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Abstract

The increasing power consumption of the Internet infrastructure has attracted a lot of world-wide attention because of the severe impact on the environment. Many research works have started to search for solutions of how to reduce the energy consumption in data networks. Other works have considered that generation of electricity from fossil-based fuel emits greenhouse gases into the atmosphere, which leads to global warming. Consequently, another approach for sustainable networks is the utilization of renewable energy to power the infrastructure.

This thesis introduces a new backbone Internet routing protocol that performs routing considering the different renewable energy availability at various geographical locations. A Border Gateway Protocol (BGP)-based routing algorithm using a new metric is proposed to increase the utilization of renewable energy. The aim of the presented protocol is to maximize the total renewable energy usage of the backbone network and reduce the non-renewable energy consumption for different traffic load. The new metric is based on a linear energy power consumption model for the selected routers. This linear model describes the power efficiency of routers using a scaling factor (SF), which the proposed algorithm incorporates into the routing metric and combines with a per-packet load balancing scheme to increase the renewable energy power consumption. Simulations with various configurations were implemented to evaluate the performance of the presented routing algorithm.

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Chapter 1

Introduction

1.1 Motivation

As the Internet grows rapidly and steadily, the power consumption of the networks has become a significant issue in the last few years. The competition between the network development and the energy consumption is also conspicuous. For the vast amount of energy consumption, almost 1% to 2% of the worlds total electricity [1], network expansion is considered as a factor of the global warming problem. The Information and Communication Technology (ICT) devices and services gradually become an indispensable part of human life. According to the study of [2], the three main categories of ICT has 7% growth rate which is higher than the growth rate of worldwide electricity consumption. Moreover, the work in [3] shows the power consumption associated to ICT increasing from 2% to 10% of the whole world power consumption. In this context, ICT is responsible for the rapid growth of the global energy consumption. On the other hand, ICT also accounts for the emission of greenhouse gases (GHG), such as carbon dioxide (CO2). Within the GHG emissions related to ICT, 80% of the total emissions come from equipment usage [4]. In addition, telecommunication infrastructure and devices account for 37% of the total GHG emissions. Alternatively, the increasing energy consumption also constrains the network growth in the near future. It is a huge challenge to balance energy efficiency, increasing network capacities and the impact on the environment.

Energy consumption of backbone IP networks, which is a significant component of the overall ICT energy consumption, is also increasing on account of the overwhelming network expansion. The network devices like IP router not only plays an important role in the communication network but also in the reduction of the energy consumption. Researchers make a lot of effort to enhance the energy efficiency of IP router and whole network, which aims at reducing the traditional fossil energy consumption. In recent research, one promising solution for these considerations is the use of renewable resources, such as solar and wind energy, which has a less harmful impact on the environment. Smart grid power distribution networks adopt the technology that dynamically switches the energy utilization of green renewable energy and fossil-based energy [5]. The communication between the network and the smart grid give a chance to improve the future network. The study in [6] shows that combine the telecommunication network and smart grid control plane is an effective strategy to improve the performance and minimize the energy requirements. Besides, using renewable energy instead of the traditional fossil energy can directly reduce the GHG emission. Renewable energy is clean and sustainable energy that generated from the wind, natural sunlight, tide and other power. Most of the renewable energy is zero GHG emission which means they are harmless to the environment. Nonetheless, the renewable energy resources have their geographical limitations, for example, the wind resources in the central U.S. is fewer than in the east coast. Therefore, some researchers begin to explore how to make use of these available renewable resources. The study in [7] proposes a new heuristic method that maximized the number of nodes powered by renewable energy to reduce the total power consumption of the network. In a concept of data-follows-the-energy, routing algorithms that designed to increase the renewable energy usage is a trend to minimize the overall energy consumption.

Since solar and wind energy is varying according to the local weather conditions and the time of day, the geographical location becomes an important factor. The dynamic weather conditions make the renewable energy generation intermittent and unstable, numbers of studies have proposed approaches to predict the renewable energy production. Generally speaking, the solar and wind energy can be predicted with high accuracy based on the local weather forecast [8], [9]. The work in [4] also recognizes that the sky cover and wind speed are two primary factors that determine the solar and wind energy harvest. The amount of energy generation comes from solar panels and wind turbines can be estimated according to the weather data during a period of time [9]. Thus, the renewable energy generation on different location is predictable within a certain time slot, which needs accurate weather forecast data. It can be used to establish an energy-aware network which aims to operate more renewable energy following the renewable energy availability.

