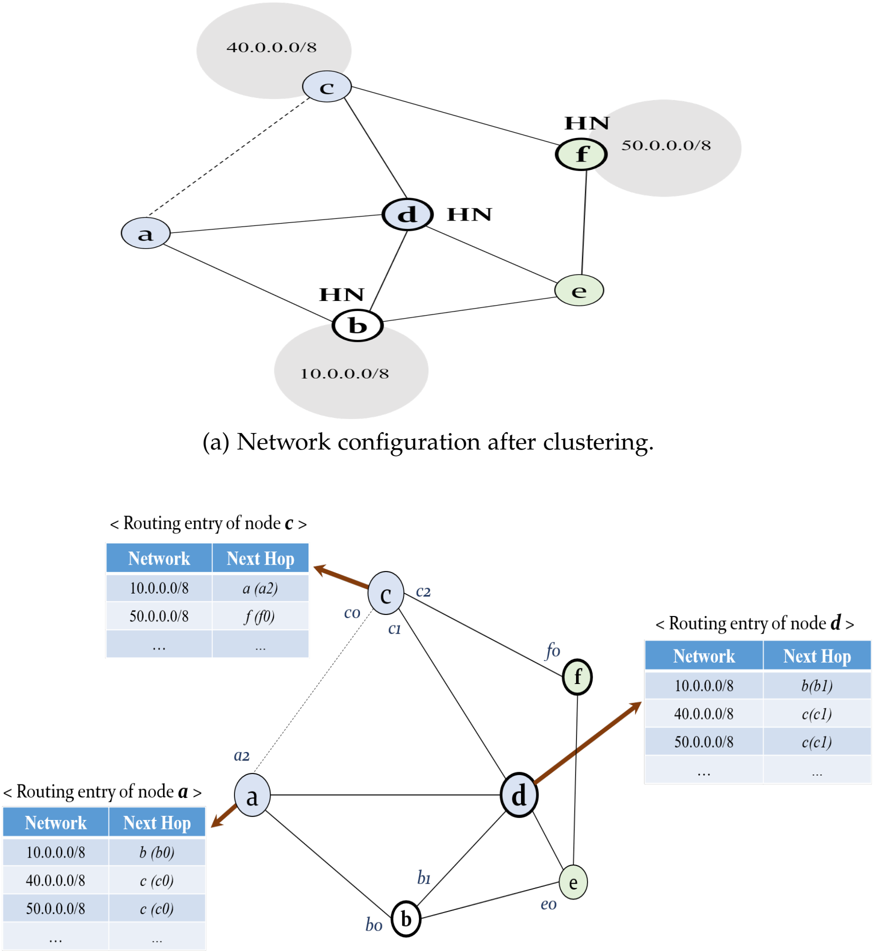
Algorithm 3: Clustering procedure in MNs

forall *member node* $j = 1$ *to* $j = N$ **do**
  MNreceiveFromHN (node$_{i \to j}$, u_i, $u_{i,j}$) ;
  updateNeighborTable (node$_j$, $u_i + u_{i,j}$) ;
end
MNselectHN(node j, node i) ; /* Member node j selects the least utilized header node i if there are multiple HNs */
MNjoinHN(node j, node i) ; /* Member node j sends a joint message to header node i */

Figure 3.6a illustrates network configuration after clustering. In this example, three clusters $\{a, c, \mathbf{d}\}$, $\{\mathbf{b}\}$, $\{e, \mathbf{f}\}$ are configured, where each HN in a cluster is expressed in bold. Figure 3.6b shows the routing entry of HN (node d) and MNs (node a and d).

3.4.3 *Tag allocation and distribution*

Figure 3.7 illustrates tag allocation and distribution after routing entry update. After clustering, the MNs send routing information to their



(a) Network configuration after clustering.

(b) Initial routing entry of MN and HN.

Figure 3.6: Network clustering

HN, and the HN adds this routing information to the routing entry for identifying the reachability through the MNs. In this step, there can be several routing entries for the same next hop. For the destination 10.0.0.0/8, node *d* already has routing entry and receives routing information from node *a* and *c*. Then, the routing information from these two nodes is removed. After adding the MN information, the HN selects the shortest and non-overlapping next hop among multiple paths headed for the same destination, and updates the routing entry.

The HN then assigns tags to the next hop that can be reached through the MNs, and the tags are distributed to MNs in cluster. For the destination 50.0.0.0/8, node *d* also has routing entry and receives routing information from node *c*. Node *c* as MN must have corresponding information regarding tag before going to sleep mode. So node *d* assigns tag for the destination 50.0.0.0/8 and distributes to node *c*.

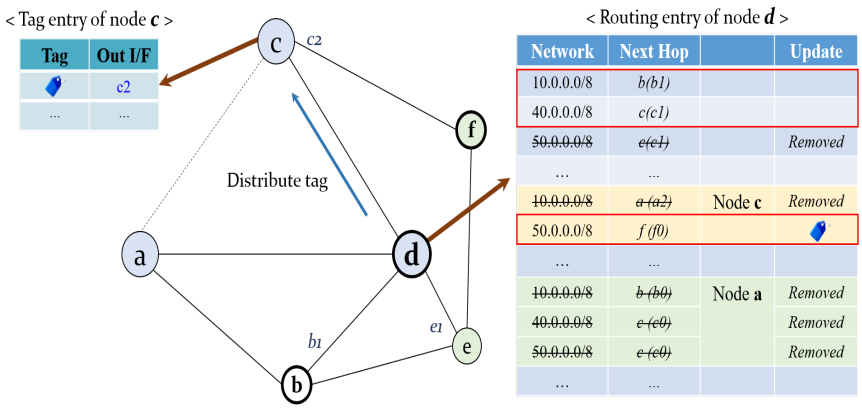


Figure 3.7: Tag allocation and distribution

For MNs where IP routing will be temporarily on sleep mode, it is required to handle incoming packet at a minimum. A tag is a specially designed identifier within a cluster for switching packets instead of IP routing, and includes the outgoing node interface. Label switching in Multi-Protocol Label Switching (MPLS) architecture [88] can be an alternative when IP processing is on sleep. MPLS is a routing technique in networks directing data from one node to the next based on short path labels rather than long network addresses, thus avoiding complex lookups in a routing table and speeding traffic flows. However, this switching method has some overhead to solve the problem given in Section 3.3, and all network nodes should be MPLS enabled routers.

Table 3.3 summarizes several constraints between the two identifiers. Therefore, a new and simple identifier is proposed for packet switching in MNs.

Upon receiving tags from an HN, the MNs temporarily put the routing-related function in layer 3 to sleep and conduct packet switching using a tag. If the MNs receive packets without a tag, the packets are directly forwarded to the cluster HN.

3.4.4 *Packet switching*

Figure 3.8 illustrates packet switching operation of GreenPS. When node *a* receives packets without tags and forwards them to its HN, node *d*, as an operating assumption, the MN (node *a*) forwards packets to the HN if there is no tag information in the routing entry of the MN. Upon receiving packets, node *d* looks up the routing entry, encapsulates it with the tag, and forwards all of the packets to node *c*. Node *c* performs packet switching and forwards the packets to node *f*. Finally, packets with a tag arrive at node *f*, which removes the tag and routes the packets to the destination.

Table 3.3: Comparison between MPLS and proposed tag switching

Index	MPLS	Proposed tag switching
identifier	label(20bits)	tag(implementation dependent)
operation	label switching between ingress and egress LERs	tag switching between HNs
purpose	high-speed switching (without IP routing)	energy saving (temporarily sleeping IP routing engine)
path calculation	LDP	results of HN selection and clustering procedures
QoS support	strong (RSVP)	weak (do not need QoS control)
scalability	weak	strong
installation cost	expensive (MPLS module must be equipped)	relative cheap (implement on softwarable router)

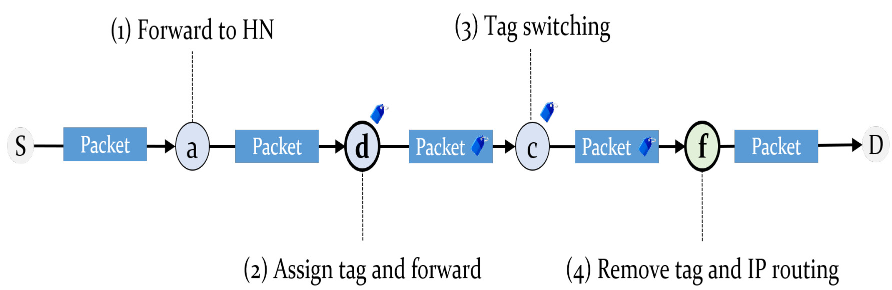


Figure 3.8: Packet switching operation of GreenPS

3.5 PERFORMANCE EVALUATION

In this section, we validate the GreenPS algorithm compared with other existing energy-saving routing schemes.

3.5.1 *Experimental setup*

For evaluating routing algorithms, we used the Network Simulator (Version 2) [91], widely known as NS2. NS2 is an event-driven simulation tool that has proved useful in studying the dynamic nature of communication networks. Simulations of network functions and protocols (routing algorithms, TCP and UDP) can be done using NS2. NS2 provides users that can specify such network protocols and simulate their corresponding behaviors. Figure 3.9 illustrates basic architecture of NS2.

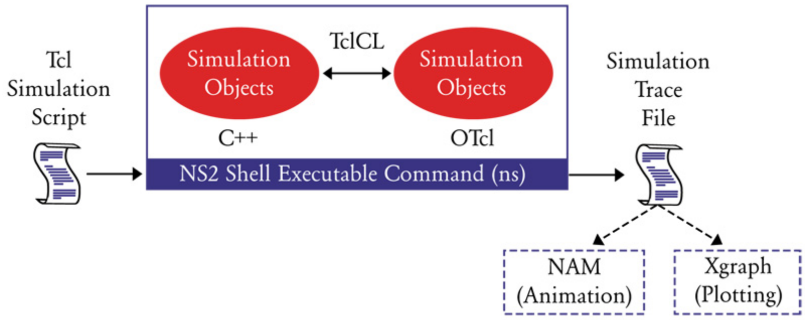


Figure 3.9: Basic architecture of NS2 [91]

Several simulation were conducted under the National Science Foundation NETwork (NSFNET), Exodus, and Ebone from the Rocketfuel project [124]. Table 3.4 presents basic information about topologies. Two types of networks to describe scale in networks were considered for simulation [32], namely the random network and scale-free. The random network's nodal degree distribution follows a Poisson's distribution, and most nodes in this network usually have the same number of links. The scale-free network's nodal degree distribution follows a power law, and many nodes have only a few links and a few nodes have a large number of links. Figure 3.10 provides the graphical presentation using the NAM program in NS2 of these topologies.

Table 3.4: Simulation topologies information

AS	# of nodes	# of links	Nodal degree	Type
NSFNET	14	42	3.0	random
Exodus	79	294	3.75	scale-free
Ebone	87	322	3.72	scale-free

For measuring the energy consumption, the power consumption of a network node is set to 700W (e.g., Cisco 7500 Series Router [44]), and 490W is used for IP routing, whereas the residual is used for tag switching [120]. The power consumption of a network link is set to 235W according to [18]. Furthermore, the GreenOSPF [41] and ILP [38] as candidate green solutions designed to deploy to core IP networks are chosen for comparative analysis. Lastly, in case of GreenOSPF, the number of ER (explained in Section 2.1.1.3) is set to 10% of total nodes. The parameters used in simulation are summarized in Table 3.5.

(a) NSFNET (US).

(b) Exodus (US).

(c) Ebone (Europe).

Figure 3.10: The realistic backbone network topologies used in the simulation

Table 3.5: Simulation settings

Parameter	Value
Power consumption of node	700W
Power consumption of link	235W
Maximum link capacity	1Gbit/s
HN ratio (R_{HN})	0.1, 0.2, 0.3, 0.4
Power consumption ratio of L3	0.7
Topologies	NSFNET, Exodus, Ebone
Strategies	GreenPS, *GreenOSPF*, *ILP*

For more information of simulation, in case of NSFNET with 14 nodes and 42 links, 182 ($= 14 \times 13$) connections from all sources and destinations pair (s, d) are established. Then, the amount of traffic offered in network is 16.8 ($= 42 \times 0.4$) if the offered traffic load in network is 0.4, and an average offered load per each connection is estimated to 0.092 ($= 16.8/182$) or 92Mbit/s.

The simulation's main purpose is to investigate energy efficiency (i.e., how much energy can be saved according to algorithms) focusing on network provisioning. This is the same method applied to evaluate the performance of existing green routings in [38, 41]. Although network dynamicity for ever-changing environments in QoS perspective has not been seriously included in performance analysis, it is worth analyzing the energy perspective because the GreenPS is initially designed to apply less traffic load condition (i.e., off-peak time).

3.5.2 *Complexity analysis*

The complexity of the GreenPS is investigated before simulation study. In general, green routing solutions follows three phases and each phase is described as below:

- Phase I: Gathers the network information and disseminates it throughout the networks
- Phase II: Determinates unnecessary network resources (nodes and links) for reducing power consumption
- Phase III: Forwards an incoming flow along the re-routing path

The existing green algorithms [38, 41] basically use Dijkstra's algorithm to determine routing path using link state protocols such as OSPF. Then, it is assume that Dijkstra's algorithm uses Fibonacci heap and its computational complexity is $\mathcal{O}(N \log N + L)$ where N and L indicate the total number of network nodes and links, respectively.

Tab 3.6 summarizes the complexities of existing green routings and the GreenPS regarding each phase.

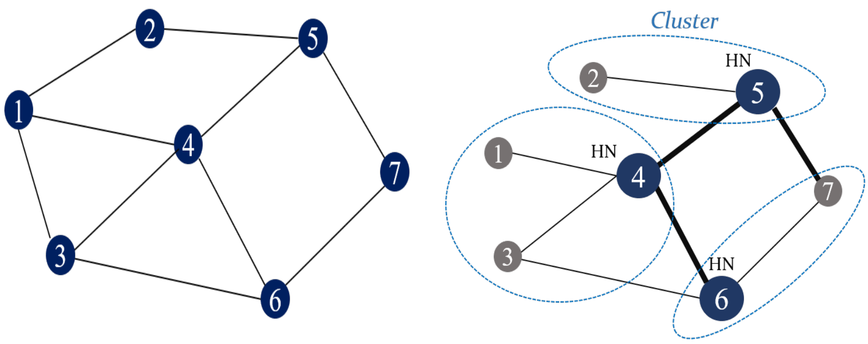
In phase I, all algorithms gather the network information and disseminate it. Green routings perform these tasks via existing routing protocols such as OSPF, while GreenPS starts with HN selection procedure and does not make any attempt in this phase. Hence, it is assumed that the basic topological information is given by existing routing protocols such as OSPF. Accordingly, the complexity of GreenPS in this phase is same as $\mathcal{O}(N \log N + L)$, the one of the Dijkstra's algorithm if OSPF is deployed.

In phase II, all algorithms try to solve the energy minimization problem which is NP-hard to determine unused links. However, solving this problem exactly is only available in trivial case and intractable especially for large-scale networks. Although previous green routings can greatly reduce the computational complexity, they still require a considerable amount of time. The complexities of ILP and GreenOSPF algorithms in this phase estimated in [105] are $\mathcal{O}(L \log L + LN^2 \log N + L^2 N)$ and $\mathcal{O}(N^2 \log N + LN)$, respectively. Compared with previous algorithms, the GreenPS does not make any

Table 3.6: Comparison of routing phases

Phase	Green routings [38, 41]	GreenPS
I	Assume that the tasks in this phase are performed via the existing routing protocols	Assume that the tasks in this phase are performed via the existing routing protocols
II	Run their proposed algorithms to determine the unused links based on the gathered information, but require high computational complexity	Do not make any attempt for this phase. Unused links are autonomously determined by phase 3
III	Re-calculate routing path under the modified network topology (which excludes the determined unused links) and forward the flow	Re-calculate routing path after network clustering and forward the packet carrying out tag switching

attempt for this phase. In case of the GreenPS, the unused links are autonomously determined by network clustering in phase 3.



(a) Before clustering

(b) After clustering

Figure 3.11: Example of network configuration before and after clustering

In phase III, the green routings re-calculate the routing paths under the modified network topology and then forward the incoming flows along the re-calculated routing paths. Figure 3.11 gives an example of a network configuration after clustering. Figure 3.11a shows the topology before the clustering procedure and three nodes (node 4, 5 and 6) are selected as HN in this example. After clustering (Fig. 3.11b), three clusters are configured in the network and each cluster can be seen as a single node for re-calculating the routing path in a network perspective. Then, the GreenPS configures the network with a reduced number of nodes and links after clustering. The GreenPS also updates the routing path within the cluster by checking the reachability of MNs and then assigns the tag and allows the incoming flows to be forwarded according to the tag's path. For this purpose, each cluster re-calculates switching path, and the complexity is estimated to be lower than $\mathcal{O}(n^{HN} \times (\log n_k))$ where n^{HN} and n_k are the numbers of HN in the network and the nodes in cluster k, respectively. GreenPS re-configures network after clustering and locally updates the routing path in the cluster compared with existing green routings. This results in a lower complexity than existing green routings [38, 41].

3.5.3 *Results*

In simulation environments described in Section 3.5.1, we first investigated effects from HN selection and clustering procedure and the results are illustrated in Fig. 3.12 and Fig. 3.13.

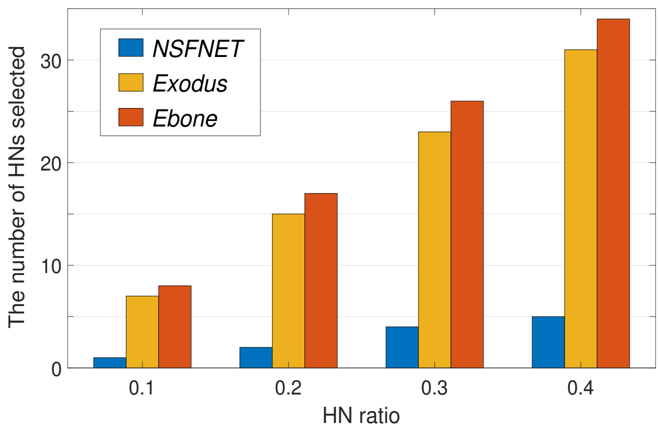


Figure 3.12: The number of HNs after HN selection procedure

Figure 3.12 shows the number of HNs selected from Algorithm 1 according to HN ratio increment when the offered traffic load is 0.4. It is easily measured using HN ratio and the number of nodes in the topology.

Figure 3.13 shows the average number of nodes, including HN and MNs in a cluster with its standard deviation after HN selection and network clustering procedures. As the HN ratio increases, the average number of nodes in the cluster decreases. This behavior is caused by the situation when MN receives an advertising message from multiple HNs and selects one HN. The standard deviation (Fig. 3.13) also shows the variety of cluster size except for one case (i.e., only one cluster is configured with four MNs when HN ratio is 0.1 in NSFNET). For example, the largest and smallest cluster sizes are observed as 11 (one HN and 10 MNs) and 1 (one HN without MN) during simulation

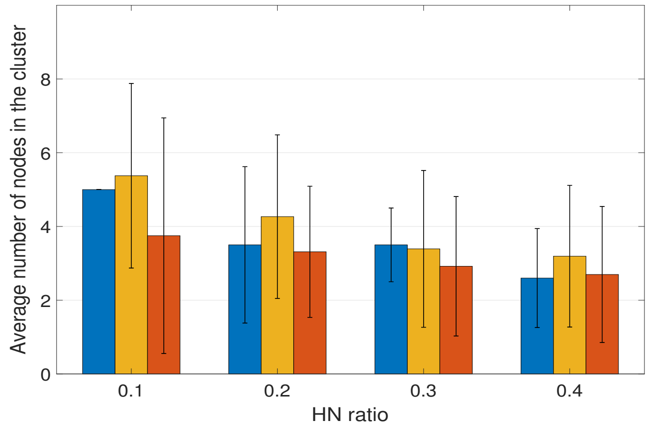


Figure 3.13: Average number of nodes in the cluster

when HN ratio is 0.1 in Ebone. The configuration of cluster depends on the network topology and a higher energy saving is expected when nodes with a higher nodal is selected to be HN.

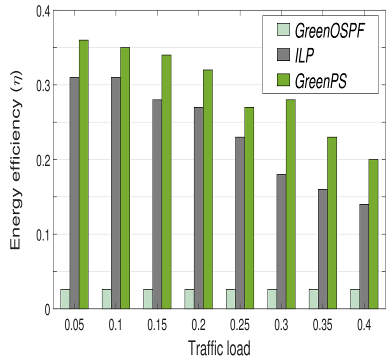
Energy efficiency is the key performance index for energy saving and we measured this index indicating the ratio of the nodes and links to be switched off to all nodes and links.

For an exact comparison, we define the energy efficiency η as

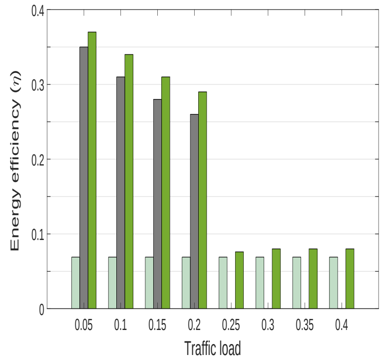
$$\eta = \sum_{\{v \in V, l \in L\}} \frac{P_{off}}{P_N} \tag{3.16}$$

where P_N and P_{off} are the total power consumption of network (Section 3.3.2) and the total amount of power consumption from power-off node v and link l, respectively, and V, L is the set of nodes, links in the given network topology.

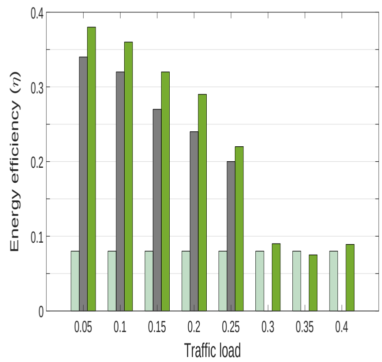
Figure 3.14 shows the results obtained from the evaluation of the performance of the proposed algorithm under various topologies. As the offered load increases, energy efficiency is reduced in all network topologies. However, in the cases of Exodus and Ebone, both of which are scale-free networks, the energy efficiency decreases rapidly when the offered load is greater than 0.3 because a few nodes tend to have a large number of links in these networks. However, less reduction is observed as the load increases in NSFNET, which is a random network. This behavior is caused by traffic congestion at nodes with high nodal degree in the Exodus and Ebone topology with a smaller offered load. We can easily expect that as the number of nodes with high nodal degree increases, the energy efficiency also increases because the node will eventually switch off all other links, except one. In an



(a) NSFNET



(b) Exodus



(c) Ebone

Figure 3.14: Energy efficiency under various topologies regarding the algorithms according to the traffic load

NSFNET, less congestion occurs because most nodes have the same number of links. Thus, the GreenPS shows better performance in random networks than scale-free networks regardless of the offered load. Overall, the GreenPS can be applied to both random and scale-free network topologies, as objective is to reduce power consumption during off-peak periods.

Figure 3.15 summarizes energy efficiency when the offered load is 0.2. All previous algorithms attempt to reduce energy consumption by turning off the nodes and links. Therefore, the energy efficiency of ILP is much higher than GreenOSPF because ILP determines the nodes and links to be turned off using a complicated optimization technique. Turning off the network equipment allows incoming flows passing by the elements to be rerouted to other candidate paths, resulting in paths longer than the shortest paths.

The behavior described above causes the traffic to be aggregated on the links that are still turned on; hence, the average link load for such links increases as illustrated in Fig. 3.15.

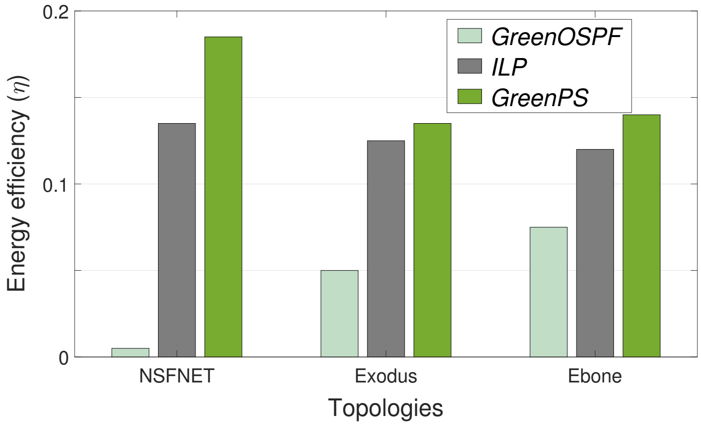
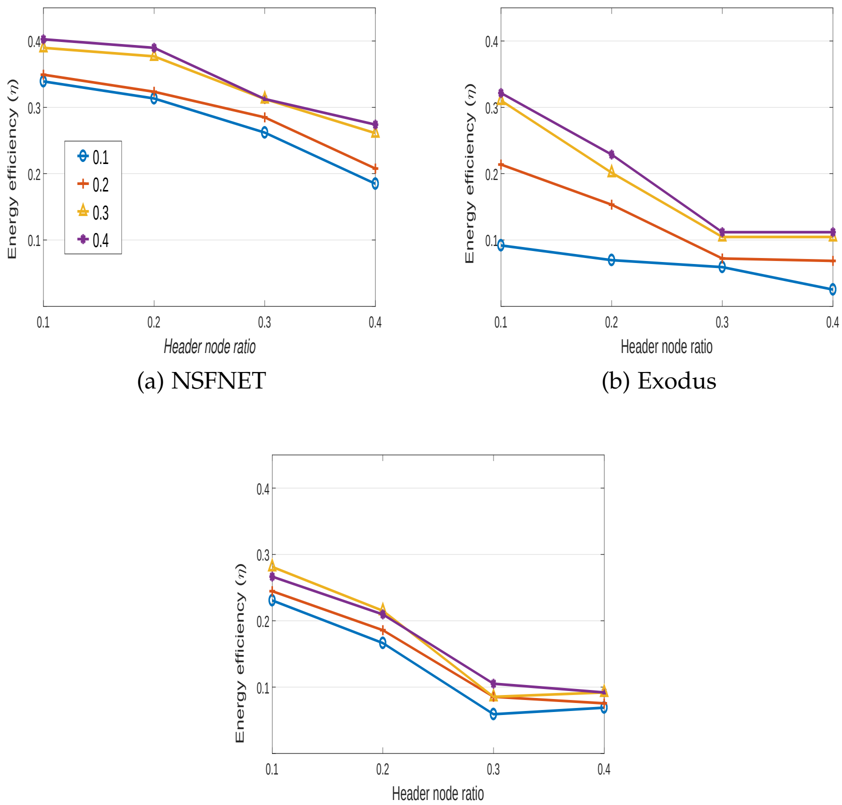


Figure 3.15: Energy efficiency under various topologies regarding to the algorithms



(a) NSFNET (b) Exodus

(c) Ebone

Figure 3.16: Energy efficiency under various topologies regarding the ratio of HNs according to the traffic load

If some nodes with a high nodal degree start to experience congestion because of traffic re-routing, the algorithm might no longer support the energy consumption, which is why the energy efficiency of an ILP stops at 25%. Contrary to previous approaches, the GreenPS turns off the L3 routing function while maintaining the network connectivity to the HN. Accordingly, the candidate paths are no longer than the original shortest paths, thereby reducing the energy consumption more than previous methods.

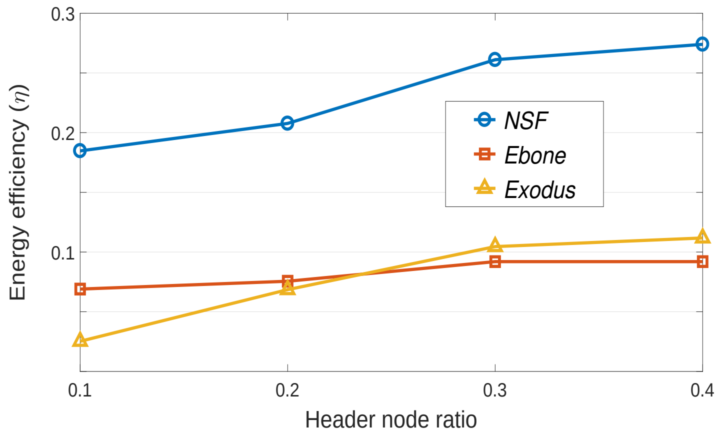


Figure 3.17: Energy efficiency under various topologies regarding the ratio of HNs

Figure 3.16 illustrates the energy efficiency under various network topologies according to the change in HN ratio by adjusting the threshold value in the HN selection procedure according to the change in the traffic load and Fig. 3.17 summarizes when the offered load is 0.4 for comparison. As the number of HNs increases, the energy efficiency in an NSFNET also increases. As explained in Fig. 3.15 and Fig. 3.17, NSFNET has fewer hot spot nodes and less congestion caused by re-routing after clustering. However, congestion can easily occur at several nodes with a high nodal degree in a scale-free network. We, therefore, can estimate the conditions maximizing the energy efficiency under the given traffic load and HN ratio.

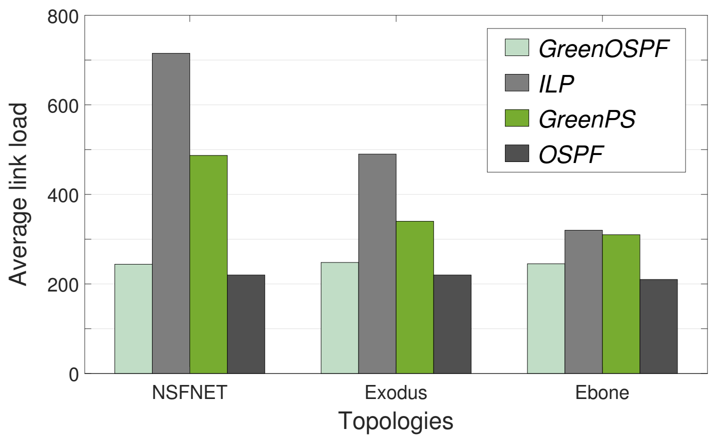


Figure 3.18: Average link load under various topologies regarding the algorithms

Figure 3.18 plots the average link load estimated over the links that turn on when the offered load is given by 0.2. As described earlier, in the case of the ILP algorithm, the average link load is high at approximately 700Mbps; therefore, ILP takes much longer paths compared to the shortest paths. Contrarily, the candidate paths of the proposed algorithm are not much longer. Note that the average link load affects the end-to-end delays of the flows. As the load is proportional to delay, the GreenPS can support more moderate quality of services than the ILP algorithm while reducing the energy consumption efficiently.

3.5.4 *Conclusion*

In this chapter, green packet switching for IP networks was newly proposed as the first step toward green networking. As a preliminary study, several terminology and basic green packet switching ideas were introduced and discussed compared with the shortest and green paths.

As a goal of this chapter, the energy minimization network problem was defined and reformulated with several primitives. It includes the functional separation of routing and switching functioned in layers 3 and 2, respectively, in which each layer in the OSI model must be operated independently.

According to the HN selection method, the green packet switching algorithm (GreenPS) configures the clusters of one HN and multiple MNs to minimize energy consumption in a network, especially for off-peak times. Network utilization of network node was considered in this chapter and estimated how much energy could be saved according to the operation mode, either HN or MN, in a heuristic manner. The selected HNs made a cluster with neighboring nodes and MNs in the cluster slept their routing-related function and performed packet switching using tags.

Simulations using several topologies were performed to validate the solution regarding energy efficiency. The results showed that the GreenPS successfully reduces energy consumption, and the performance of GreenPS is more energy-efficient than previous works.

In Chapter 4, GreenPS is extended, including renewable energy's impact from availability and cost perspectives, and analyzed under real network and renewable energy environment.

4

GREEN IP ROUTING WITH RENEWABLE ENERGY

To truly transform our economy,
protect our security,
and save our planet from the ravages of climate change,
we need to ultimately make clean,
renewable energy the profitable kind of energy.

— Barack Obama (Former U.S. President)

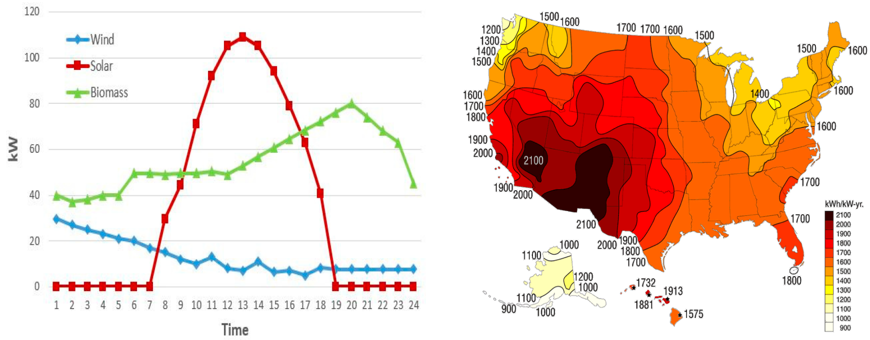
As a second step toward green networking and continuation of Chapter 3, this chapter discusses a novel energy-efficient packet switching using renewable energy in IP networks.

This chapter is structured as follows. Section 4.1 motivates this chapter. Section 4.2 provides general technical preliminaries before the details of the packet switching using renewable energy. Section 4.3 presents the network min-energy problem to be solved. Section 4.4 gives the design of green IP routing using renewable energy. A performance analysis using a simulation is developed and the results are presented in Section 4.5 with the conclusion of this chapter.

4.1 MOTIVATION

There has been a growing demand to deliberate on environmental cognition in various industries, especially the ICT sector [107]. The energy generated by renewable energy is getting more attention because it reduces GHG emissions and protects the environment. Renewable energy from solar panels, wind turbines, geothermal heat pumps, and other sources is now a mainstream option in the power generation sector globally. Several research described in Section 2.2.1 have focused on green networking solutions to reduce traditional fossil-fuel energy consumption and encourage using power from various renewable energy sources.

In using renewable energy, it is critical to consider that available renewable energy is strongly dependent on period and geographical location [158], as illustrated in Fig. 4.1. Each renewable energy source (e.g., solar power, wind power, biomass power, geothermal power) has its properties. For example, wind energy is an eco-friendly energy source because its generation has no damage to environment, as shown in Fig. 4.2. However, its generation cost is expensive than other renewable energy sources, as illustrated in Fig. 4.3 and only available in limited areas, such as seashores and hillsides.



(a) Renewable energy power generation per time [127].

(b) Solar power generation in US [3].

Figure 4.1: Example of renewable energy power generation patterns

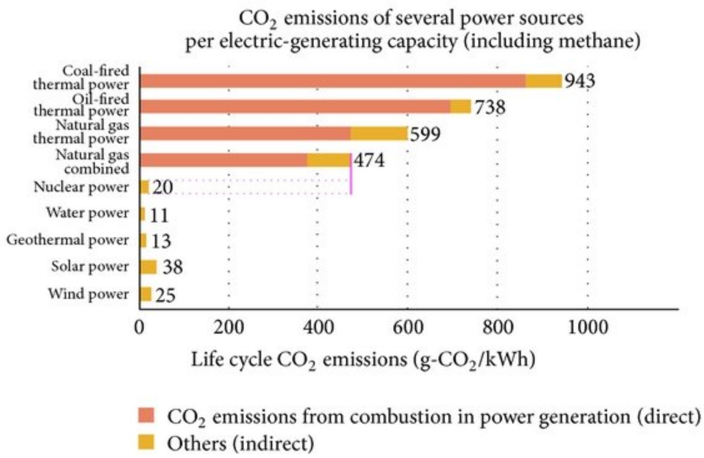


Figure 4.2: GHG emissions from various energy sources [2]

Motivated by encouraging using renewable energy to networks and different properties per energy source, we considered the renewable energy for green IP routing. Considering the importance of renewable energy, we discussed a novel energy-efficient packet switching using renewable energy in IP networks.

4.2 PRELIMINARIES

This section provides basic information to understand a packet switching algorithm using renewable energy (referred to as GreenPSR).

The basic framework of GreenPS is illustrated in Fig. 3.3 of Section 3 with the functions of HNs and MNs. GreenPSR also follows

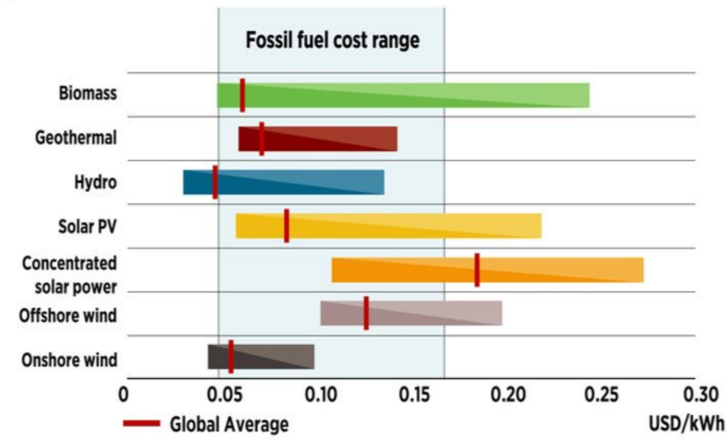


Figure 4.3: Renewable power generation costs in 2018 [149]

this framework and assumes to be powered by combining multiple energy sources, as illustrated in Fig. 4.4. Nodes (e.g., routers) in networks equipped with additional devices (e.g., solar panel and wind turbine) locally would be powered by combining multiple energy sources soon. Recently, this assumption is being actualized, especially in mobile network systems [35, 128]. Furthermore, renewable energy is becoming part of the power grid nowadays [10], and the proportion of energy sources applies to all domains (including telecommunication) to the whole area in general. This study also follows this assumption. Particularly, we aimed to design a green IP routing using renewable energies, especially with wind and solar power as renewable energy sources.

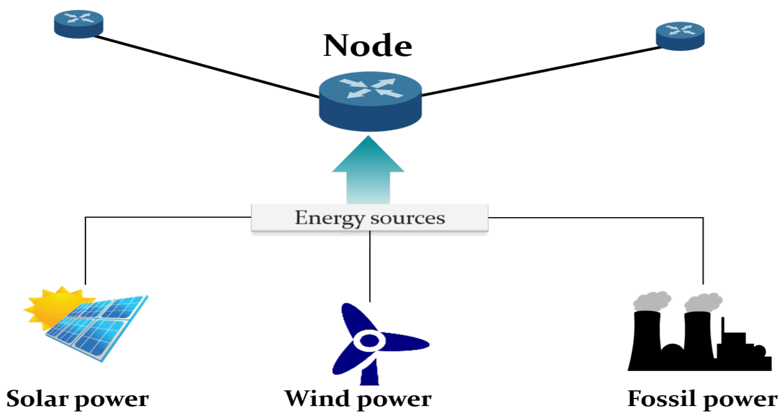


Figure 4.4: GreenPSR node architecture with multiple energy sources

To consider the effect of renewable energy, we considered two kinds of primitives from renewable energy to define network energy problem: (i) availability of renewable energy in the nodes and (ii) production and environmental cost per energy sources. The first concern is minimizing traditional fossil-fuel power usage, instead of maximizing usage from renewable energy. A cost-based approach is to define energy cost, including generation and environmental costs. Environmental cost indicates how each energy source emits CO_2. The second concern is minimizing energy cost based on weighting factors indicating the importance of both costs. These concerns for problem definition strongly depend on each energy source's availability varying from time and nodes' geographical location. Considering all concerns regarding renewable energy, we introduced in the following section the problem formulation.

4.3 PROBLEM DEFINITION AND FORMULATION

In Section 3, minimizing power consumption in a network is solved by designating either HNs or MNs and putting routing (L3) function in MNs on sleep. However, the chapter's problem is different because several primitives of renewable energy are necessary to consider before formulating the problem. In other words, HNs selection and network clustering procedures need to be modified using renewable energy primitives. Now, the problem is defined and reformulated, including both aspects: availability and energy sources' cost.

4.3.1 *Renewable energy impact*

4.3.1.1 *Energy metric*

There are many different electrical generation methods, and each method has advantages and disadvantages to operational cost, environmental impact, and other factors. Diligent computation of generation cost includes the initial capital, discount rate, continuous operation, fuel, and maintenance. Hydroelectric power is the cheapest renewable energy source, whereas concentrated solar power is the most expensive renewable energy source, as illustrated in Fig. 4.3. About GHG emissions, each generation method produces GHGs in varying quantities through construction, operation (including fuel supply activities), and decommission. Some generation methods such as coal fired power plants release most GHGs during operation, as shown in Fig. 4.2.

To measure such an impact of renewable energy from different sources, we introduced a new concept called the *Bill of Energy* by considering ation of production and environmental costs regarding multiple energy sources available in a network node. Table 4.1 describes the notations used in this section.

Table 4.1: Notations

Symbol	Description
$u_x(i)$	Power generation cost (US\$/KWh) of energy source x at node i where $x \in \{s, w, f\}$
$\hat{u}_x(i)$	Normalized power generation cost (US\$/KWh) of energy source x at node i
$v_x(i)$	CO_2 emission (g/KWh) of energy source x at node i where $x \in \{s, w, f\}$
$\hat{v}_x(i)$	Normalized CO_2 emission of energy source x at node i
$e_x(i)$	The available power of node i from energy source x where $x \in \{s, w, f\}$
$\tilde{e}_x(i)$	The power power consumption of node i actually used from energy source x and satisfies $0 \leq \tilde{e}_x(i) \leq e_x(i)$

Definition 2 *(Bill of energy (BoE)) To evaluate the energy impact of a network node considering generation and environmental costs from multiple energy sources, a cost index of node i, we defined BoE as*

$$E(i) = \sum_{x \in \{s,w,f\}} c_x(i)\tilde{e}_x(i) \tag{4.1}$$

where node i indicates network node (i.e., router) powered by multiple energy source and x represents a type of energy sources (s, w, and f stand for solar power, wind power, and fossil-fuel power respectively). We will consider another energy source type. We also defined a cost variable $c_x(i)$ for each energy source at node i using the generation cost to produce 1kWh and the environmental cost incurred by consuming 1kWh:

$$c_x(i) = \sigma\hat{u}_x(i) + (1 - \sigma)\hat{v}_x(i) \tag{4.2}$$

where $c_s(i)$, $c_w(i)$, and $c_f(i)$ are the cost variables of solar, wind, and fossil energy of node i, respectively. The terms $\hat{u}_x(i)$ and $\hat{v}_x(i)$ are the normalized power generation cost and the normalized CO_2 emission rate per energy source $x \in \{s, w, f\}$ at node i, respectively, which can be calculated as follows. Table 4.2 shows the results of the calculation.

$$\hat{u}_x(i) = \frac{u_x - \min(u_x)}{\max(u_x) - \min(u_x)}, \qquad \hat{v}_x(i) = \frac{v_x - \min(v_x)}{\max(v_x) - \min(v_x)}$$

Table 4.2: Generation cost and CO_2 emission per energy source [150]

	Generation cost ($/kWh)	CO_2 emission (gram/kWh)
Fossil	0.095	1,182
Wind	0.135	124
Solar	0.125	731

σ is a weighting variable for the generation cost and assumed to be given by network providers (e.g., telco). GreenPSR aimed to be deployed in core IP networks maintained by network operators. A network provider provides carrier services and owns or controls the infrastructure necessary to sell and deliver services and seeks a profit by reducing operational cost. Energy consumption constitutes between 20% and 40% of network operating expenditure, and electricity occupies a non-neglectable portion of network maintenance expense [46, 139]. Thus, a network provider can adjust σ, resulting in an operational cost, *BoE*. In a special case, the government sometimes can prescribe this value for all network providers as a policy.

4.3.1.2 *Consideration for priority of energy sources*

Another concern for using renewable energy is prioritizing energy sources for *BoE* evaluation (e.g., to minimizing *BoE*). According to the geographical locations of nodes, the available renewable energy sources and their production cost are different (e.g., wind power costs 84 US$ and 216 US$ per kWh to operate the wind turbine if the plant is located onshore and offshore, respectively [150]). Accordingly, node's geographical information needs to be considered to address the generation cost of wind energy. Using *BoE*, we found that the node can decide the energy source order with economic and eco-environmental aspects if multiple energy sources are available in a node.