In order to characterize an energy awareness network, estimating the energy consumption of the backbone network, an energy model which can estimate the power consumption of each router or switch is necessary. The studies in [10], [11] and [12] present a linear energy model which can describe the power consumption of routers in different traffic situations. In this energy model, each of routers was considered to be in an idle status when there is no traffic on it. As the router stays in idle state, it consumes half of the maximum power consumption. Also in [10], a special parameter called scaling factor (SF), measured in W/Gbps, which is a power efficiency metric describes the power consumption the router transmits 1 Gbps traffic. It was calculated from the detail configuration of the router in the router datasheet. Therefore, the total energy consumption of the entire network can easily be scaled up for different traffic loads.

At the backbone level routing, one of the most popular routing protocols is the Border Gateway Protocol (BGP) which works to route the Internet traffic between different autonomous systems (ASs) [13]. The autonomous system represents an independent entity that controlled by a specified routing policy. It often contains a group of network devices and always has a certain AS number identified by BGP. Each AS is considered as a small network that connected to a smart grid which can operate green renewable energy resources and the brown fossil-based energy resources. The BGP exchanges routing information among different gateway hosts of ASs on the Internet which contains the information of renewable energy. The optimal route chosen by the BGP routing algorithm makes route decisions through the routing table which consist of several relevant information, such as the list of known routers, the reachable addresses and the cost metric related to the path to each router. As the previous considerations of this thesis, we modify the routing algorithm to make it possible to route packets depending on the renewable energy availability at each node. According to the routing process of BGP, a new routing metric is necessary which can take into account renewable energy availability of each route. Also, in order to improve the efficiency of renewable energy usage, we consider a load balancing scheme using a renewable energy-awareness metric while routing the Internet packets. Thus, in this thesis, a renewable energy-awareness load balancing routing algorithm will be presented which maximizes the renewable energy usage and reduces the waste of available renewable resources of the network.

1.2 Contribution

The main contribution of this thesis is developing a routing algorithm which is aware of renewable energy at each node and maximizes the renewable energy usage of the entire backbone network. To achieve the goal of greening Internet, utilization of renewable resources is an efficient and sustainable strategy. A new routing metric that operating the renewable energy resources is presented, which works in the route selection process.

This new BGP-based routing algorithm is modified to accommodate the energy-awareness and aims at addressing the renewable energy utilization problem. Essentially, it is aiming at using as much renewable energy as possible through distributing the traffic load to the other routes that have available renewable energy to transport the traffic data. The proposed algorithm makes an effort to balance the incoming traffic while keeping the whole network running. Moreover, the traffic engineering strategy considered in the algorithm uses the idea of per-packet load balancing mechanism, which makes each packet selects a route towards to the destination depending on the probability during each route selection process and this probability is associated with the renewable energy availability at each route. With this consideration, the route with more renewable availability will have higher priority to be chosen. Thus, the load balancing algorithm drives the incoming traffic to the possible routes according to the specific metric which is determined by the renewable energy availability.

The rest of this thesis will show how the BGP-based routing algorithm works in the backbone network and discuss the performance of this algorithm through comparing with single path algorithm. The rest part of the thesis is structured as follow: Chapter 2 presents some relevant works and background information for this study. In Chapter 3, the linear energy model which calculates the power consumption of the backbone network route is briefly described. Chapter 4 mainly introduces the renewable energy-awareness load balancing routing algorithm and explain the working mechanism through a simple example. The simulation results and analysis is presented in Chapter 5. The last chapter draws a conclusion of this thesis..