Lemma 1 *If $c_f(i) > c_s(i) > c_w(i)$, then the node i is preferred to consume power (in order): wind energy, solar energy, and fossil energy.*

To decide the renewable energy source's order, we evaluated and compared $g_x(i)$ using statistics [47, 150] according to the weighting variable for the generation cost σ, as given in Table 4.3:

Table 4.3: Cost variables of node i according to σ

σ	$c_s(i)$	$c_w(i)$	$c_f(i)$
0.1	0.588	0.1	0.9
0.2	0.606	0.2	0.8
0.3	0.624	0.3	0.7
0.4	0.642	0.4	0.6
0.5	0.66	0.5	0.5
0.6	0.678	0.6	0.4
0.7	0.696	0.7	0.3
0.8	0.714	0.8	0.2
0.9	0.732	0.9	0.1
1.0	0.75	1.0	0.0

The decision for the priority of energy sources is to maximize energy source by which coefficient in Eq. 4.1 has a minimum value depending on the value of σ shown in Table 4.3. As a result, the node i first consumes power generated consecutively from wind energy to solar energy to fossil energy if renewable energy is not sufficient to support the required power consumption of node i in case of giving $c_f(i) > c_s(i) > c_w(i)$.

4.3.2 *Network design problem using renewable energy*

There are two manners to consider using renewable energy in the network node: availability and energy sources' cost. The former indicates that the design problem is defined to maximize the usage from renewable energy, whereas the latter is defined to minimize energy cost, *BoE*. Both problem definitions are described in the following section.

4.3.2.1 *Renewable energy usage based on availability*

Let us consider a communication network modeled as a directed graph $G(V, L)$, where V and L are the sets of network nodes and directed network links, respectively. Notations and their properties are also defined in Section 3.3.1 without distinction among nodes. In other words, the power consumption of node i (denoted as e^v) equals to that of node j if both nodes operate in the same mode (either HN or MN). Considering the availability of renewable energy in each node, we need to identify each node as $e^v(i)$ and link as $e^l(l_{ij})$ even if both nodes work in the same mode (i.e., $e^v(i) \neq e^v(j)$). Now, the notations and properties, including each node's identification are described in the following.

A link that connects node $i \in V$ to another node $j \in V$ is denoted by l_{ij}. The set of neighbors of node i is denoted by $\{N_i \in V, l_{ij} \in L\}$. Each node $i \in V$ and link $l \in L$ are characterized by the power consumption $e^v(i)$: $V \to \mathbb{R}^+$ and $e^l(l_{ij}) : L \to \mathbb{R}^+$, respectively. The consumption of node i operating in the HN and MN with L3 functions disabled are characterized by $e^{HN}(i)$, $e^{MN}(i)$, respectively. The power consumption required to manage the hardware (e.g., heating and cooling) is not considered in the definition of $e^v(i)$.

Considering renewable energy usage, we denoted by $E_f(i)$ and $E_r(i)$ the available power from the fossil and the renewable energy in node i, respectively. We assumed that the node and link could be turned into low-power mode to save energy by introducing decision variables $\alpha_i, \beta_{ij} \in \{0, 1\}$ for node and link. The similar decision variable is also introduced in Section 3.3.2, as $\gamma(l_{ij})$ specifying whether the link l_{ij} between nodes i and j is powered on or off and has a binary value {0, 1}. However, no decision variable is assigned to activate of HNs in Section 3.3.2 because of the following two reasons: (i) All nodes are powered by traditional fossil energy without renewable energy involvement. (ii) The number of HNs and MNs is considered to estimate nodes' total power consumption in networks, as defined in Eqs. 3.6- 3.8. In other words, the node designated as HN consumes the same amount of traditional fossil power as other HNs do.

Power consumption of node i from fossil energy, depending on the value of α_i and β_{ij}, can be represented by

$$P_f(i) = \max\left\{\Big(\alpha_i e^{HN}(i) + (1-\alpha_i)e^{MN}(i) + \frac{1}{2}\sum_{j\in N_i}\beta_{ij}e^l(l_{ij}) - E_r(i)\Big), 0\right\} \tag{4.3}$$

where β_{ij} indicates whether link l_{ij} is powered on or not. The above formula stands for the total power consumption from fossil energy and equals the $\sum_{i \in V} \tilde{e}_f(i)$. It is zero if renewable energy is enough to support the node's total power consumption with half of the links that are incident to the node. Denoting by $V^1, ..., V^K$, the K clusters of the network nodes after the HN selection and the clustering, we can formulate the network design problem with the following integer program.

$$\begin{aligned}
&\textit{Minimize} && \sum_{i \in V} P_f(i) && \\
&\textit{subject to} && \sum_{i \in V^k} \alpha_i = 1,\ \forall k \in [K], && (4.4a)\\
& && \cup_{k \in [K]} V^K = V, && (4.4b)\\
& && V^{k_1} \cap V^{k_2} = \emptyset,\ \forall k_1, k_2 \in [K] && (4.4c)
\end{aligned}$$

where the constraint (Eq.4.4a) ensures that each cluster of nodes contains only one HN. Constraints (Eqs. 4.4b and 4.4c) represent that every node in V belongs to only one of the clusters. The last constraint enforces that nodes can only be in the mode of HN or MN, and links can only be put on or off. β_{ij} serves only as an indicator, and no decisions will need to be made on it. More specifically, $\beta_{ij} = 1$ if and only if it satisfies $\alpha_i = 1$ or $\alpha_j = 1$, and there exists $k \in [K]$ such that $i, j \in V^k$. The classical flow conservation constraints (Eqs. 3.2 and 3.3) in Section 3.3.2 also need to be satisfied to ensure that the traffic can be successfully routed on the derived network.

4.3.2.2 *Renewable energy usage based on cost*

This approach aimed to minimize *BoE* in networks, and the problem is defined using several notations and their properties used in Section 4.3.2.1.

The power consumption cost of node i (i.e., *BoE*), depending on the value of α_i and β_{ij}, is defined in Eq. 4.1 as

$$G(i) = \sum_{x \in \{s,w,f\}} g_x(i) \tilde{e}_x(i)$$

and the power consumption of node i used from energy source x can be represented by

$$\tilde{e}_x(i) = \left\{(\alpha_i e_x^{HN}(i) + (1-\alpha_i)e_x^{MN}(i) + \frac{1}{2}\sum_{j\in N_i}\beta_{ij}e_x^{l}(l_{ij})\right\} \tag{4.5}$$

Denoting by $V^1, ..., V^K$ the K clusters of the network nodes after HN selection and clustering, we can formulate the problem with the following integer program.

$$\begin{aligned}
&\textit{Minimize} && \sum_{i\in V} G(i) \\
&\textit{subject to} && \sum_{i\in V^k}\alpha_i = 1,\ \forall k\in[K], && \text{(4.6a)}\\
& && \cup_{k\in[K]} V^K = V, && \text{(4.6b)}\\
& && V^{k_1}\cap V^{k_2} = \emptyset,\ \forall k_1, k_2 \in [K], && \text{(4.6c)}
\end{aligned}$$

The aforementioned constraints presented are analogous to Section 4.3.2.1. Constraint (Eq. 4.6a ensures that each cluster of nodes contains only one HN. The constraints (Eqs. 4.6b and 4.6c) represent that every node in V belongs to only one of the clusters. Note that β_{ij} serves only as an indicator, and no decisions will need to be made on it. More specifically, $\beta_{ij} = 1$ if and only if it satisfies $\alpha_i = 1$ or $\alpha_j = 1$. There exists $k \in [K]$ such that $i, j \in V^k$. The classical flow conservation constraints (Eqs. 3.2 and 3.3) in Section 3.3.2 also need to be satisfied to ensure that the traffic can be successfully routed on the derived network.

The following section discusses some proposed heuristics, including two aspects of renewable energy usage to solve the given network design problems.

4.4 DESIGN OF GREEN IP ROUTING WITH RENEWABLE ENERGY

As an objective of green packet switching using renewable energy for IP networks, GreenPSR algorithms in the availability and cost perspectives are presented along with several detailed procedures in this section.

4.4.1 *HN selections*

Basic procedures of HN selection and corresponding network clustering are analogous to those of GreenPS in Sections 3.4.1 and 3.4.2. With the involvement of renewable energy, this section describes the enhanced procedures.

4.4.1.1 GreenPSR *using the availability of renewable energy*

The HN selection procedure of GreenPSR using renewable energy availability (referred to as GreenPSR$_a$) is summarized in Algorithm 4, which is applied to each node $i \in V$ with the three steps.

Algorithm 4: HN selection of node i in GreenPSR$_a$

Step 1:	Compute $savedE_f^{HN}(i)$ and $savedE_f^{MN}(i)$
	Exchange computed $savedE_f^{HN}(i)$ and $savedE_f^{MN}(i)$ with neighboring nodes
Step 2:	Compute $savedE_f(i)$
	Exchange computed $savedE_f(i)$ with neighboring nodes
Step 3:	Node i is selected to be an HN if if $\max\left(savedE_f(i), \cdots, savedE_f(j)\right) = savedE_f(i)$

Each node first computes how much fossil energy is saved if the node can be powered by renewable energy sources in HN and MN. The amount of power consumption saved from fossil energy is denoted as node i operating at HN and MN denoted as $savedE_f^{HN}(i)$ and $savedE_f^{MN}(i)$, respectively. Each is estimated

$$savedE_f^{HN}(i) = \begin{cases} E_r(i) & \text{if} \quad E_r(i) < E_f(i) \\ E_f(i) & \mathit{Otherwise} \end{cases} \tag{4.7}$$

$$savedE_f^{MN}(i) = \begin{cases} E_f(i) & \text{if} \quad E_r(i) \geq \rho E_f(i) \\ (1-\rho)E_f(i) + E_r(i) & \mathit{Otherwise} \end{cases} \tag{4.8}$$

where $E_f(i)$ and $E_r(i)$ indicate available power from fossil and renewable energy at node i, respectively, and ρ means the ratio of power consumption in L3. Each node calculates $savedE_f^{MN}(i)$ and $savedE_f^{MN}(i)$ and shares this information with neighboring nodes, as summarized in step 1.

In receiving $savedE_f^{MN}(j)$ from node j, the neighboring node of node i, node j calculates how much fossil energy can be saved if node i operates as HN (i.e, neighboring nodes of node i operate as MN). It is denoted by $savedE_f(i)$ and estimated as

$$savedE_f(i) = savedE_f^{HN}(i) + \sum_j savedE_f^{MN}(i) \tag{4.9}$$

Each node calculates $savedE_f(i)$ and shares this information with neighboring nodes, summarized in step 2.

As a result of step 2, node i knows the amount of fossil energy saved in node i itself and its neighboring nodes. $savedE_f(i)$ means the amount of saved fossil energy if the node itself operates as an HN and the other neighboring node operate as MNs. To find the case that can save fossil energy maximally, in each node i, we compared $savedE_f(i)$ with that of neighbor nodes and node i is selected as HN if condition in Eq. 4.10 is satisfied.

$$\max\left(savedE_f(i), \cdots, savedE_f(j)\right) = savedE_f(i) \tag{4.10}$$

4.4.1.2 GreenPSR *using renewable energy's cost*

GreenPSR$_a$ aimed to reduce power consumption from fossil energy by consuming renewable energy as much as possible. Hence, the amount of available renewable energy in the node is under consideration, and there is no concern regarding energy sources' priority. However, GreenPSR using renewable energy's cost (referred to as GreenPSR$_c$) takes the energy source's priority into account the HN selection procedure because the order that energy source consumes first affects *BoE*. Therefore, concern for energy source's priority is discussed in Section 4.3.1.2, and the order is determined according to the weighting variable of production cost σ.

The GreenPSR$_c$'s HN selection procedure is analogous to that of GreenPSR$_a$ except how renewable energy is under consideration for consumption. Algorithm 5 summarizes with three steps on determining HNs.

For HN selection procedure, each node first defines the mode (either *solar first* or *wind first*) as a result of priority selection and computes op-

Algorithm 5: HN selection of node i in GreenPSR$_c$

	(Assuming $g_w(i) < g_s(i) < g_f(i)$)
Step 1:	Compute $\Theta^{HN}(i)$ and $\Theta^{MN}(i)$
	Exchange computed $\Theta^{HN}(i)$ and $\Theta^{MN}(i)$ with neighbor nodes
Step 2:	Compute $\Theta(i)$
	Exchange computed $\Theta(i)$ with neighbor nodes
Step 3:	Node i is selected to be a HN if $\min(\Theta(i), \cdots, \Theta(j)) = \Theta(i)$

erational cost of node i (referred to either $\Theta^{HN}(i)$ or $\Theta^{MN}(i)$ according to the operation mode) calculated as:

$$\Theta^{HN}(i) = \begin{cases} g_w e^v & \text{if } e_w(i) \geq e^v \\ G_w(i) + g_s(e^v - e_w(i)) & \text{if } e_w(i) + e_s(i) \geq e^v \\ G_w(i) + G_s(i) + g_f(e^v - e_w(i) - e_s(i)) & \text{if } e_w(i) + e_s(i) < e^v \end{cases} \tag{4.11}$$

$$\Theta^{MN}(i) = \begin{cases} g_w \rho e^v & \text{if } e_w(i) \geq \rho e^v \\ G_w(i) + g_s(\rho e^v - e_w(i)) & \text{if } e_w(i) + e_s(i) \geq \rho e^v \\ G_w(i) + G_s(i) + g_f(\rho e^v - e_w(i) - e_s(i)) & \\ & \text{if } e_w(i) + e_s(i) < \rho e^v \end{cases} \tag{4.12}$$

where $\Theta(i)$ indicates the amount of *BoE* resulting from power consumption per energy source, and ρ means the ratio of power consumption in L3. Each node calculates $\Theta^{HN}(i)$ and $\Theta^{MN}(i)$, and shares this information with neighboring nodes, as summarized in step 1.

In receiving $\Theta^{MN}(i)$ from node j, neighboring node of node i, the node j calculates how much *BoE* can be saved if node i operates as

HN (i.e, neighboring nodes of node i operate as MN). It is denoted by $\Theta(i)$ and estimated as

$$\Theta(i) = \Theta^{HN}(i) + \sum_{j}^{k} \Theta^{MN}(j) \tag{4.13}$$

Each node calculates $\Theta(i)$ and shares this information with neighboring nodes, summarized in step 2.

As a result of step 2, node i knows BoE in node i itself and its neighboring nodes. $\Theta(i)$ means the cost, including generation and environmental costs, by consuming multiple energy sources if the node itself operates as an HN and the other neighboring nodes operate as MNs. To find case that can minimize BoE, in each node i, we compared $\Theta(i)$ with that of neighboring nodes, and node i is selected as HN if condition below is satisfied.

$$\min\left(\Theta(i), \cdots, \Theta(j)\right) = \Theta(i) \tag{4.14}$$

After the HN selection procedure, the nodes selected as HNs send advertising messages to the adjacent nodes. Once the neighboring nodes receive a message from multiple HNs, they compare $\Theta(i)$ from HNs and select the HN with the minimum $\Theta(i)$. If nodes receive an advertising message from other HNs, they then discard the advertising message. In special cases, there will be a node not receiving any advertising message from neighboring HNs. Afterward, a node is designated as HN and makes a single cluster without MNs.

4.4.2 *Network clustering*

After HN selection, the network clustering procedure is analogous to clustering procedures (Algorithms 2 and 3) in Chapter 3.4.2.

For GreenPSR$_a$, the nodes selected as HNs send advertising messages to the adjacent nodes after the HN selection procedure. Once neighboring nodes receive a message from the HNs, they compare $savedE_f(*)$ from multiple HNs and select the HN has the maximum $savedE_f(*)$. If nodes receive an advertising message from other HNs, they then discard the advertising message. These clustering procedures of HNs and MNs are summarized in Algorithms 6 7, respectively.

Similarly, the nodes selected as HNs send advertising messages to the adjacent nodes in GreenPSR$_c$ after the HN selection procedure.

Algorithm 6: Network clustering of HNs in GreenPSR$_a$

forall *header node* $i = 1$ *to* $i = N$ **do**
  HNsendToMN (node$_{i \to j}$, $savedE_f^{HN}(i)$) ;
end
discardFromHN(node k) ; /* Advertising message from other header node k is discarded */
HNallowMN(node i, node j) ; /* Header node i receives a join message from member node j and allows to join cluster */

Algorithm 7: Network clustering of MNs in GreenPSR$_a$

forall *member node* $j = 1$ *to* $j = N$ **do**
  MNreceiveFromHN (node$_{j \leftarrow i}$, $savedE_f^{HN}(i)$) ;
end
MNselectHN(node j, node i) ; /* Member node j selects the header node i with maximum $savedE_f^{HN}(i)$ if there are multiple HNs */
MNjoinHN(node j, node i) ; /* Member node j sends a joint message to header node i */

Once neighboring nodes receive a message from the HNs, they compare $\Theta(*)$ from multiple HNs and select the HN with the minimum $\Theta(*)$. If nodes receive an advertising message from other HNs, they then discard the advertising message. These clustering procedures of HNs and MNs are summarized in Algorithms 8 and 9, respectively.

Algorithm 8: Network clustering of HNs in GreenPSR$_c$

forall *header node* $i = 1$ *to* $i = N$ **do**
  HNsendToMN (node$_{i \to j}$, $\Theta(i)$) ;
end
discardFromHN(node k) ; /* Advertising message from other header node k is discarded */
HNallowMN(node i, node j) ; /* Header node i receives a join message from member node j and allows to join cluster */

4.4.3 *Tag allocation and distribution*

The procedure of tag allocation and distribution is analogous to the procedure defined in Section 3.4.3, and both GreenPSR$_a$ and GreenPSR$_c$ follow this procedure.

Algorithm 9: Network clustering of MNs in GreenPSR$_c$

forall *member node* $j = 1$ *to* $j = N$ **do**
  MNreceiveFromHN (node$_{j \leftarrow i}$, $\Theta(i)$) ;
end
MNselectHN(node j, node i) ; /* Member node j selects the header node i with minimum $\Theta(i)$ if there are multiple HNs */
MNjoinHN(node j, node i) ; /* Member node j sends a joint message to header node i */

4.4.4 *Packet switching*

The operation of packet switching is analogous to the procedure in Section 3.4.4 and both GreenPSR$_a$ and GreenPSR$_c$ follow this procedure.

4.5 PERFORMANCE EVALUATION

This section describes the simulations carried out to evaluate GreenPSR's energy-saving performance.

4.5.1 *Experimental setup*

To investigate the proposed GreenPSR's performance, we conducted several simulations using an NS-2 simulator under the well-known NSFNET [124] with 14 nodes and 42 links, as shown in Fig. 4.5 with actual distance.

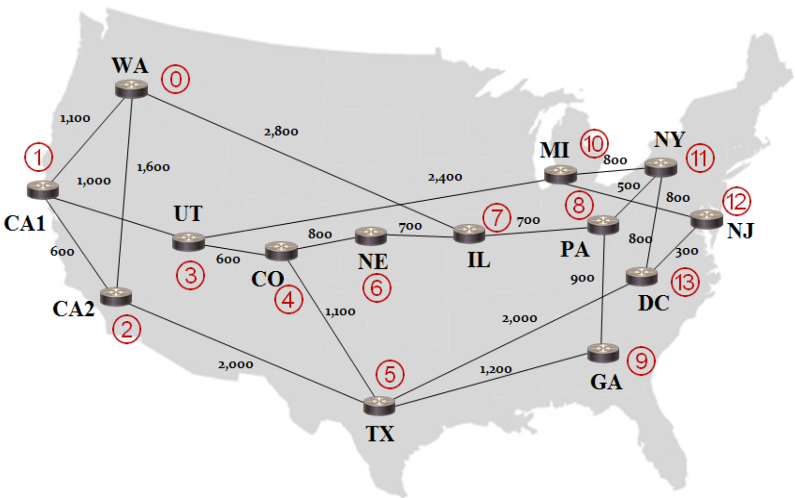


Figure 4.5: NSFNET topology in US

To consider the renewable energy's impact, we used the meteorological data available from the *National Solar Radiation database* [134] and got the real weather dataset of the 14 nodes, including the following: (i) *global horizontal irradiance(GHI)*, a widely used metric to estimate how much solar power could be achieved from photovoltaic solar panels, and (ii) wind speeds for every hour in a year. [132] provides the distribution of available renewable energy in the USA using the average annual wind speed and *GHI*. To estimate the amount of power generation (P_{wind}) from a wind turbine, we usually used Eq. 4.15 as a function of air density ρ, the blade swept A, and the wind velocity v [33]. For simplicity, we use only wind speed while setting other parameters to the unit value.

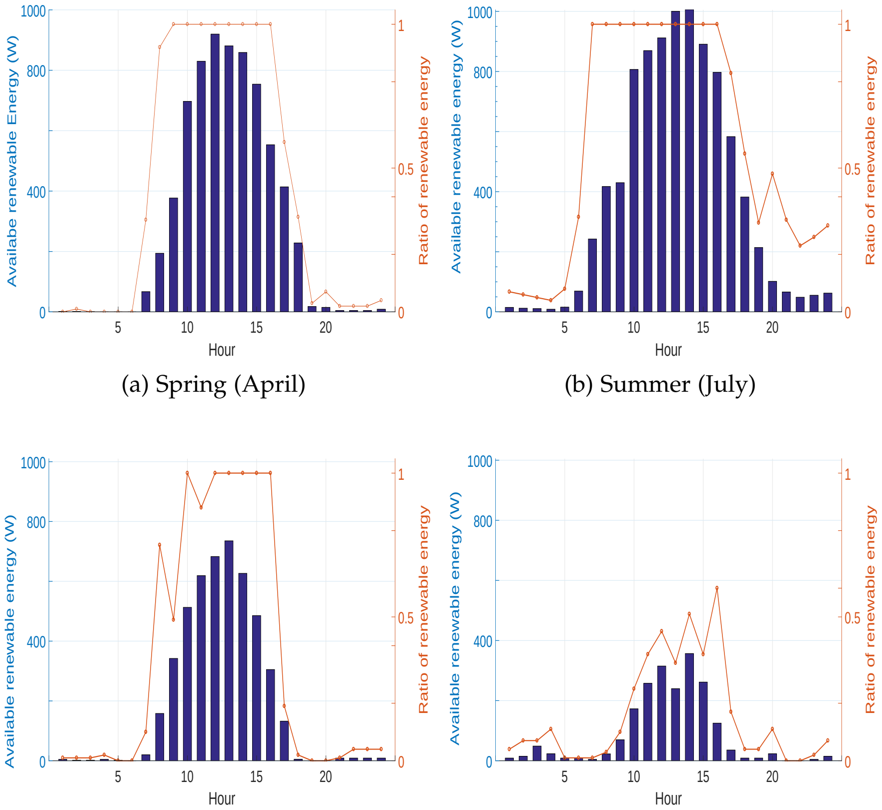
$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{4.15}$$

Except for renewable energy concerns, general simulation environments follows the information summarized in Table 3.5 of Section 3.5.1. Under these conditions, we measured the energy efficiency, defined as the rate of reduced power consumption. Particularly, we compared the GreenPSR's energy efficiency with those of the GreenOSPF [41], ILP [36] and GreenPS (Chapter 3).

4.5.2 *Results*

4.5.2.1 GreenPSR$_a$

We first measure the available energy sources. Figure 4.6 summarizes the results of evaluating how renewable energy can support power consumption per season at node 2. Located in California where there is plenty of sunshine and wind in daytime hours, node 2 can generate large amounts of power from solar panels and wind turbine.



(a) Spring (April)

(b) Summer (July)

(c) Fall (November)

(d) Winter (January)

Figure 4.6: The available renewable energy and its ratio at node 2

To investigate how much fossil energy is replaced with renewable energy after network node clustering, we defined the energy saving ratio of fossil energy, η_s, as follows:

$$\eta_s = \frac{\sum savedE_f(i)}{\sum e^v} \tag{4.16}$$

Figure 4.7 illustrates the average energy-saving ratio of fossil energy in 14 nodes. The simulation is performed over four seasons for 24 hours, a total of 96 cases.

For example, in node 2, this node is selected as HN for 69 times and MN for 27 times over season and time (Table 4.4). Consequently, the total power consumption required is estimated as 53,970W (= 700×69 + 210×27). According to the availability of renewable energy source in this node during the 96 cases, a total 13,039.1W can be used to support this node, and the energy-saving ratio is estimated to be 24%.

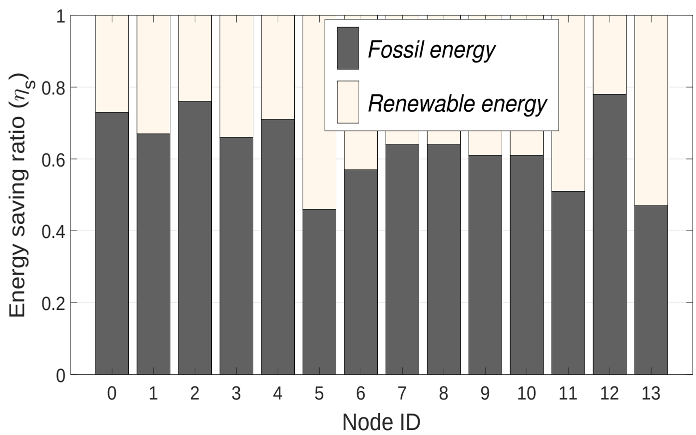


Figure 4.7: The average ratio of power sources consumed in 14 nodes over season and time

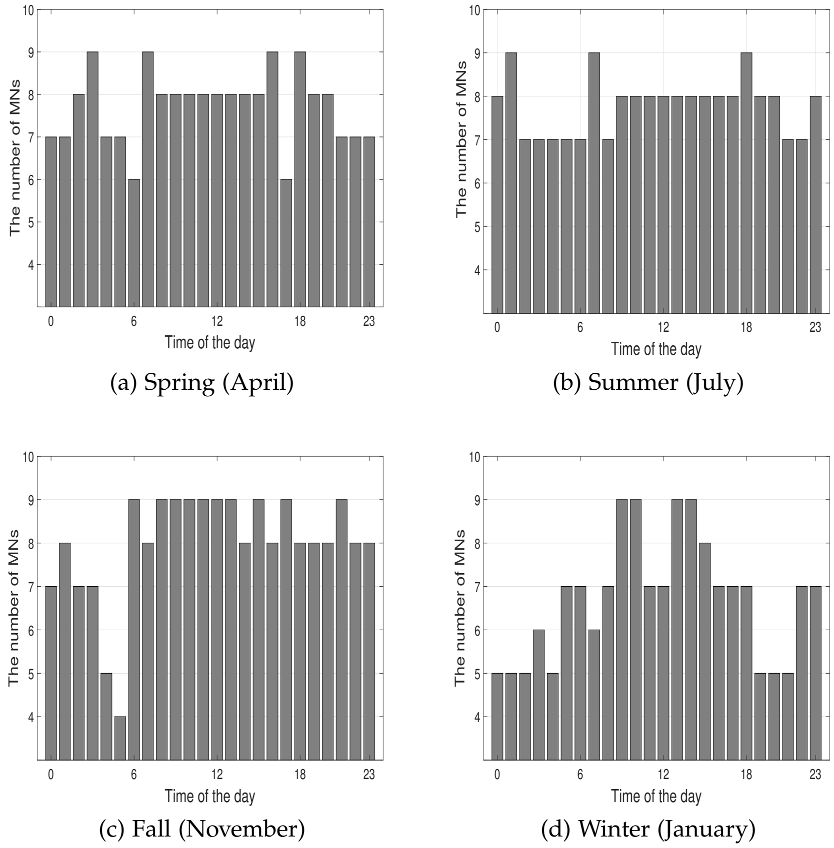
Table 4.4: The number of the frequency selected as HN and MN in node 2

Season	**HN**	**MN**
Spring	16	8
Summer	17	7
Fall	17	7
Winter	19	5
Total	69	27

These energy sources can be either partially or completely consumed in the node according to gGreenPSR algorithm's result. The node attempts to consume power from renewable energy first according to Algorithms 4, 6, 7, and fossil energy later if renewable energy sources are insufficient to power. Overall, fossil energy consumption can be reduced to 37% and replaced by renewable energy sources in network perspective .

This behavior is strongly dependent on the operational mode (either HN or MN) and its available energy sources. Even though the available energy from a renewable source is insufficient to support HN, the ratio $\eta_s(i)$ is equal to 1 if the node i is designated as MN and then, $E_r(i) \geq 210$ W. In spring, 10:00, node 2 is selected as MN and the amount of available renewable energy is measured as 730.6 W (638 W and 92.6 W from the solar power and wind power, respectively). Operating as MN, this node requires 210 W and the renewable energy can fully support this node resulting in $\eta_s = 1$ under this time.

More energy from fossil energy is reduced as more nodes selected as MNs. Figure 4.8 shows the result of the number of MNs configured over season and time for an averaged hourly profile for one representative month per season.



(a) Spring (April)

(b) Summer (July)

(c) Fall (November)

(d) Winter (January)

Figure 4.8: Number of MNs designated (from a total of 14 nodes)

We compared the energy efficiency of the GreenPSR$_a$ with those of Green OSPF, ILP, and GreenPS. Figure 4.9 illustrates the energy efficiencies defined in Eq. 3.16 under existing routing algorithms according to the offered load change.

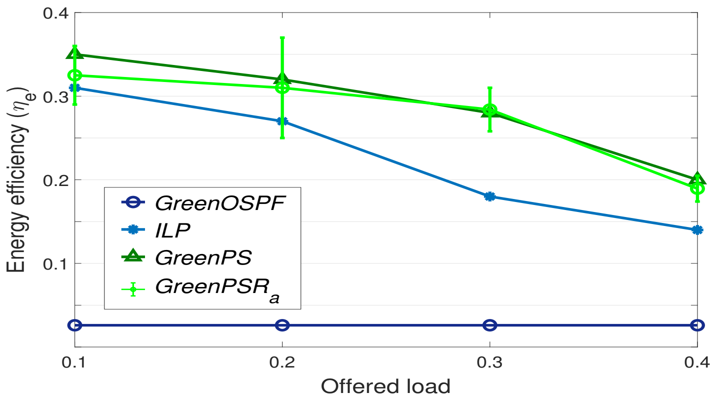


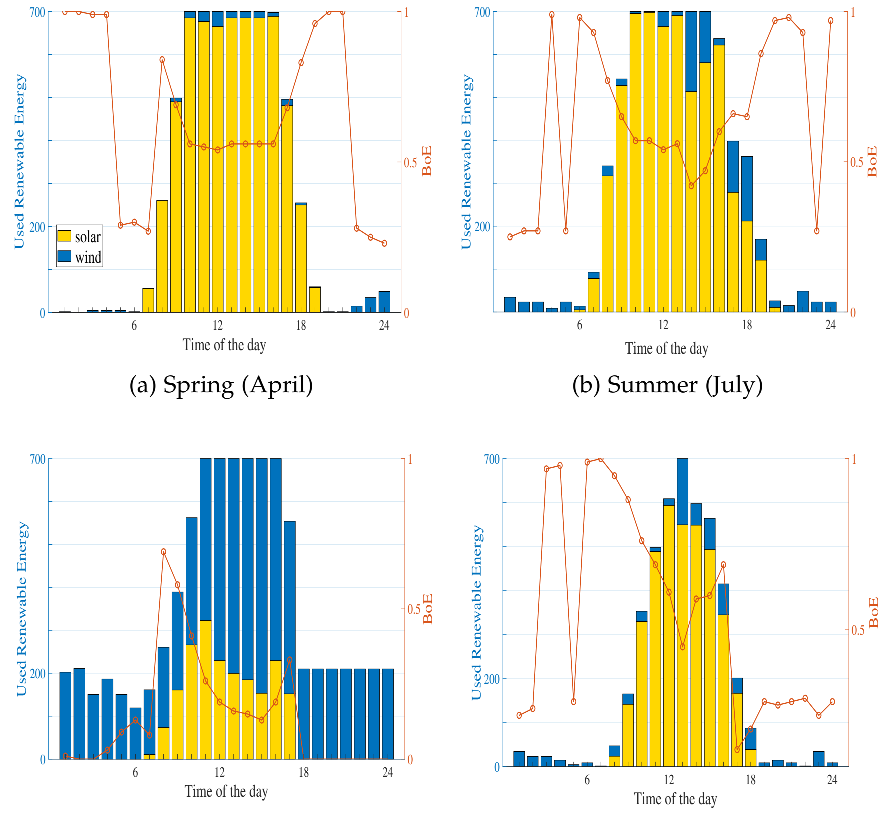
Figure 4.9: Energy efficiency concerning the algorithms

Similar to Fig. 3.14a, energy efficiency is reduced in all algorithms. As the offered load increases, both GreenPS and GreenPSR$_a$ perform tag switching after network clustering, showing a similar pattern in energy efficiency. GreenOSPF shows the lower energy efficiency than other algorithms because of the number of ER (explained in Section 2.1.1.3) set to 10% of the total nodes in simulation (described in Chapter 3.5.1). Such behavior is caused by traffic congestion of nodes and links after turning off. To solve a hotspot problem caused by traffic congestion in certain nodes, we need to turn MNs into HNs and switch on unused links in GreenOSPF and ILP. Even though GreenPS$_a$'s energy efficiency differs according to time and season, it encourages the consumption of available renewable energy first. Thus, GreenP$_a$ shows less reduction in energy efficiency as the offered load increases.

4.5.2.2 GreenPSR$_c$

We analyze how each renewable energy can support power consumption and its corresponding *BoE* in a single node after clustering. Figure 4.10 summarizes the results obtained at node 5 located in Texas, where there is plenty of sunshine in daytime hours and strong wind especially in the fall when $\sigma = 0$. In this case, clustering is performed to consider and minimize CO_2 emissions. From Fig. 4.10, it can be inferred that the more wind energy consumed, the less *BoE* is evaluated. Renewable energy features (i.e., availability and cost variable of each energy source) have an influence on *BoE*, and do the operational mode of nodes (either HN or MN).

Table 4.5 shows the available and the used energy sources according to the operation mode. The *BoE* is estimated to be zero (02:00) if there is no renewable energy available. Between 05:00 and 07:00, this node operates as MN and its *BoE* is reduced because less power from fossil



(a) Spring (April)
(b) Summer (July)
(c) Fall (November)
(d) Winter (January)

Figure 4.10: The used renewable energy and its *BoE* at node 5

energy is required than HN under limited renewable energy condition. Even though this node operates as HN, the *BoE* is also reduced if there are plenty of power from renewable energy sources (between 10:00 and 15:00).

Figure 4.11 illustrates the energy efficiencies of other algorithms (GreenOSPF, ILP, and GreenPSR$_a$) according to the offered load change. For GreenPSR$_c$'s energy efficiency of the, we derived the average value, including a maximum and minimum value, based on the fluctuations of available renewable energy over season and time. As the offered load increases, energy efficiency is reduced in all algorithms. Except for GreenPSR, both algorithms turn on additional nodes and links when the constraints (Eqs. 3.2 and 3.3) are violated. Such behavior is caused by traffic congestion of nodes and links. Despite the change in weather conditions, the GreenPSR$_c$ encourages power consumption from renewable sources and it tends to increase the number of MN. Thus, the GreenPSR shows better performance than other algorithms regardless of the offered load.

Table 4.5: Available and used energy sources in node 5

Time	Available		Mode	Used			*BoE*
	Wind	Solar		Wind	Solar	Fossil	
1	1.7	0	HN	1.7	0	698.3	0.9976
2	0	0	HN	0	0	700	1
3	4.6	0	HN	4.6	0	695.4	0.9934
4	4.6	0	HN	4.6	0	685.4	0.9934
5	4.6	0	MN	4.6	0	205.4	0.2934
6	1.7	0	MN	1.7	0	208.3	0.2976
7	0.0	56	MN	0	56	154	0.2656
8	0.0	260	HN	0	260	440	0.8403
9	8.8	490	HN	8.8	490	201.2	0.6864
10	14.9	692	HN	14.9	685.1	0	0.5579
11	23.3	852	HN	23.3	676.1	0	0.5510
12	34.5	955	HN	34.5	655.5	0	0.5417
13	14.9	983	HN	14.9	685.1	0	0.5579
14	14.9	948	HN	14.9	685.1	0	0.5579
15	14.9	847	HN	14.9	685.1	0	0.5579
16	8.8	689	HN	8.8	689	2.2	0.5642
17	14.9	481	HN	14.9	481	204.1	0.6832
18	14.9	250	HN	14.9	250	435.1	0.8251
19	1.7	58	HN	1.7	58	640.3	0.9620
20	1.7	0	HN	1.7	0	698.3	0.9976
21	1.7	0	HN	1.7	0	698.3	0.9976
22	14.9	0	MN	14.9	0	195.1	0.2787
23	14.9	0	MN	14.9	0	175.5	0.2508
24	14.9	0	MN	14.9	0	161.3	0.2305

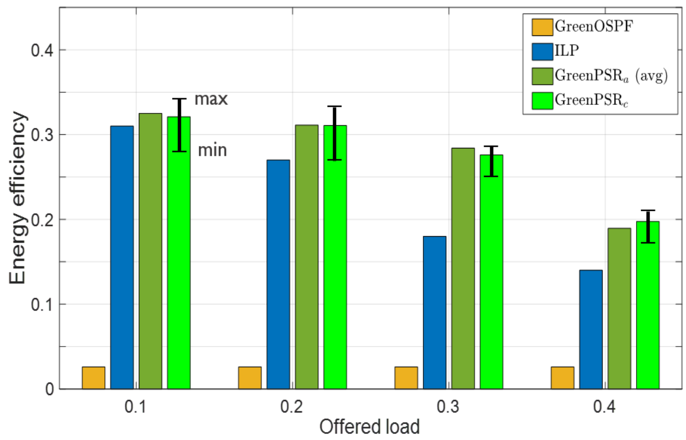


Figure 4.11: Energy efficiency concerning the algorithms

Figure 4.12 illustrates the average end-to-end delay of generated flows between all sources and destinations. For measuring of delay, propagation delay computed as the ratio between the link length and the propagation speed over the medium. The proposed GreenPSR$_c$ shows a longer delay than other green solutions because of the re-routing after clustering procedure. The average delay increases as the traffic load increases. However, unlike this pattern, the GreenPSR$_c$ shows a longer delay under a lower traffic load condition.

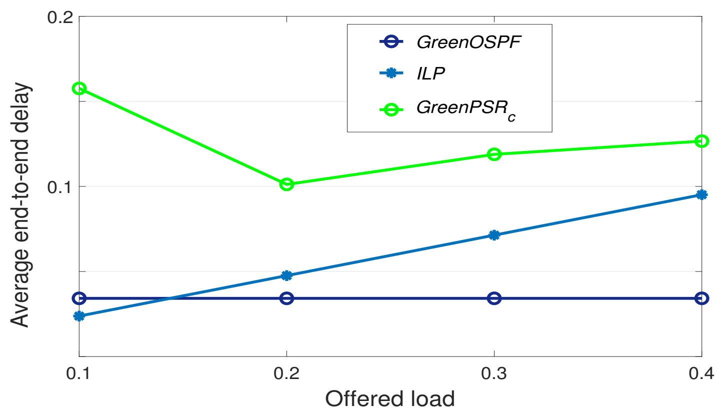


Figure 4.12: Average end-to-end delay concerning the algorithms

Figure 4.13 shows the number of links powered-off after clustering and its corresponding delay and offers insight into investigating this behavior. It indicates that the path between source and destination can be different, whereas the number of links powered-off is identical according to the clustering procedure result. During the simulation, 14 of 42 links were powered off after clustering, leading to following path identified by tag instead of achieving the shortest path between a source and a destination. Consequently, it can be stated that the average end-to-end delay can be affected by the traffic load and the number of links powered-off after clustering.

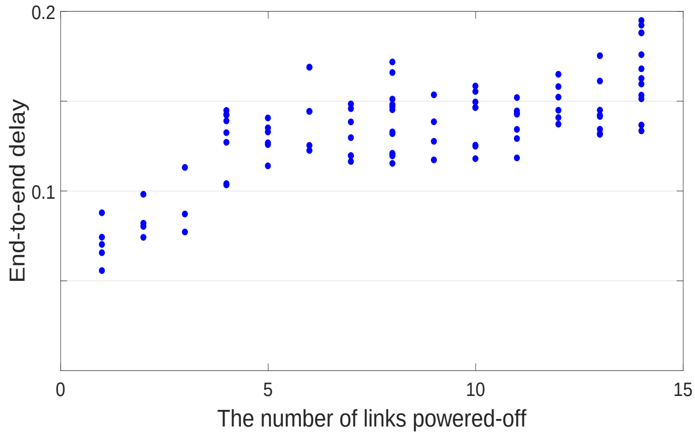
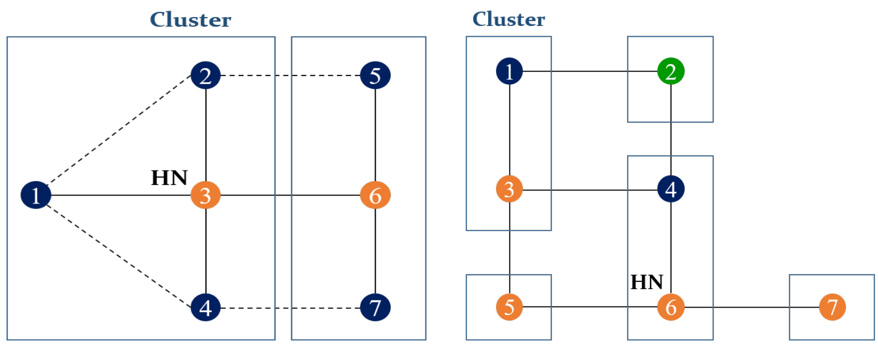


Figure 4.13: End-to-end delay measurement

4.5.2.3 *Discussions*

Section 3.2.3 briefly discusses the comparison between the shortest path and tag switching path. A path identified by GreenPS and GreenPSR after network clustering procedure is established toward higher energy efficiency. However, it can affect another performance index, such as longer network delay (Fig. 4.12). A trade-off between energy saving and service degradation may occur. It is challenging to investigate the performance affected by topological and network environmental reason.



(a) Best case. (b) Worst case.

Figure 4.14: Best and worst configurations after the clustering procedure

Figure 4.14 shows the possible two cases regarding network clustering using seven network nodes. For the best case configuration (Fig. 4.14a), two clusters are configured in the network with five MNs, and four links are powered off. For the worst case configuration (Fig. 4.14b), five clusters are configured in the network with two

MNs, and no link is powered off. (In this case, node 2 also operates as HN after not joining any cluster) This comparison shows that energy efficiency does not always increase according to the number of HNs. More energy efficiency can also be achieved with more links between MNs from the different clusters (e.g., nodes 2 and 5 in Fig. 4.14a) are configured.

GreenPS and GreenPSR aimed to select HNs and make clusters using some heuristics (traffic load in GreenPS and renewable energy in GreenPSR) to achieve energy efficiency. Even though results in Sections 3.5.3 and 4.5.2 show better performances in energy efficiency than other existing green solutions, more detailed investigation regarding the network re-configuration is worthy of improving other performance indices. For example, an additional constraint can be applied to HN selection procedure to prevent two nodes with one hop relation (i.e., nodes 6 and 7 in Fig. 4.14b) from being designated to be HNs.

4.5.3 *Conclusion*

As an extension of the green routing in IP networks in Chapter 3, renewable energy was newly considered for green IP routing in two perspectives (availability and renewable energy's cost).

The design problem of green IP routing using renewable energy was formulated using renewable energy impact. It defines a new metric, called the *BoE*, as a quantitative metric for measuring energy source's availavbility, generation and environmental cost in the network node. We proposed a green IP routing using renewable energy (GreenPSR) that uses an energy metric to solve this problem. This routing scheme follows GreenPS's packet switching procedure in Chapter 3, including the functional separation of routing of layer 3 and switching of layer 2. To support GreenPSR in the existing network, we assumed partial power consumption from multiple energy sources in the network node.

To encourage energy consumption from especially renewable energy available, we found that the GreenPSR first configures clusters consisting of one HN and multiple MNs according to the availability of renewable energy (GreenPSR$_a$), generation cost, and carbon emission per unit of energy (GreenPSR$_c$).

We performed simulations using realistic network topology and renewable energy statistics from the USA to validate the solution regarding renewable energy impact and energy efficiency. The results showed that GreenPSR successfully reduces the power consumption from fossil energy in real IP networks and enables more energy and cost-efficient performance from renewable energy than previous works.

In Chapter 5, a green routing scheme is extended to a green content networking and design content routing strategy based on renewable energy impact from an eco-friendly perspective.

5 GREEN CONTENT ROUTING IN NDN

I've been very passionate about renewable energy for many years, particularly solar energy and its capacity to bring abundant clean, sustainable energy to millions around the globe.

— Richard Branson (Founder of Virgin Group)

As the next step toward green networking and as a continuation of Chapter 3, this chapter provides a green strategy for content networking using renewable energy in NDN.

This chapter is structured as follows: Section 5.1 presents the motivation of this chapter; Section 5.2 provides general technical preliminaries before the details of content routing using renewable energy; Section 5.3 presents the content network energy problem to be solved; Section 5.4 gives the design of green content routing using renewable energy; and Section 5.5 presents the developed performance analysis using a simulation and the results and conclusion of this chapter.

5.1 MOTIVATION

It is fairly common knowledge that the Internet is absolutely loading with video traffic (Fig. 5.1 and Fig. 5.2). The paradigm shift of the current Internet architecture to efficiently correspond with this growing video traffic has been briefly introduced in Chapter 1. As an advanced Internet architecture for content delivery, the NDN emerged with the mission to solve the fundamental design limitations of IP [187]. The NDN essentially adopts a data-centric methodology by naming data instead of identifying location-based IP addresses and enables data packets to be meaningfully independent of its origin or where it will be forwarded. Thus, the data can be cached inside the network to satisfy future requests. For this reason, caching and forwarding in the NDN are being magnified as a critical factor.

The energy consideration for routing and forwarding has also become one of the important concerns in NDN research. Despite the aforementioned efforts in Section 2.1.2, very few have studied the consideration of the usage of renewable energy for routing and caching in NDN. Hence, it is worthy to jointly consider the strategy for routing and caching in NDN with renewable energy impact. Extended

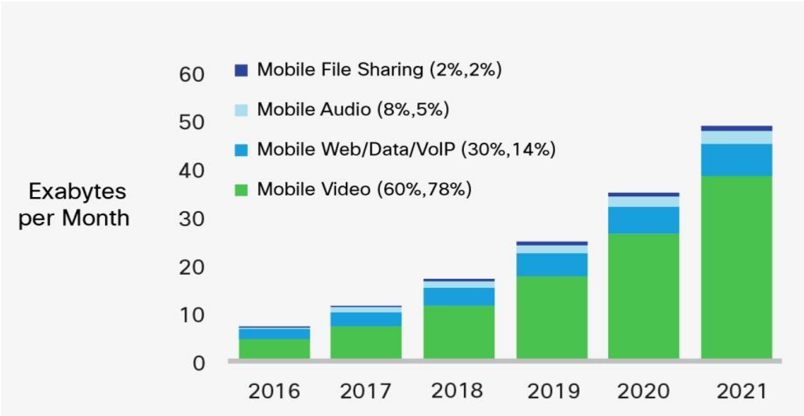


Figure 5.1: Global mobile video traffic share [42]

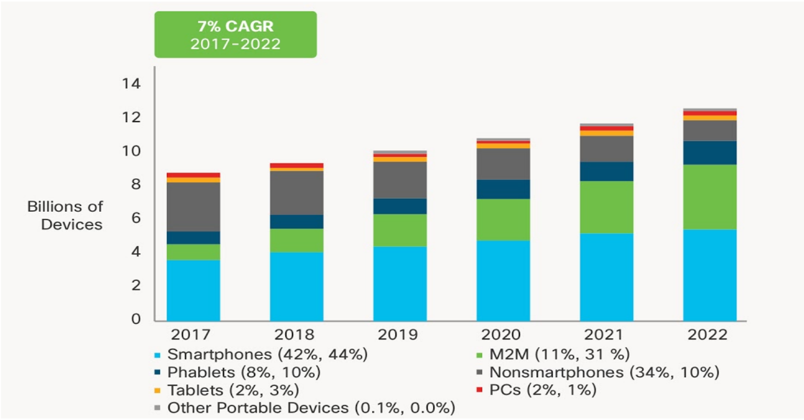


Figure 5.2: Global mobile devices and connections growth [43]

from the green IP network in Chapter 4 to the green content network, this chapter provides an eco-friendly content caching and forwarding strategy in NDN using renewable energy.

5.2 PRELIMINARIES

This section provides a description of several terminologies to describe the eco-friendly NDN content routing, referred to as GreenCR.

5.2.1 *Terminology*

Several terminologies necessary for describing a GreenCR are defined as follows:

Green Node (GN)
An GN indicates an NDN node designated by the green node selection algorithm. The role of GNs is to compute the green

path considering the greenness of nodes in the path and share this green path with the neighboring nodes.

Associated Green Node (aGN)
An aGN indicates a neighboring node of GN.

Green Path (GP)
A green path is a special path configured from the GN to all destination nodes according to the greenness of the nodes in the network.

Associated Green Path (aGP)
The associated green path is a special path configured from the aGN to all destination nodes according to GP of GN in the network.

5.3 Problem Definition and Formulation

5.3.1 *Renewable energy impact*

The network node defined in Chapter 4 for green IP routing with renewable energy is assumed to be powered by multiple energy sources (Fig. 4.4). The NDN node in this chapter also follows this assumption.

A metric, called ***greenness***, is newly introduced to characterize the environmental impact of an NDN node. The greenness $g(i,t)$ of each node i at time t denotes the proportion of eco-friendly energy sources that can be used by node i at time t and is formally defined by

$$g(i,t) = \sum_{x \in \{s,w,f\}} \frac{\big(1 - \hat{v}_x(i)\big)\tilde{e}_x(i,t)}{P(i)} \tag{5.1}$$

where, $\tilde{e}_x(i,t)$ denotes the actual energy consumed by node i from energy source x at time t and $P(i)$ denotes the total energy required by NDN node i and is equal to $\sum_{x \in \{s,w,f\}} \tilde{e}_x(i,t)$. The term $\hat{v}_x(i)$ is the normalized CO_2 emission rate per energy source $x \in \{$**s**olar, **w**ind and **f**ossil$\}$ at NDN node i, as defined in Table 4.2. If an NDN node can be powered by eco-friendly energy source, then $g(i,t) \rightarrow 1$.

Note that the metric to measure energy impact is also defined as *BoE* in Section 4.3.1 with regard to generation and environmental cost per energy source. To include an eco-friendly aspect of renewable energy, the metric *greenness* considers CO_2 emission per energy source in this chapter. In this chapter, we aim to increase the eco-friendly impact (i.e., maximize greenness), while we seek to minimize *BoE* in Chapter 4.

To consume more power from eco-friendly energy, we assume that the NDN node consumes energy with the priority of wind energy first, solar energy second and fossil energy last as $\hat{v}_w < \hat{v}_s < \hat{v}_f$. Accordingly, each $\tilde{e}_w(i)$, $\tilde{e}_s(i)$, and $\tilde{e}_f(i)$ in a given time t is calculated as

$$\tilde{e}_w(i,t) = \begin{cases} e_w(i,t), & e_w(i,t) < P(i) \\ P(i), & e_w(i,t) \geq P(i) \end{cases} \tag{5.2}$$

$$\tilde{e}_s(i,t) = \begin{cases} e_s(i,t), & e_s(i,t) < P(i) - \tilde{e}_w(i,t) \\ P(i) - \tilde{e}_w(i,t), & e_s(i,t) \geq P(i) - \tilde{e}_w(i,t) \end{cases} \tag{5.3}$$

$$\tilde{e}_f(i,t) = \begin{cases} P(i) - \tilde{e}_w(i,t) - \tilde{e}_s(i,t), & \tilde{e}_w(i,t) + \tilde{e}_s(i,t) < P(i) \\ 0, & \tilde{e}_w(i,t) + \tilde{e}_s(i,t) = P(i) \end{cases} \tag{5.4}$$

$$0 \leq \tilde{e}_x(i,t) \leq e_x(i,t) \tag{5.5}$$

Fossil power is the default power source, and it is assumed that there is always enough energy for all demands because the potential fossil energy capacity is well over-provisioned and production can be increased as the demand increases. With such reason, $e_f(i) = P(i)$ is satisfied to support the NDN node if there is no available power from the renewable energy source.

5.3.2 *Eco-friendly NDN design problem*

A network model $G(V, L)$ and an energy consumption model, including $e(i)$ and $e(l_{ij})$ defined in Section 3.3.1, are used in this section to describe an eco-friendly NDN design problem. The power consumption of the NDN node, $e(i)$, consists of the power consumption for caching and forwarding characterized by $e^{ndn}(i)$ and power consumption needed to maintain the active status of the node characterized by $e^{act}(i)$. The power consumption of NDN node i considering multiple energy sources can be represented by

$$P(i) = e^{act}(i) + e^{ndn}(i) + \frac{1}{2}\sum_{j \in N_i} e(l_{ij}) \tag{5.6}$$

We assume that both the NDN node and the link can be a part of the green path by introducing decision variables $\alpha_i, \beta_{ij} \in \{0, 1\}$ for node and link, respectively. If the node and the link belong to the green path, α_i and β_{ij} are set to 1. Depending on the α_i and β_{ij} value, we define the eco-friendly impact of node i, $E_p(i)$, by consuming power considering multiple energy sources as

$$E_p(i) = g(i)\Big(\alpha_i(e^{act}(i) + e^{ndn}(i)) + \frac{1}{2}\sum_{j \in N_i} \beta_{ij} e(l_{ij})\Big) \tag{5.7}$$

The goal in this chapter is to configure the greenest path from the receivers to the origin servers using *greenness*. Thus, the eco-friendly NDN design problem can be formulated as

$$\textit{Maximize} \qquad \sum_{i \in V} E_p(i) \tag{5.8}$$

$$\textit{subject to} \qquad \sum_{x} \bar{e}_x(i) = P(i) \tag{5.9}$$

where, constraint 5.9 indicates the node and the link partially powered by multiple energy sources and constraints 5.2, 5.3, 5.4, and 5.5 to estimate $\tilde{e}_x(i)$ are added to Eq. 5.8. To solve this problem, a heuristic approach is developed in the subsequent section.

5.4 DESIGN OF ECO-FRIENDLY CONTENT CACHING

This chapter aims to present the eco-friendly content routing algorithm (GreenCR) in this section. The purpose of this algorithm is to minimize the environmental cost (i.e., maximize greenness) when consuming power from variable energy sources. This goal can be achieved by designating special nodes, GNs and aGNs. The role of a GN is to compute the green path considering the greenness of the nodes in the path and share this green path with the aGNs.

The algorithm can proceed by following these steps: *i*) network knowledge sharing; *ii*) green node selection; *iii*) green path evaluation; *iv*) forwarding path update.

The sample network topology referred to as '5Net' in Fig. 5.3 is used to demonstrate the design operation. The sample network consists of five NDN nodes. The link cost of each link evaluated by the distance between two nodes is also shown. Each NDN node has direct access to the name prefixes shown in Table 5.1, which also displays the origin router of each name prefix. Each node is initially configured with the name prefixes they want to advertise.

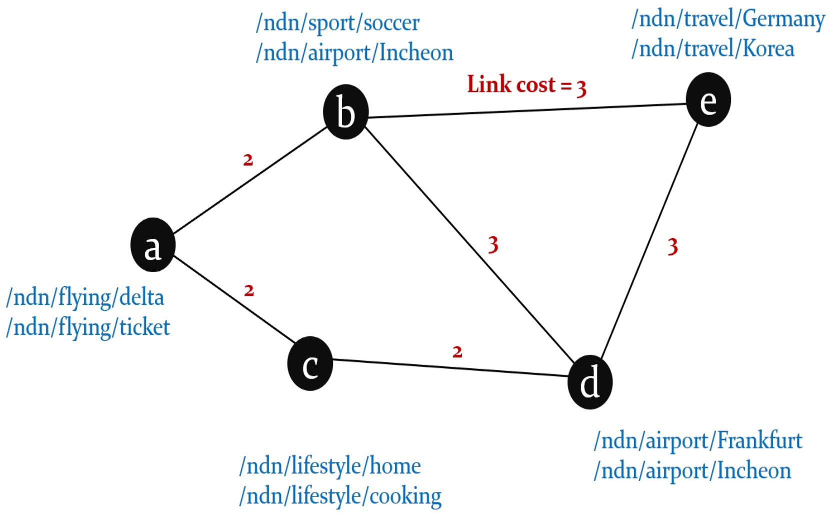


Figure 5.3: Example network topology, 5Net

Table 5.1: Name prefixes and greenness originated by each NDN node

node	Name prefixes	Greenness
node *a*	`/ndn/flying/delta` `/ndn/flying/ticket`	0.4
node *b*	`/ndn/airport/Incheon` `/ndn/sport/soccer`	0.2
node *c*	`/ndn/lifestyle/home` `/ndn/lifestyle/cooking`	0.9
node *d*	`/ndn/airport/Frankfurt` `/ndn/airport/Incheon`	0.5
node *e*	`/ndn/travel/Germany` `/ndn/travel/Korea`	0.3

5.4.1 *Network knowledge sharing*

Each NDN node can share information, including connectivity and content information, and finally gain full knowledge of the networks, thanks to link-state protocols, such as OSPFN [170] and NLSR [86] in CCN/NDN. For easy deployment, we assume that the greenness information of the NDN node is added to the Link State Advertisement (LSA) in the existing link state protocols in CCN/NDN. Table 5.2 shows the greenness information included in the content of the adjacent LSA in the NLSR.

Table 5.2: Content of an LSA

Type	**Content**
Adjacent LSA	# Active Links (N) Neighbor 1: Name, Link Cost, *Greenness*, ... Neighbor N: Name, Link Cost, *Greenness*
Prefix LSA	isValid Name Prefix

Each NDN node builds an LSA message for each name prefix in its configuration and advertises to the network according to [171]. On receiving advertisement from other nodes, each node can build a name prefix table containing the prefix names of all contents advertised in the network. Table 5.3 presents node c's name prefix table. The corresponding origin router is identified for each name prefix.

Each NDN node will then construct forwarding information base (FIB) entries for each unique name prefix in its name prefix table. In the following example, an FIB entry for node c will be constructed for the name prefix `/ndn/airport/Incheon`. First, the origin router (or routers) for the name prefix is looked up in the name prefix table. Second, the next hops to the origin routers are obtained from the routing table by the OSPF procedure shown in Table 5.4.

For a name prefix advertised by a single router, an FIB entry is constructed containing the name prefix and the next hop to the origin router. The constructed FIB entry is then inserted into the FIB. If a name prefix is advertised by multiple routers, FIB entries are constructed for each next hop to the origin routers. These FIB entries are added in the FIB in a decreasing order of the path cost to the origin routers. A higher preference is given to the lower cost paths. To find node c's next hops regarding `/ndn/airport/Incheon`, the origin router(s) of the prefix (i.e., node b and d) are first looked up in the routing table. The lower value of the link cost has a priority to be the primary path (node d in this example). In the NDN concepts that

Table 5.3: Node c's name prefix table

Name prefixes	**Advertising NDN node**
`/ndn/flying/delta`	node a
`/ndn/flying/ticket`	node a
`/ndn/airport/Incheon`	node b
`/ndn/sport/soccer`	node b
`/ndn/lifestyle/home`	node c
`/ndn/lifestyle/cooking`	node c
`/ndn/airport/Frankfurt`	node d
`/ndn/airport/Incheon`	node d
`/ndn/travel/Germany`	node e
`/ndn/travel/Korea`	node e

Table 5.4: Node c' OSPF routing table

Destination	**Next hop**	Cost
node a	node a	2
node b	node a	4
node d	node d	2
node e	node d	5

support a multipath configuration, node c can have a backup path. In our case, `/ndn/airport/Incheon` is also offered on node b, for which we find the next hop to be node a (Table 5.4). Therefore, a backup path with "next hop is node a" is entered in the FIB. Finally, a similar process is performed to obtain the next hops for the other prefixes, as summarized in Table 5.5.

5.4.2 *GN selection*

Next, we start with several procedures of how to select GNs and aGNs. It is important to decide which nodes can act as GNs due to

Table 5.5: FIB of node c

Name prefix	**Next hop**
`/ndn/airport/Incheon`	node d
`/ndn/airport/Incheon`	node a
...	...
`/ndn/travel/Germany`	node a
`/ndn/travel/Germany`	node d
...	...

the influence of the proposed algorithm to the performance. In this chapter, we consider both the availability of renewable energy sources and the environmental effect per renewable energy source as the key factors of green caching and forwarding.

In selecting GNs, each NDN node must gather information of the greenness from other NDN nodes in the network because the greenness strongly depends on the ever-changing renewable energy (i.e., per geographic location, time).

Along with the method of deciding on GNs, the ratio of GNs (referred to as R_{GN}) can also affect the performance. For instance, if more nodes are likely to be designated as GNs (i.e., $R_{GN} \rightarrow 1$), then content delivery paths tend to be established depending on green path based on greenness, rather than the classical shortest path based on the link cost. Ideally, GNs should be chosen for NDN nodes to maximize the benefit from sharing GNs' GP as much as possible under the constraint of the properties of the ever-changing renewable energy and the network topology. Considering this reason, it is a challenging and complex task. Therefore, we suppose that the value of R_{GN} is fixed and a priori given by the ISP. Our focus is to define a simple strategy to determine how to select GNs. Finally, each NDN node can decide whether an NDN node itself belongs to GN or not according to R_{GN}. Assuming $R_{GN} = 0.2$, only one node (node c) is designated as the GN in this example.

Having full knowledge of the networks (Table 5.1), each node sorts greenness information from highest to lowest.

5.4.3 *Green path evaluation*

Designated as GN, GN computes the green path to all destinations in the network with two steps described in Algorithm 10. The green path is a path that maximizes eco-friendly impact by consuming various energy sources in all intermediate nodes in the path.

Algorithm 10: Green path evaluation

Step 1:	Create green graph gG using greenness $g(i,t)$ in G
Step 2:	Evaluate green path from GNs to all destinations in gG
Step 3:	Evaluate the associated green path from the aGNs to all destinations in gG

The first step of the green path evaluation is to create a green graph (referred to as gG) based on an existing network model G in Section 5.3.2. The link cost in G indicates the distance between two adjacent nodes. The shortest path is established to minimize the path from source to destination. However, the link cost in gG needs to consider the eco-friendly aspect for the green path evaluation. Greenness, $g(i)$, is defined in Section 5.3 to evaluate the degree of how node i is powered by an eco-friendly energy source. Considering this impact, the node selects the next hop with the highest greenness value toward the destination. A new link cost in gG from nodes i to j is defined to be $1 - g(j)$, where nodes i and j are adjacent nodes connected via link l_{ij} in gG.

The second step is to evaluate green path from the GNs as described in Algorithm 11. Similar with the existing Dijkstra algorithm used to compute the shortest path, the green path is computed to find the greenest path from the GN to all destinations in a heuristic manner. It consists of the following steps:

1. Initialization of the green node $g \in \mathbb{GN}$ with green cost zero
2. Initialization of the green cost from node g to all nodes not belonging to $\mathbb{GN}$ with infinite; initialization of a set of unvisited nodes, S with empty; including all nodes in gG to a set node, Q, by marking all nodes unvisited.
3. Marking of the green cost of the starting node as permanent and all other green costs as temporary
4. (While Q is not empty) Selecting the element of Q with the minimum green cost value from node g (node u in Algorithm 11)

5. Calculation of the temporary green cost of all neighbor nodes of node u by summing up its green cost with the link cost from nodes u to v
6. If such a calculated green cost of a node is smaller as the current one, update the green cost and set the current node as an intermediate node of the green path
7. Setting of the node with the minimal green cost as active and marking its green cost as permanent
8. Repeating steps 5 to 7 until no nodes are left with a permanent green cost; the neighbors still have a temporary green cost

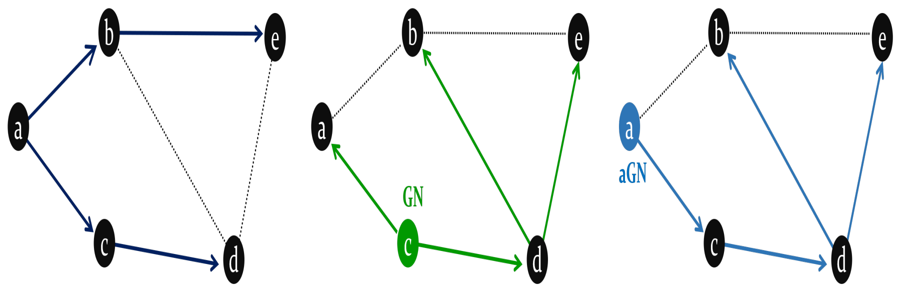
Algorithm 11: Green path evaluation procedure

```
gCost[g ∈ GN] ← 0 ;
forall v ∈ V − {g} do
    gCost[v] ← ∞ ;
    S ← ∅ ;
    Q ← V ;
    while Q ≠ ∅ do
        u ← mingCost(Q, gCost) ;
        S ← S ∪ {u} ;
        forall v ∈ neighbors[u] do
            if gCost[v] > gCost[u] + gCost(u, v) then
                gCost[v] ← gCost[u] + gCost(u, v) ;
            end
        end
    end
end
```

In establishing the green path of GNs, the final step is estimate the associated green path from the aGNs, the neighbor nodes of GNs. aGNs already have a delivery path according to the link cost to all destinations in G. However, selected as aGNs, aGNs must update the delivery path to benefit from the eco-friendly impact of the green path. Therefore, aGN sets the corresponding GN to the next hop for all destinations and follows the green path of GN.

Figure 5.4 shows an example of the green path evaluation. In this example, node c is selected as the GN. Accordingly, the neighbors of node c, namely nodes a and d, are designated as the aGN. All nodes, except for the GN, evaluate their shortest path to all destinations. Figure 5.4a depicts the shortest path of node a. As a GN, node c computes the green path to all destinations according to Algorithm 11.

The green path of node b is then calculated (Fig. 5.4b), and node a as the aGN updates the path tree using the green path of node c (Fig. 5.4c).



(a) Shortest path computed by node a (aGN).

(b) GP computed by node c (GN).

(c) aGP of node a (aGN).

Figure 5.4: Green path evaluation procedures

5.4.4 *Forwarding path update*

Each NDN node maintains an FIB to determine which interface the interest packet is forwarded based on the shortest path. For instance, if the content of the name prefix `/ndn/travel/Germany` is stored in node e, the corresponding next hop was node b according to the FIB in node a. On updating the path tree, node a updates its FIB according to the associated green path (Table 5.6), and node c becomes the new next hop of the primary path for a given name prefix. The former next hop, node b, remains as an alternative path for further usage.

Table 5.6: Forwarding information base at node a

Name prefix	**Next hop**	**Cost**	
`ndn/travel/Germany`	udp4://etho.C.com (node c)	7	Primary (green path)
`ndn/travel/Germany`	udp4://eth1.B.com (node b)	5	Alternative (shortest path)
...	...	...	

5.5 PERFORMANCE EVALUATION

5.5.1 *Experimental setup*

We evaluated the performance of the eco-friendly green caching and forwarding strategy presented above using ICARUS [156], a Python-based discrete-event simulator based on the *fast network simulation setup (FNSS)* and the *Networkx* toolchain [56, 138, 154]. ICARUS is designed for evaluating the performance of caching and routing strategies and caching policies.

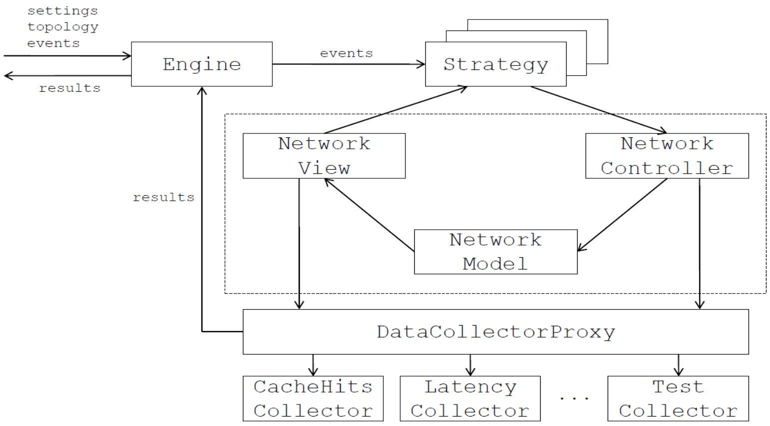
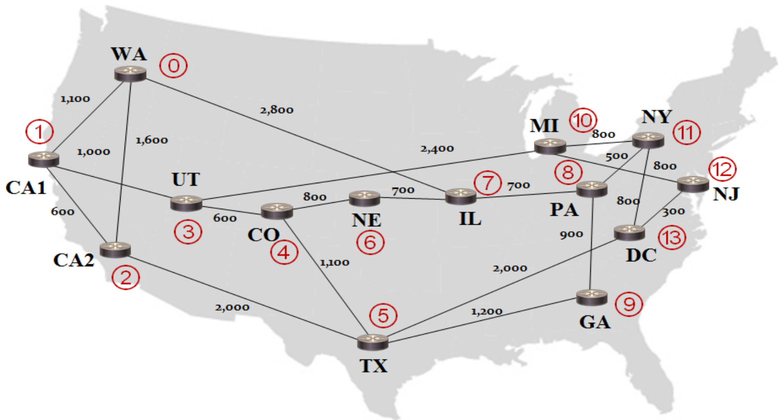


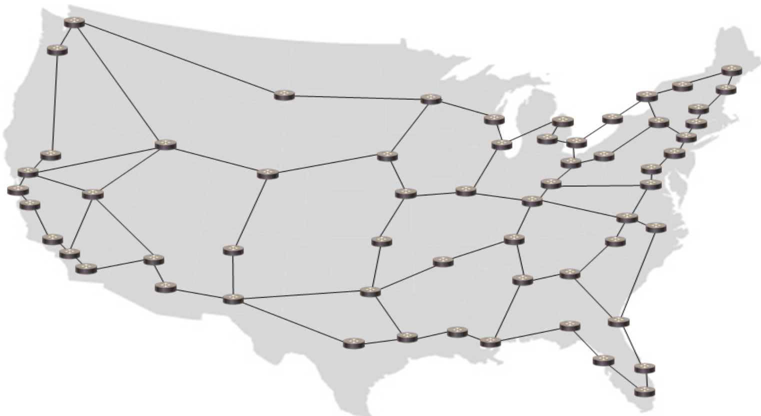
Figure 5.5: ICARUS simulator framework [156]

Simulations were conducted on two real US topologies to achieve more attainable results: NSFNET [124] already used in Chapters 3 and 4 and CORONET (Defense Advanced Research Project Agency (DARPA) Core Optical Networks) [157].

We also used real weather datasets considering the geographical location of nodes in the topology from the National Solar Radiation Data Base available in [134] to estimate the available power generation. NDN nodes were previously assigned with constant cache sizes. Content requests were modeled as Poisson processes, while content popularity was modeled with a Zipf distribution with the skewness parameter τ. The content popularity model is a function that establishes the popularity of every piece of content (i.e., how frequently every single piece of content is going to be requested). The content popularity is commonly modeled with a probability distribution function, such as a Zipf [5]. In the literature, the τ parameter ranges roughly between 0.6 and 2.5 [21]. We set τ to be between 0.6 and 1.2 according to [155] in this simulation. All caching schemes were evaluated assuming that the contents are evicted according to a Least Recently Used (LRU) policy. Table 5.7 summarizes all chosen parameters for the simulation.



(a) NSFNET with actual distance (km).



(b) CORONET.

Figure 5.6: Network topologies in the US

The network cache size denoted as C means the cumulative size of the network caches as a fraction of the total content population.

Comparing GreenCR with the state-of-the-art content caching strategies, we chose the leave copy everywhere (*LCE*) [92], probabilistic in-network caching (*ProbCache*) [144] and asymmetric hash routing (*AssymHR*) [155] schemes as examples of on-path and off-path caching strategies. Each strategy is briefly described as below:

- *Leave copy everywhere* (LCE): default caching and forwarding strategy in the CCN based on the shortest path. Every node stores a copy of every data message that has passed by it
- *Probabilistic in-network caching* (ProbCache): a probabilistic algorithm for distributed content caching along a path of caches. ProbCache selects the best node to cache the content in a path of caches. It pretends to leave a caching space for other flows and fairly distribute content through a shared path

Table 5.7: Simulation settings

Index	Value
Ratio of GN (R_{GN})	0.2
Content popularity skewness (μ)	$0.6, 0.8, 1.0, 1.2$
Network cache size (C)	$0.01, 0.05$
Number of contents	10^4
Number of requests	3×10^6
Cache update policy	LRU (Least Recently Used)
Topologies	NSFNET, CORONET
Strategies	*LCE, GreenCR, ProbCache, AsymmHR*

- *Asymmetric hash routing*: an asymmetric algorithm to forward interest packets according to the hashing function. Content is delivered not through the reverse path of interest packet, but through the shortest path from the source to the requesting client as the forward and return paths are asymmetric.

5.5.2 *Results*

5.5.2.1 *Preliminary results: green path vs. shortest path*

According to Algorithm 11, the green path is established based on the value of the greenness of network nodes rather than the distance-based link cost. Figure 5.7 illustrates the problem discussed herein regarding the green path compared with the traditional shortest path in NDN. Under the given conditions, node a as a receiver sends the request packet to the origin server, node e. The shortest path is then established as $\{a, b, e\}$, and its corresponding cost is 5. However, the green path is established as $\{a, c, d, e\}$, which is one hop longer than the shortest path, and its link cost is 7. This is inefficient in IP packet routing, which causes a longer delay and a lower throughput.

The preliminary result of comparison between the green path and the shortest path was performed using a simple 5Net topology to investigate the feasibility of whether a given green path is efficient in NDN. Figure 5.8 shows the average traffic load in the network, average delay, and cache hit ratio. According to [21, 190], the NDN

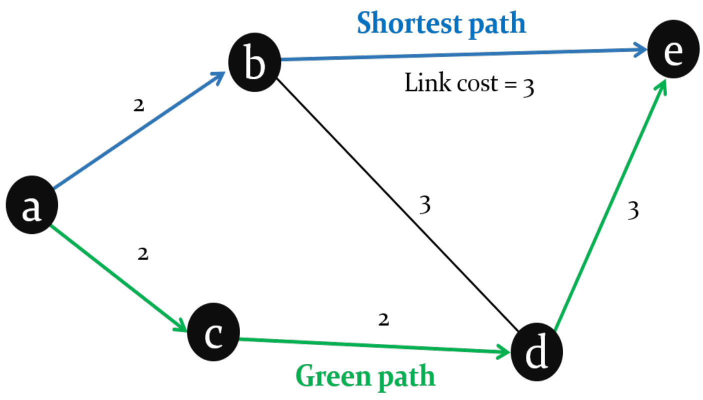


Figure 5.7: Question from the green path and the shortest path

performance is strongly dependent on the network topology. Even though 5Net used in this comparison was not sufficient to describe the performance of both paths, the green path seems to have similar a performance with an acceptable difference.

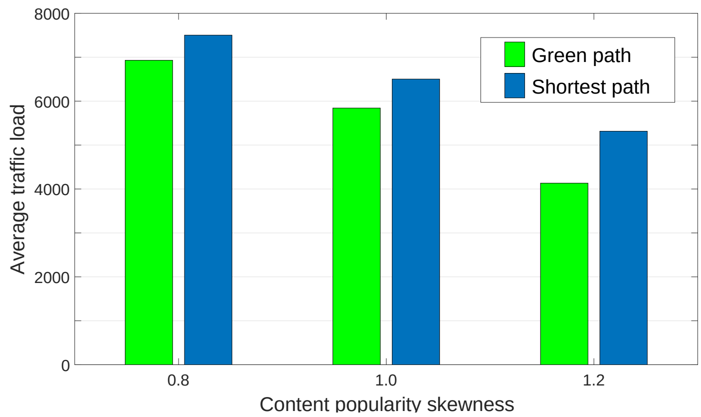
The average link load is one of the main performance indices caused by the functionality of in-networking caching in the intermediate nodes between source and receiver. The green path shows less average link load than the shortest path in a given topology (Fig. 5.8a). The actual information on the traffic load between nodes imposed during simulation is illustrated in Tables 5.8 and 5.9.

Table 5.8: Actual traffic load per link ($\tau = 1.0$)

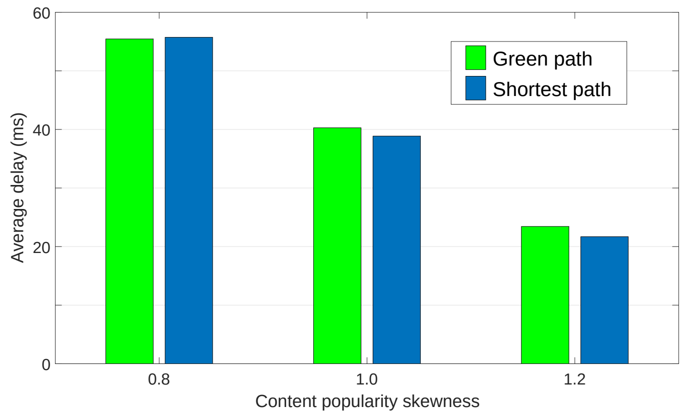
Link	**Traffic load**	
node $a \leftrightarrow$ node b	16,800	shortest path
node $b \leftrightarrow$ node e	9,270	
node $a \leftrightarrow$ node c	16,520	green path
node $c \leftrightarrow$ node d	9,358	
node $d \leftrightarrow$ node e	9,177	

Table 5.9: Average link load ($\tau = 1.0$)

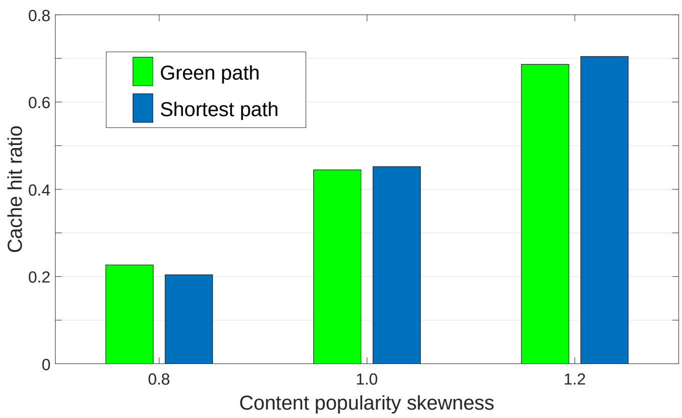
Link	**Total link load**	**# of links**	**Avg. link load**
Shortest path	26,070	2*2	6,501.75
Green path	35,055	3*2	5,842.50



(a) Average link loads.



(b) Average delay.



(c) Cache hit ratio.

Figure 5.8: Comparison between green path and shortest path

As another concern for the performance index, both paths had a similar behavior on the average delay and propagation delay in this example (Fig. 5.8b). Due to the topology deficiency, even though it was unclear which path was superior, the green path with one more hop is expected to have critical inferiority. This issue will be discussed with more realistic network topologies in the next subsection.

Lastly, the cache hit ratio as the most critical index in NDN, was measured during the simulation. Table 5.10 presents the cache hit ratio of each node per path. The cache hit ratios of the shortest path and the green path were calculated as 0.452 and 0.4445, respectively. A slight difference between the two paths is found in Fig. 5.8c due to the topological restriction of 5Net.

Table 5.10: Cache hit ratio ($\tau = 1.0$)

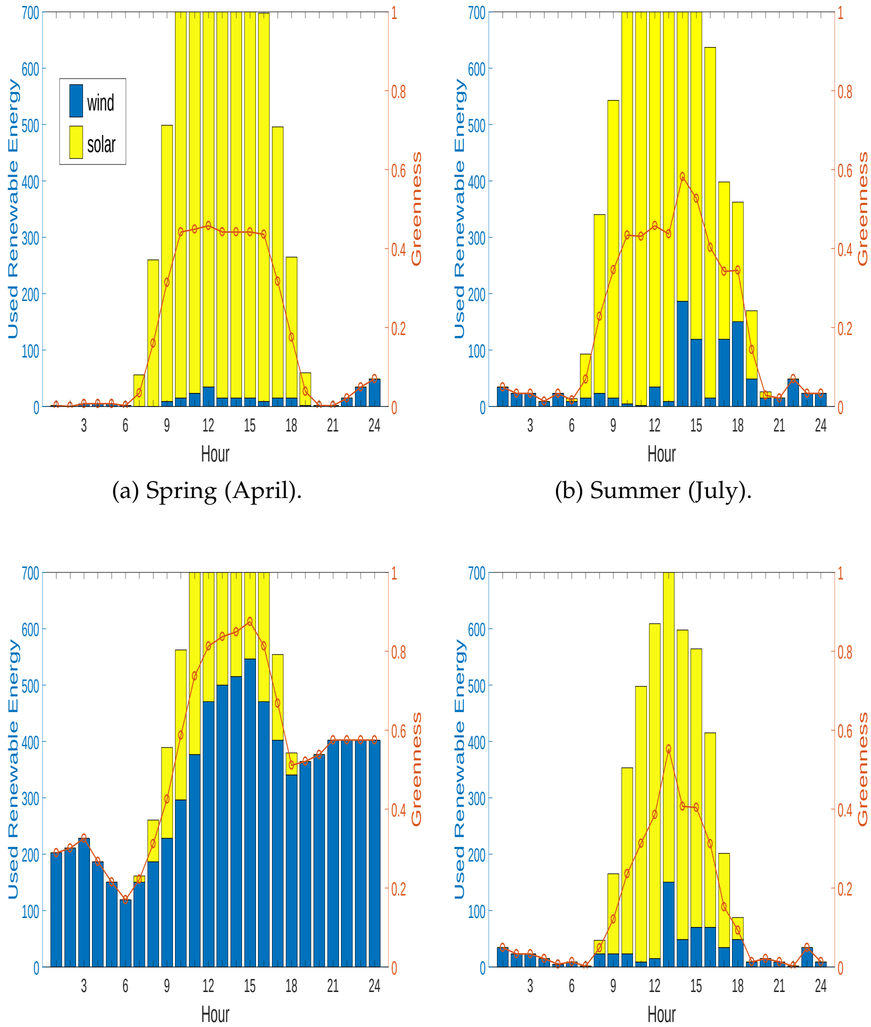
Path	**node** a	**node** b	**node** c	**node** d	**node** e
shortest path	-	0.452	0	0	0.548
green path	-	0	0.4335	0.0111	0.5555

The comparison of the green path and the shortest path was analyzed using a simple topology. The preliminary results showed that the green path, which has one more hop between the source and receiver and expected to have a longer latency, has no critical defect from a performance perspective.

5.5.2.2 *Impact of renewable energy*

First, we investigated how renewable energies from wind turbines and solar panels can influence the value of greenness. As discussed in Section 4.1, the available renewable energy is strongly dependent on the time period and geographical location. Figure 5.9 summarizes the seasonal results obtained at node 5 located in Texas, where there is abundant sunshine in the daytime hours and strong winds, especially in fall. According to Table 4.2, wind is the cleanest energy source. The larger the amount of wind power available, the more the node can achieve higher greenness with lower CO_2 emissions. This explains why the greenness of node 5 tends to reach higher values, especially in fall compared with other seasons.

Second, we measured the frequency count of GN and aGN selected in NSFNET during a 24h period per season (Fig. 5.11). According to the geographic location of nodes, a node and its neighboring node tend to generate a similar amount of power from renewable energy. Nodes 10 (Michigan), 11 (New York), and 12 (New Jersey) located in the east area of the US are frequently selected as the GN due to the ample amount of available renewable energy compared with other nodes. Even though node 13 is close to nodes 11 and 12, it does not belong to the GN due to R_{GN}. Node 13, as a neighboring node of GN,



(a) Spring (April).

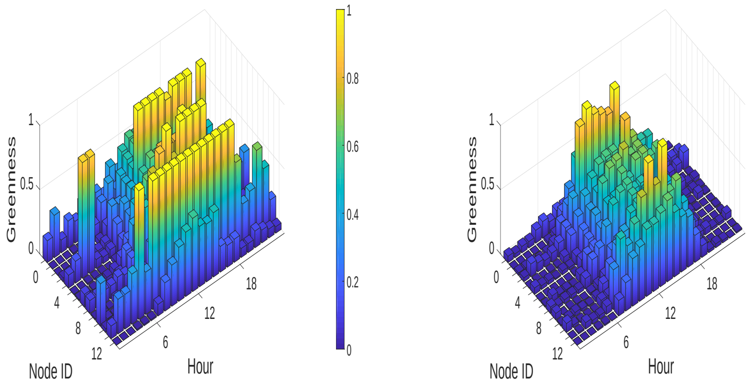
(b) Summer (July).

(c) Fall (November).

(d) Winter (January).

Figure 5.9: Used renewable energy and *greenness* of node 5 in Texas

can serve as an aGN with a higher frequency and consume renewable energy for caching and forwarding.



(a) Spring (April).

(b) Summer (July).

(c) Fall (November).

(d) Winter (January).

Figure 5.10: *Greenness* distribution

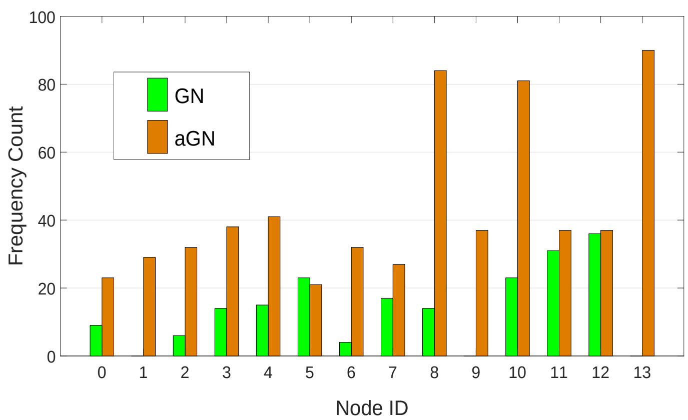


Figure 5.11: Numbers of GN and aGN

The number of GN and aGN can also affect the green path's performance. Table 5.11 shows the configuration of GNs and aGNs in the NSFNET during spring's daytime when most nodes can have power from renewable energy. Figure 5.12 illustrates the number of GNs and aGN after configuration.

Table 5.11: GNs and aGNs according to R_{GN} in NSFNET

R_{GN}	*GNs*	*aGNs*
0.1	*node 12*	*node 10, 13*
0.2	*node 12, 8, 7*	*node 10, 13, 11, 9, 6*
0.3	*node 12, 8, 7, 6*	*node 10, 13, 11, 9, 4*
0.4	*node 12, 8, 7, 6, 5, 4*	*node 10, 13, 11, 9, 3*
0.5	*node 12, 8, 7, 6, 5, 4, 2*	*node 10, 13, 11, 9, 3, 1*
0.6	*node 12, 8, 7, 6, 5, 4, 2, 3*	*node 10, 13, 11, 9, 1*
0.7	*node 12, 8, 7, 6, 5, 4, 2, 3, 13, 9*	*node 10, 11, 1*
0.8	*node 12, 8, 7, 6, 5, 4, 2, 3, 13, 9, 0*	*node 10, 11, 1*
0.9	*node 12, 8, 7, 6, 5, 4, 2, 3, 13, 9, 0, 10, 1*	*node 11*
1.0	*All nodes*	*None*

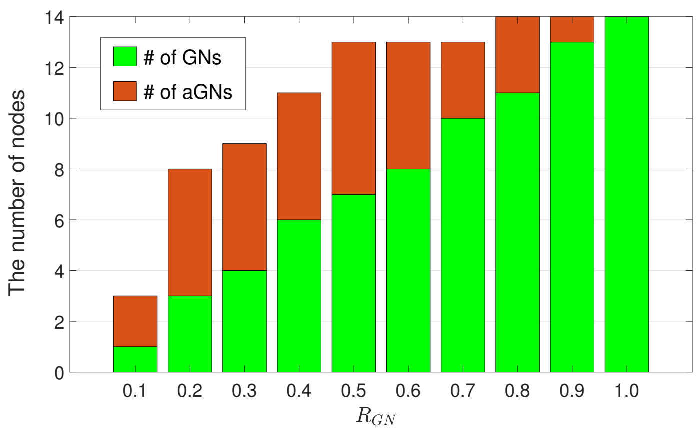


Figure 5.12: The number of GN and aGN according to R_{GN}

According to R_{GN}, which is assumed to be given by ISP, as described in Section 5.4.2, the GNs and corresponding aGNs are designated. Generally, the number of GNs is proportional to the increment of R_{GN}. However, the number of aGNs depends on the designated GNs and the node's location in the topology. For example, node 6 (neighboring node of node 7) (Fig. 5.6a), is designated as aGN when R_{GN}=0.2 and GN when R_{GN}=0.3. Then, node 4 (neighboring node of node 6) is designated as a new aGN. Because of this topological reason, the number of aGNs keeps increasing until R_{GN}=0.5 and then decreases in the NSFNET.

5.5.2.3 *Cache hit ratio and latency*

The cache hit ratio is an important performance index in NDN evaluated as follows:

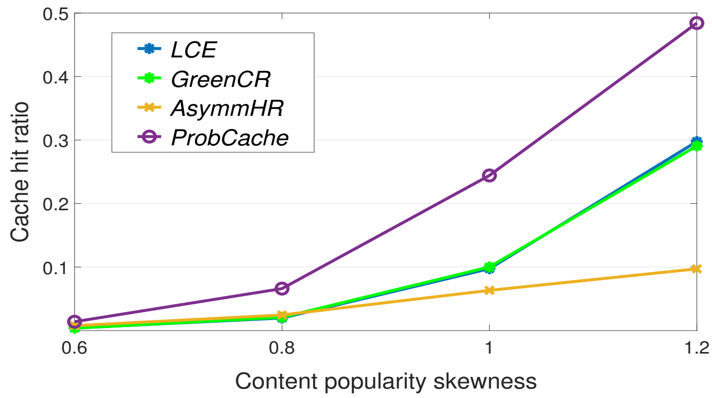
$$H = \sum_{i \in V | i \neq s} h_i = 1 - h_s \tag{5.10}$$

where, h_i is the cache hit ratio of node i in the path from the receiver to the origin server, and h_s is the cache hit ratio of the origin server. A higher cache hit ratio suggests that more content requests are served from intermediate caches, consequently reducing the load on the origin server.

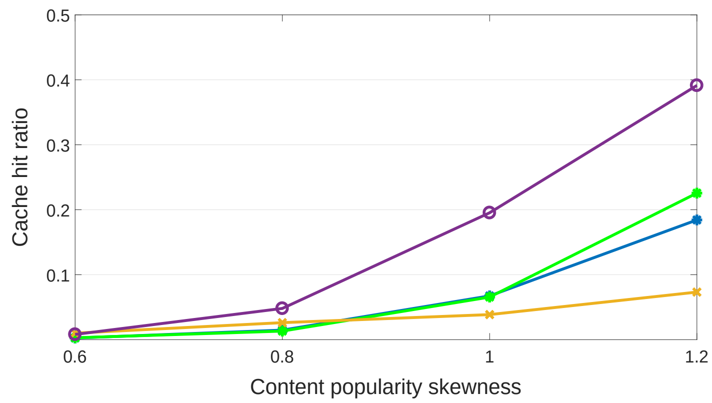
Figure 5.13 shows the cache hit ratio against the τ variations in both topologies with C=0.01. As seen from Fig. 5.13 and as somewhat expected, on-path caching schemes (i.e., *ProbeCache*, *GreenCR*, and *LCE*) outperform the off-path one (i.e., *AsymmHR*). This is caused by the limited amount of cacheable traffic traversing some cache nodes in *AsymmHR*, whose effects become more severe as the cache size and content distribution skewness increase. Although the proposed *GreenCR* scheme was originally designed to follow both the green path and the shortest path, instead of the shortest path as used in the *LCE*, both schemes showed a similar cache hit ratio. Such behavior was caused by the network topology. The performance difference between these two schemes increased as the network topology became more complex, and more renewable energy is available.

The cache size also affects the cache hit ratio (Fig. 5.14) under τ=1 and CORONET topology. The more cache space a node has, the more cache hit ratio is increased as expected. The *Green* scheme had a similar result to the *LCE*.

Latency is also one of the key indices for the NDN performance. NDN is usually expected to reduce latency because more contents are cached in the intermediate nodes. Figure 5.15 demonstrates the latency results for different schemes for both topologies with C=0.01. In spite of a similar cache hit ratio, our proposed *GreenCR* scheme has more latency compared to the *LCE* in NSFNET. This behavior was caused



(a) NSFNET.



(b) CORONET.

Figure 5.13: Cache hit ratio vs topology

by the differences in how the content delivery paths were configured (Fig. 5.16 and Table 5.12).

Table 5.12: Comparison between green path vs shortest path in NSFNET

Type	**Path**	**Distance**
Shortest path	(4) → (6) → (7) → (8) → (11)	2700km
Green path	(4) → (5) → (13) → (11)	3900km

During the simulation, the green path was configured with fewer links, but a longer distance from the receiver to the origin server. In the case of CORONET, the *GreenCR* latency was almost similar and less when $\tau > 1$. Figure 5.13b and Fig. 5.15b depict that the contents are more cached in the green path with less distance than the shortest path.

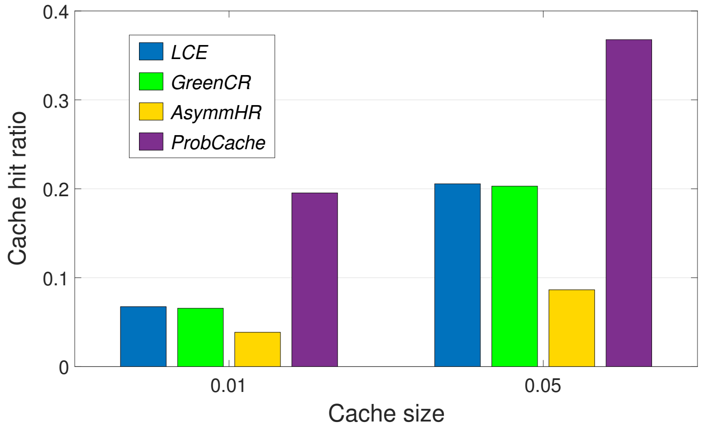
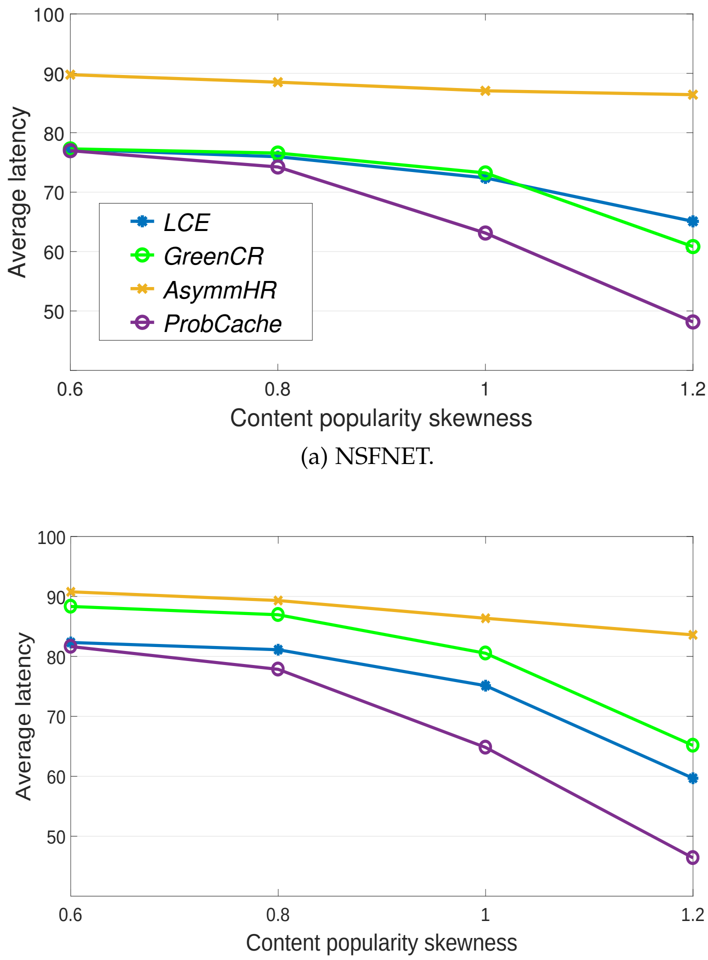


Figure 5.14: Cache hit ratio vs. cache size



(a) NSFNET.

(b) CORONET.

Figure 5.15: Latency vs. topology

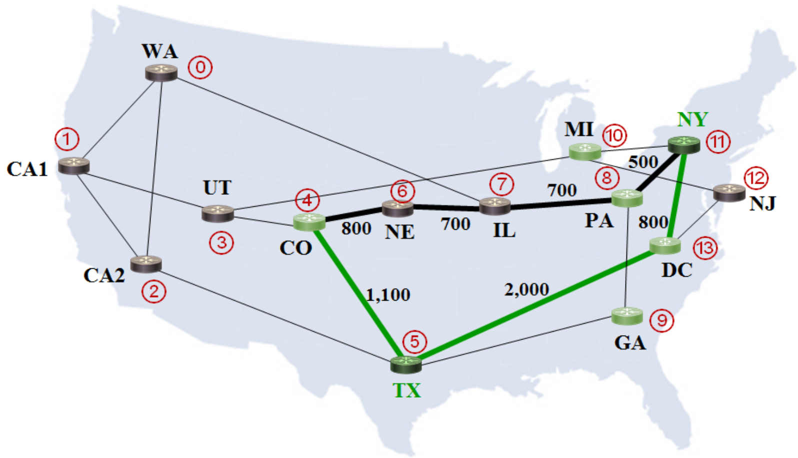


Figure 5.16: Green path and shortest path in NSFNET

5.5.2.4 *Green cache hit ratio*

The general performance indices in NDN (e.g., traffic load, latency, and cache hit ratio) were measured and discussed. As described in Section 5.4, the objective of the green caching and forwarding schemes was to encourage traffic into the paths with greener nodes. Consequently, more eco-friendly renewable energy can power the nodes in caching and fetching contents. The simulation results discussed so far prove that the proposed scheme shows neither a strong supremacy nor a critical deficiency compared with other strategies. We now focus more on a new index with a strong dependency on the node greenness.

For the greenness evaluation, we imbued the existing cache hit ratio with the meaning of greenness and introduced a new performance index, that is, *green hit ratio* (H_g), as follows:

$$H_g = \sum_{i \in V | i \neq s} g_i(t) h_i \tag{5.11}$$

where, h_i is the cache ratio of node i in the path from receiver r to the origin server s, and h_s is the cache hit ratio of the origin server. H_g implies how the contents are likely to be cached and serviced at the nodes in the green paths.

This index is derived from the cache hit ratio (Table 5.10) and corresponding greenness value (Table 5.13). Figure 5.17 shows a comparison of the green cache hit ratios between the green path and the shortest path as a result obtained from Section 5.5.2.1.

In this example, node c in the green path shows higher cache hit ratio and greenness of the node and results in a higher green cache

Table 5.13: Greenness of nodes in 5Net

node *a*	node *b*	node *c*	node *d*	node *e*
0.4	0.2	0.9	0.5	0.3

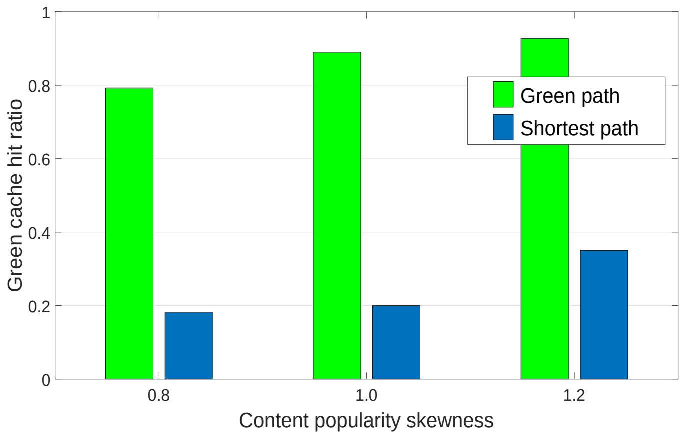


Figure 5.17: Green cache hit ratio: green path vs shortest path

hit ratio. Unlike other results in Section 5.5.2.1, the green path has a strong superiority as regards the green cache hit ratio. More contents are expected to be cached and serviced at the green path nodes.

Extending to general topologies, from the average green cache hit ratio (Fig. 5.18) and min and max values (Table 5.14 and Table 5.15), we conclude that the *GreenCR* scheme performed best among the existing strategies in both topologies. According to the node where and when contents are served, the available renewable energy of the node changes, and this behavior brings differences in this performance index. For instance, the green cache hit ratio is calculated as zero if the node is served with a higher ratio without power from the renewable energy sources. As a greener solution in NDN, the proposed scheme encourages more contents to be cached in the green path by consuming more eco-friendly power in the nodes.

Table 5.14: Green hit ratio vs strategies in NSFNET

	LCE	GreenCR	*AsymmHR*	*ProbCache*
Min.	0.002	0	0.015	0.006
Max.	0.364	0.482	0.147	0.392

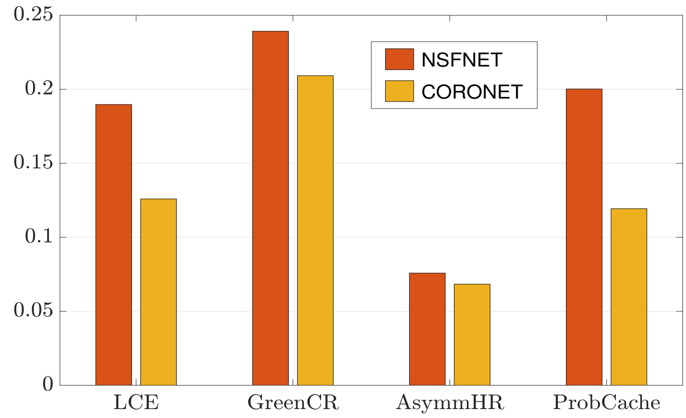


Figure 5.18: Green cache hit ratio vs strategies

Table 5.15: Green hit ratio vs strategies in CORONET

	LCE	GreenCR	*AsymmHR*	*ProbCache*
Min.	0.002	0.036	0.018	0
Max.	0.261	0.391	0.118	0.254

Figure 5.19 illustrates the green cache hit ratio in both topologies according to the increment of R_{GN}. The green cache hit ratio in both topologies increases as more GN and aGN involve the green path establishment. However, the behavior between the number of GN and aGN and green cache cache hit ratio is not always proportional.

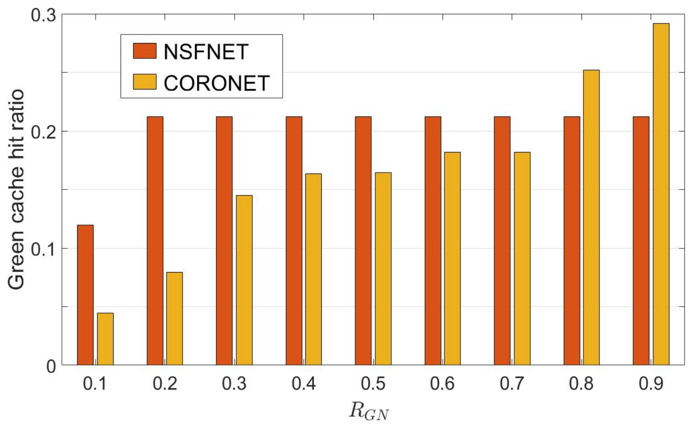


Figure 5.19: Green cache hit ratio vs R_{GN}

To achieve higher green cache hit ratio, nodes must have enough power from renewable energy source and store contents to be served. Moreover, GN and aGN belong to the intermediate nodes of content delivery path from receivers to origin servers. Otherwise, the green path is established regardless of content delivery path leading to lower content cache hit ratio. The green cache hit ratio in NSFNET keeps increasing until R_{GN} = 0.2 as designated GNs and corresponding aGNs involve in the content delivery path. No additional benefit from renewable energy is expected after R_{GN} = 0.2 as GNs and aGNs are designated regardless of content delivery path. However, in CORONET more complicated network topology than NSFNET, the green cache hit ratio increases steadily because more nodes have an opportunity to be newly designated as either GN or aGN and involve in green path.

In conclusion, several main observations can be drawn from these results. First, the NDN performance is strongly dependent on environmental factors, such as the network topology complexity, cache size, content popularity skewness, and the location of receiver and origin server. For NDN provisioning, these should be carefully considered to take advantage of the paradigm shift for what NDN was designed for. Second, intending to maximize the usage of eco-friendly renewable energy, the proposed scheme outperformed others in the green hit ratio regardless of the environment. Lastly, as a trade-off, we found some performance degradation of the proposed scheme compared with the superior scheme *ProbCache*, which was initially designed to fairly optimize and multiplex content. This provides a clue on the enhancement of the proposed *GreenCR* strategy to increase not only the green hit ratio but also the cache hit ratio for further discussion.

5.5.2.5 *Transition analysis*

As explained above, the performance of the proposed *GreenCR* strategy is strongly dependent on the available renewable energy. It is impossible to expect a green performance without enough sunshine and wind. In addition, topology information, including the location of origin servers, receivers, and corresponding intermediate nodes and corresponding weather information can affect the cache hit ratio and green cache hit ratio as demonstrated in [172]. Consequently, it is important to investigate when the delivery path needs to be switched among multiple paths to maximize the NDN performance.

The cache hit ratio is the most significant factor in the NDN evaluation. Even though other performance showed good outcomes, they were not acceptable if a serious degradation of the cache hit ratio is found. Figure 5.20 shows a comparison of the strategies with regard to the cache hit and green cache hit ratios in the given simulation environments. As described in the previous section, the on-path caching schemes (i.e., *LCE, GreenCR, ProbCache*) outperformed the off-path caching scheme (i.e., *AsymmHR*) in both hit ratios. Thus, *AsymmHR* was excluded from the transition analysis. We then commenced the

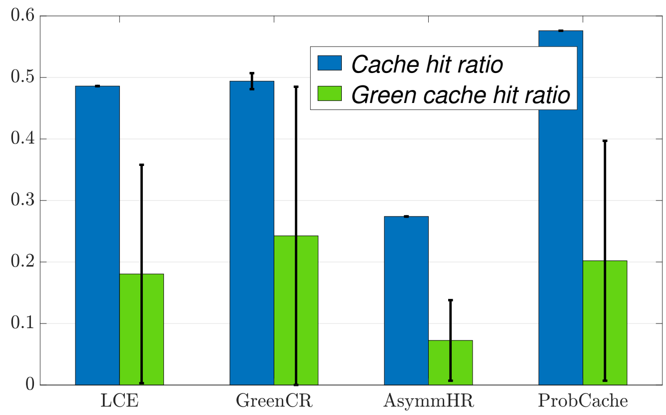


Figure 5.20: Comparison between on-path caching and off-path caching in NSFNET

transition analysis to investigate which strategy showed a better performance under which condition. First, we set the *GreenCR* strategy to the basic scheme and compared it with other single strategies.

Case I: *GreenCR vs LCE*

In this case, the candidate strategies show similar cache hit ratios (i.e., the difference is acceptable), but differ in the aspect of the green cache hit ratio. The comparison between *Green* and *LCE* belongs to this case (Figs. 5.8c and 5.17, Table 5.16).

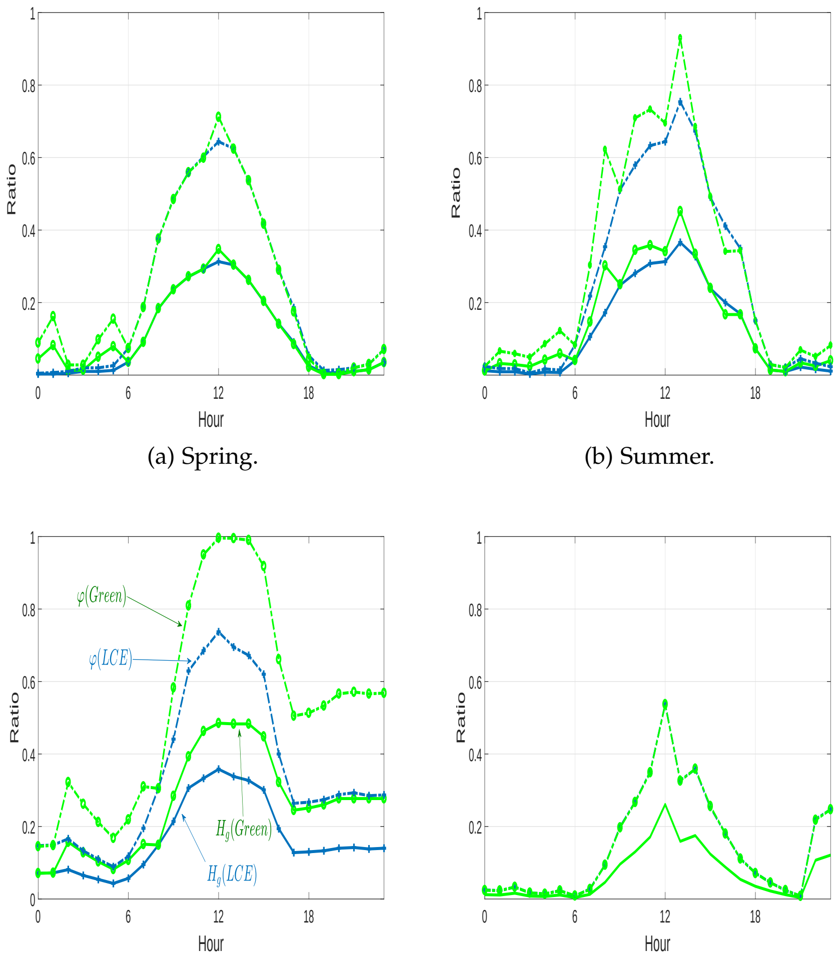
Table 5.16: Comparison between *Green* and *LCE* in NSFNET

Index	***LCE***	***Green***
Cache hit ratio	0.486	0.481 - 0.507
Green cache hit ratio	0.003 - 0.358	0.002 - 0.483

Drawing a decision on which strategy outperforms is more complex because both indices are crucial to the performance, and the available renewable energy is ever changing. We now introduce an incidental factor, φ, measuring *'the green quality'* of the serving node:

$$\varphi = \frac{H_g}{H} \tag{5.12}$$

$\varphi \to 1$ (i.e., $H \approx H_g$) indicates that the content requests are likely to be cached at the green nodes in the green path. In this context, the green nodes are fully supported by power from the wind turbines (i.e., $g_i \to 1$).



(a) Spring. (b) Summer.

(c) Fall. (d) Winter.

Figure 5.21: Green cache hit ratio (H_g) and green quality (φ)

Figure 5.21 illustrates the relationship between the green cache hit ratio and the corresponding green quality according to the change of time and season. The quality of the path (φ) of the two strategies showed similar patterns, especially in spring and winter, due to the limited renewable energy resources. However, *Green* showed more dynamic patterns and outperformed the other in summer and fall. Consequently, a greener path was established to increase the delivery path quality. With more focus on fall, Fig. 5.22 showed the dynamic change of the quality for the two strategies. The blue box (between 12:00 and 14:00) indicates the ideal situation where the content requests are served at intermediate green nodes (i.e., $g_i \approx 1$) in the green path. Finally, the content delivery path was selected by comparing φ_{Green} with φ_{LCE}.

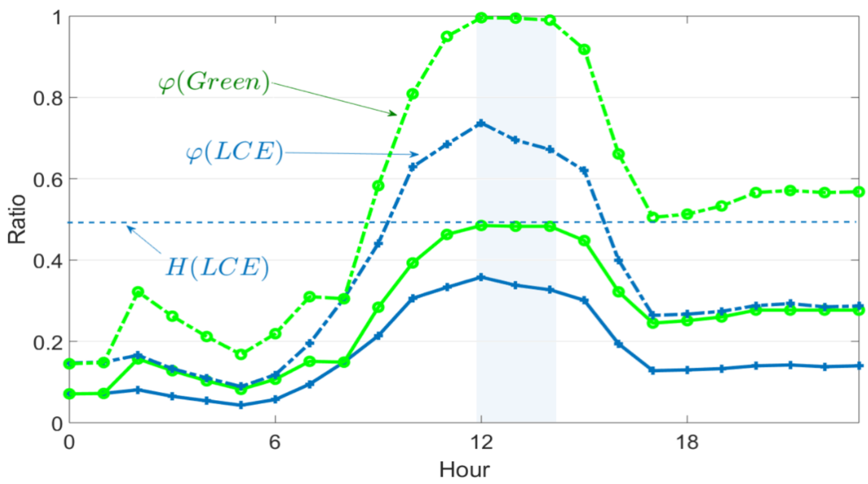


Figure 5.22: Green cache hit ratio vs strategies

***Case II:** GreenCR vs ProbCache*

The second case shows a different cache hit ratio (i.e., the difference is somewhat unacceptable) and a different green cache hit ratio. The comparison between *GreenCR* and *LCE* belongs to this case (Figs. 5.8c and 5.17, Table 5.17).

Table 5.17: Comparison between *GreenCR* and *ProbCache* in NSFNET

Index	***GreenCR***	***ProbCache***
Cache hit ratio	0.481 - 0.507	0.576
Green cache hit ratio	0.002 - 0.483	0.007 - 0.397

We introduced the weighting factor μ to compare both strategies, putting more emphasis on either cache hit ratio or green cache hit ratio:

$$\Phi = \mu H_g + (1-\mu)H \qquad 0 \leq \mu \leq 1 \tag{5.13}$$

$\mu \to 1$ indicates that the green cache hit ratio (H_g) was more considerable, while $\mu \to 0$ means that more emphasis on the cache hit ratio was imposed to decide on the superior strategy.

Figure 5.23 and Table 5.18 present the simulation results. Table 5.19 summarizes the time frequency when $\Phi_{GreenCR} > \Phi_{ProbCache}$. The *GreenCR* strategy outperformed the *ProbCache* strategy during few hours in spring and fall and was inferior to it in winter. Figure 5.24 shows the difference between two content routing strategies, especially in fall season. The weather information showed that even though the green path was established according to the node greenness, some nodes in the path from *ProbCache* resulted in a higher hit ratio and a green cache hit ratio.

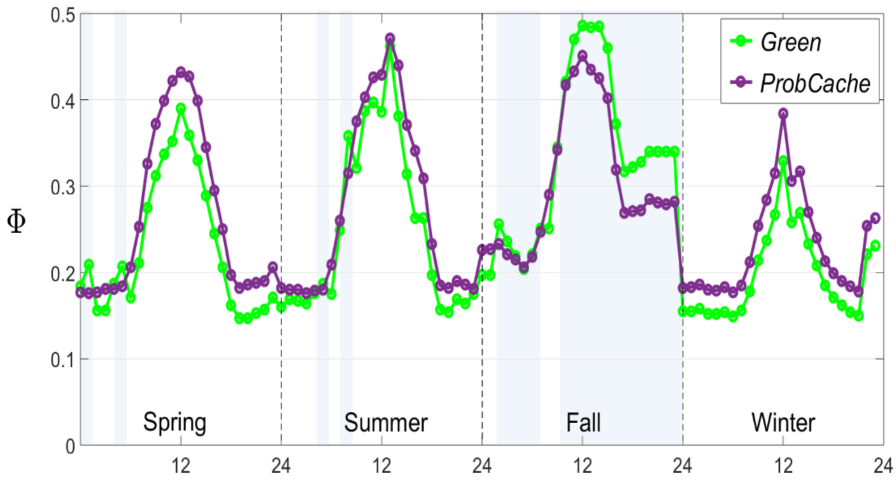


Figure 5.23: Comparison between $\Phi_{GreenCR}$ and $\Phi_{ProbCache}$ (μ = 0.7)

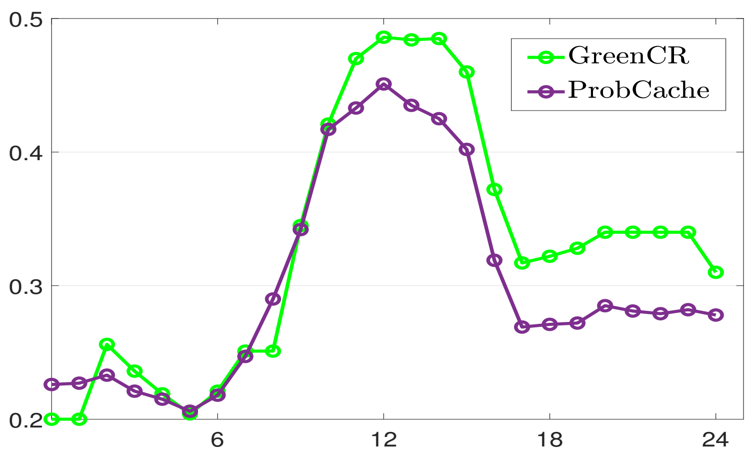


Figure 5.24: Comparison between $\Phi_{GreenCR}$ and $\Phi_{ProbCache}$ in fall (μ = 0.7)

Figure 5.25 shows the results for investigating the seasonal effects with regard to the change of μ. According to the increment of the value of the green cache hit ratio (μ), the frequency of the green path outperformance also increased seasonally. However, there was no time in winter when $\Phi_{GreenCR} > \Phi_{ProbCache}$. This pattern was also observed in CORONET (Fig. 5.26). These results provided ISP operators with guidelines on managing the content delivery paths in a more eco-friendly manner.

Table 5.18: Comparison between $\Phi_{GreenCR}$ and $\Phi_{ProbCache}$ (μ = 0.7)

Time	Spring		Summer		Fall		Winter	
	$\Phi_{GreenCR}$	Φ_{Prob}	$\Phi_{GreenCR}$	Φ_{Prob}	$\Phi_{GreenCR}$	Φ_{Prob}	$\Phi_{GreenCR}$	Φ_{Prob}
0	**0.184**	0.177	0.160	0.182	0.197	0.226	0.155	0.182
1	**0.209**	0.176	0.169	0.180	0.197	0.227	0.155	0.183
2	0.156	0.177	0.167	0.180	**0.256**	0.233	0.158	0.186
3	0.156	0.181	0.164	0.176	**0.236**	0.221	0.152	0.180
4	**0.187**	0.181	0.176	0.179	**0.219**	0.215	0.152	0.179
5	**0.207**	0.184	**0.187**	0.180	0.204	0.206	0.154	0.183
6	0.171	0.206	0.175	0.209	**0.221**	0.218	0.149	0.177
7	0.211	0.253	0.249	0.260	**0.251**	0.247	0.156	0.185
8	0.275	0.326	**0.358**	0.315	0.251	0.290	0.178	0.212
9	0.312	0.372	0.321	0.375	**0.345**	0.342	0.214	0.254
10	0.337	0.399	0.387	0.403	**0.421**	0.417	0.237	0.284
11	0.352	0.422	0.397	0.426	**0.470**	0.433	0.267	0.315
12	0.390	0.432	0.386	0.429	**0.486**	0.451	0.329	0.384
13	0.359	0.427	0.462	0.471	**0.484**	0.435	0.258	0.306
14	0.330	0.399	0.381	0.440	**0.485**	0.425	0.269	0.317
15	0.289	0.345	0.314	0.371	**0.460**	0.402	0.233	0.270
16	0.245	0.295	0.263	0.341	**0.372**	0.319	0.208	0.240
17	0.206	0.250	0.263	0.309	**0.317**	0.269	0.185	0.213
18	0.162	0.197	0.197	0.233	**0.322**	0.271	0.171	0.199
19	0.147	0.182	0.157	0.185	**0.328**	0.272	0.162	0.190
20	0.147	0.186	0.154	0.182	**0.340**	0.285	0.154	0.184
21	0.153	0.188	0.169	0.190	**0.340**	0.281	0.150	0.178
22	0.157	0.190	0.164	0.186	**0.340**	0.279	0.221	0.254
23	0.171	0.206	0.175	0.181	**0.340**	0.282	0.231	0.263

Table 5.19: Frequency when $\Phi_{GreenCR} > \Phi_{ProbCache}$

	Spring	Summer	Fall	Winter
Frequency	4	2	20	0

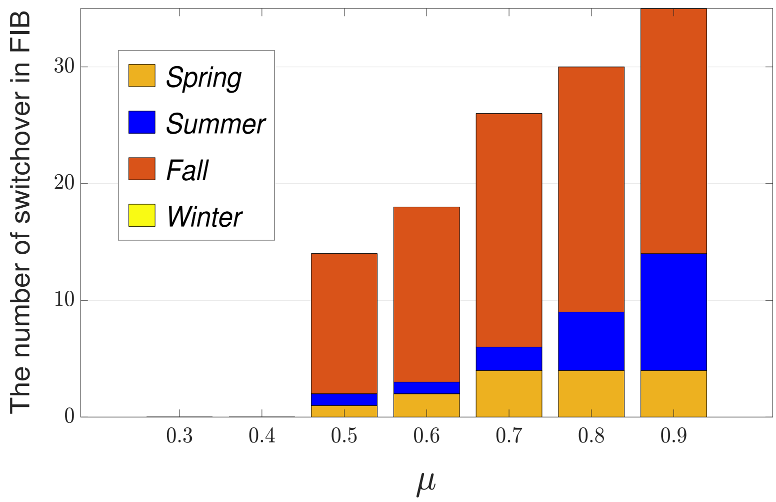


Figure 5.25: Seasonal frequency in the case of $\Phi_{GreenCR} > \Phi_{ProbCache}$ in NSFNET

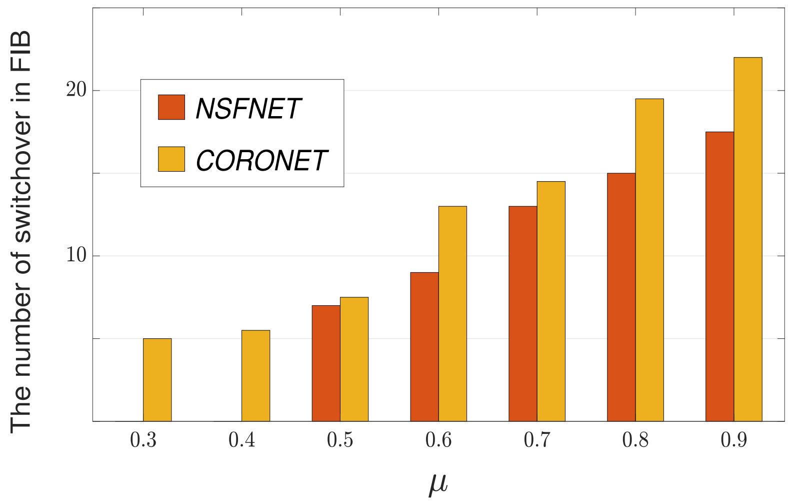


Figure 5.26: Frequency in the case of $\Phi_{GreenCR} > \Phi_{ProbCache}$

5.5.3 *Conclusion*

As an extension of the target network infrastructure from IP networks, NDN was selected and analyzed in this chapter for eco-friendly greener content routing as a new approach for green NDN.

First, the eco-friendly NDN design problem was formulated using the renewable energy impact that defines a new metric, called the greenness of nodes, as a quantitative metric for measuring the environmental footprint of the network and identifying green paths. To solve this problem, a new content routing scheme was proposed using the notion of greenness in a heuristic manner. The green content routing first defines the greenness of nodes and identifies the corresponding green paths and then encourages traffic to aggregate on the green paths powered by renewable energy that is more eco-friendly than traditional fossil energy. To support green content routing in the existing network, partial power consumption from multiple energy sources in the network node was assumed similar to Chapter 4.

A variety of simulations using realistic network topologies and renewable energy statistics from the US were performed to validate the solution regarding the green cache hit ratio. In addition, a transition analysis comparing green content routing with other routing schemes was performed to evaluate relative superiority under the renewable energy condition.

The performance of green content routing strongly depends on the status of the renewable energy, which is dynamic according to time and network node location. However, predicting renewable energy production is becoming a reality as weather predictions become possible due to the remarkable development of artificial intelligence [64, 82, 136] and rich datasets. Consequently, eco-friendly caching policy based on prediction for locating contents to the greener nodes can also result in a higher green content cache hit ratio. Similar with the transition analysis performed in this chapter, a more sophisticated analysis for eco-friendly provisioning under various real environments is also worthy of a further study.

In Chapter 6, we conclude this thesis with a summary of each chapter and give a guideline for further works.

6 CONCLUSIONS

This chapter summarizes the core contributions and findings of this dissertation, draws conclusions and presents an outlook to future work.

6.1 SUMMARY

Green networking enables more energy-efficient networks and reduces environmental impact, and is receiving increasing attention in sustainable ICT. Amid rising demand for electricity, concerns about reducing energy consumption as well as increasing environmental awareness have become high priorities. Researchers and innovators in the field are making strides toward sustainable development for network infrastructure by improving energy efficiency and leveraging renewable energy. This thesis focused on green networking strategies, especially in IP and content networking, an indispensable core component of current network design and planning. It thoroughly investigated the design principles and performance, and discussed the effect from a green perspective.

We began the dissertation with a discussion of two questions: how to reduce power consumption in the existing network infrastructure and how to reduce CO_2 emissions by powering network infrastructure in an eco-friendly manner. Since last decade, a number of solutions have been proposed to solve the first question for minimization of power consumption while guaranteeing service continuity. Unlike usual green approaches, we paid more attention to the fact that network elements should always be powered for connectivity regardless of network conditions (network volume, status, or other factors). In addition, measurement study shows the power consumption at layer 3, which is used in a routing engine and packet forwarding engine as the control and forwarding plane, respectively, and occupies 32% to 60% of the total power consumption in the current IP router architecture. Considering these two facts, we discussed architecture design under feasible assumption from a different perspective in Chapter 1. The second question brought up an interesting research direction taking green energy into consideration in network operation. It challenged us to design an eco-friendly network architecture with renewable energy property. Under the reasonable assumption that network elements are powered partially by multiple energy resources, we discussed architecture design especially for the content delivery network. These two research questions were discussed in Chapter 1, including the motivation, direction and structure of the thesis.

In Chapter 2, a comprehensive literature survey for green networking was carried out. For green IP routing, we first classified base approaches into 4 categories: *i)* adaptive link rate, *ii)* interface proxying, *iii)* energy-aware infrastructure, and *iv)* energy-aware applications. Then, outstanding works for each category were described in detail. Extending to green content networking, a number of studies toward energy-efficient CCN/ICN/NDN were introduced according to the categorization of shutdown or slowdown, energy-aware cache management and other approaches. Coping with a growing demand for electricity generation, we focused on the use of renewable energy as an attractive future energy. Then, several studies were introduced to provide approaches to how the consumption of renewable energy can make our network infrastructure eco-friendly. Through literature survey, comparative analysis of existing green solutions and discussion for further improvement were performed. From the discussion, several learnings were deduced and motivated to green IP and content routing in this thesis.

A framework for green IP routing was introduced in Chapter 3. First, we defined energy consumption problems in networks with additional primitives under the assumption that the layer in the OSI model can operate independently, and reformulated network energy consumption problems. A novel packet switching was designed for use in an IP network to reduce unnecessary energy consumption. As the first green networking approach in this thesis, we first classified the network nodes into either header or member nodes. The member nodes then put the routing-related module at layer 3 to sleep. The entire set of network nodes was then partitioned into clusters consisting of one header node and multiple member nodes. Then, only the header node in a cluster conducted IP routing and its member nodes conducted packet switching using a specially designed identifier, a tag. To investigate the impact of the green IP routing scheme, a number of simulations using well-known real network topologies were conducted. Consequently, a more energy efficient performance was achieved than in previous studies.

Chapter 4 began with the problem of achieving energy efficiency in IP networks by taking into account not only the energy consumption of the network but also the impact of various energy sources, such as renewable energies. As an extension of the green packet switching in Chapter 3, a green networking approach in which we classified network nodes into clusters and selected one header node in each cluster according to the generation cost and the carbon emission per unit of energy was designed. We developed a routing scheme using IP routing only on header nodes and conducted packet forwarding using a carefully designed identifier on other nodes to achieve a greener telecommunication system. We validated our solution with a variety of simulations using real-world renewable energy statistics, and the results showed that the proposed scheme was superior to other existing solutions, particularly in terms of energy and cost efficiency.

Green networking has recently attracted significant attention due to the rising concerns of GHG emissions. Although existing green network solutions have been proposed to maximize energy efficiency, they are not commonly designed to being environment-friendly. Triggered by the ongoing paradigm shift of internet architecture, Chapter 5 introduced a new approach for green NDN where content requests and caching perform towards greener content delivery. We designed an eco-friendly content routing strategy, where we first defined the greenness of nodes and identified corresponding green paths, and then encouraged traffic to aggregate on green paths powered by more eco-friendly renewable energy than traditional fossil energy. A variety of simulations using realistic network topologies and renewable energy statistics from the US were performed to validate our solution, and the results showed that the proposed strategy demonstrated significant green energy gain achieved over the existing caching methods.

6.2 FUTURE WORKS

Though green approaches have been proposed and brought many advantages in network infrastructure from economical and environmental perspectives, the internet is a fast and ever-changing ecosystem where today's understanding of demands, trends and corresponding technologies may be invalid tomorrow. Hence, whether green approaches are going to be the solution for future network infrastructure remains an open issue and needs time to prove. Based on the work in this thesis, some possible directions for future works are listed below.

To design green solutions, two reasonable assumptions is introduced in this thesis. One was about functional separation of the OSI model in Chapter 3 and the other was regarding partial power supply from multiple energy sources in Chapters 4 and 5. These assumptions have now earned positive reviews from experts in ICT industry. To advance provisioning of green solutions to real networks, more research to determine feasible directions with regard to existing solutions (such as softwarable routers, smart grid, etc.) need to be encouraged.

We analyzed the green routing's performance in Chapters 3 and 4 to investigate the energy-related indices focusing on network provisioning. Further research and consideration for network dynamicity, especially in QoS perspective, is needed to reduce the gap between simulation analysis and network deployment scenario.

As discussed in Chapters 4 and 5, the performance of green solutions where renewable energy is concerned is strongly dependent on not only the geographical location of the network node but also the time of day. Even though green solutions in this thesis demonstrated superiority, the results could be reversed if renewable energy for the production of electricity is insufficient to support green solutions. Predicting renewable energy production using artificial intelligence technology emerges as an alternative to alleviate the problem caused by the dependence of renewable energy usage. Consequently, eco-friendly green solutions in Chapters 4 and 5 will consider the benefits from predictions for network provisioning. Similar to the discussion on transition analysis between green and other solutions in Chapter 5, more elaborate investigation and evaluation of solutions under various environments is certainly worth further study. In addition, the investigation of ratio of GN which is critical to the performance of green NDN remains to be challenging issue.

The green solutions in Chapters 4 and 5 provide novel approaches regarding how renewable energy is harmonized with existing routing framework more focusing on eco-friendly network provisioning. Hence, additional analysis including realistic network environments is also worthwhile. For instance, it is essential to consider the traffic matrix for the deployment of green solutions under current internet and further ever-changing network environments. Given the increasing importance of the future internet, the knowledge of traffic has become critical to predict future traffic trends and corresponding network optimization.

There is a growing emphasis on future internet infrastructure that embraces content-oriented convergence services and NDN is expected to be qualified as a possible candidate. Finally, a pilot study to answer further questions (such as how green NDN can be converged into other domains and services and what the expected advantages are) is worthwhile for future work. For example, green routing and caching can be applied to vehicular networks where vehicles communicate and share data. Mobile nodes equipped with a small panel can be autonomously solar powered and communicate and cache data. This direction and its related topics surely deserve more research and engineering efforts as a follow-up to this thesis.

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