Chapter 2

Backgrounds

2.1 Related works

The emission of GHG from networking equipment has got more attention as the power consumption of the Internet increased much faster than expected [10]. As a result, recent years have seen a focus on research of power-saving network component and technology. Previous studies have shown that networking devices like backbone IP routers became the main energy consumer, which cost an enormous amount of energy in cooling and air conditioning [14]. In [15], a Green router (G-router) with a new mechanism was implemented which aimed at reducing the power wasting. At the same time, it also achieved the goal of maximizing the QoS of the network while minimizing the energy consumption. Moreover, increasing number of researchers started to investigate the issue of the overall power consumption of the backbone network instead of concentrate on single or few components only. The work in [16] proposes a study to reduce the power consumption of a backbone network while aiming at obtaining a minimal set of routers and links that satisfy different traffic load. Authors in [16] also introduce an Integer Linear Programming (ILP) formulation and a heuristic approach for synthetic and real network topologies. The results also show that the energy saving is considerable especially when the traffic is not fully loaded while using this approach. The study in [17] analyzes the performance of four IP-Over-WDM architectures, where each of the architectures has its energy consumption model which consist of various components employed at the transport layer. Different ILP formulations for power consumption minimization problem of four architectures are also presented in [17]. In [7] and [8], a Mixed Integer Linear Programming (MILP) model is developed to minimize the total energy consumption of IP-Over-WDM networks. Moreover, the work presented in [7] exploits a new heuristic which traverses as many nodes as possible that using renewable energy. The solution in [7] minimizes the non-renewable energy by reducing the total number of IP router ports and transponders. Another energy model presented in [10], is a linear energy model to describe the energy consumption of routers with different traffic load and consider scaling factor as its measurement. In [18], an offline and an online load balancing algorithm for content delivery networks were compared. The optimal local offline algorithm obtains the theoretically highest power saving by using the traffic load information of the whole network all the time. In contrast, the online algorithm just knows the past and current state of the network, which works in a more realistic situation.

Two routing algorithms that consider renewable energy usage were presented in [19] and [20]. The first algorithm called Sun-And-Wind Energy-Aware Routing (SWEAR) was designed to improve the performance of the renewable energy availability. SWEAR compares two candidate path, the one with maximum usage of renewable energy and the one with lowest transport-power consumption. If the increase transport power of the second path is compensated by the utilization of renewable energy, the second path is chosen [19]. The second algorithm, known as the Green-Energy-Routing algorithm, aims at finding the path with lowest non-renewable energy consumption. Furthermore, performance evaluation of the two renewable-energy-aware algorithms in different IP-Over-WDM network architectures was also studied in [20]. Authors in [21] presented some traffic grooming heuristics that move the optical-electrical-optical conversions and electrical processing toward the node powered by renewable energy. The research in [21] also analyzed energy-aware and emission-aware policies for routing calculation and found that maximizing the utilization of green nodes which use renewable energy can reduce the energy consumption of the entire network. In [7], authors proposed a framework to achieve eco-sustainable routing in photonic networks. The proposed single-stage wavelength routing algorithm based on the Multi-protocol label switching (MPLS) aiming at optimizing the choice of renewable energy usage and traffic load balance. Authors in [10] provided a routing algorithm that combined pure load-balancing and pure energy-aware scheme, which were switched depending on the current network traffic state. This hybrid approach optimized the free bandwidth to satisfy the traffic demand and save more energy consumption in the network. These two algorithms which considered both energy-efficiency and traffic load-balancing issues served an inspiration for our proposed algorithm. A network level approach employing energy aware routing that takes energy consumption of the equipment into account when doing path routing and traffic-engineering process was presented in [22]. The above renewable-energy-aware or potential renewable energy-aware routing algorithms in backbone networks inspire the work in the thesis based on the idea of modifying current popular protocols, for example, BGP, to account for various renewable energy availability at different geographical locations which have different weather condition that influence the renewable energy generation at each node.

In this thesis, the objective is to maximize the renewable energy usage of the whole backbone network and also to minimize the non-renewable and total power consumption as well. While seeking the optimal utilization of renewable energy resources, the proposed BGP-based load balancing algorithm also pursues less bandwidth wasting and low blocking rate.

2.2 Border Gateway Protocol

Border gateway protocol (BGP) is a scalable Internet routing protocol that exchanges routing information between the routing domains which are called autonomous systems (ASs). Each AS represents an individual network using an independent routing policy and uses BGP to advertise routes across ASs [13]. Also, it uses BGP to obtain the reachability information by listening to the advertisement announcement from other ASs. BGP is an interdomain routing protocol that works among the major Internet Service Providers (ISPs), as well in some large enterprise networks [23]. The current BGP running on the backbone networks is BGP version 4 (BGP-4), which provides some useful features to support the complex Internet.

The BGP route selection is based on several path attributes and network policies. In this section, some common path attributes that describing the characteristic of a BGP prefix is presented. These path attributes influence the routing decision. The AS_PATH attribute shows a list of ASs that the BGP prefix traversed, which lists a reverse order of the sequence of AS path [13], [23]. It is aiming to avoid loop for inter-AS routing. LOCAL_PREF is an attribute that describes the degree of preference for each route connects to other ASs, and it is exchanged between internal BGP (iBGP) peers [13]. This attribute advertises inside an AS and makes each internal peer know the degree of preference of each external route. MULTI_EXIT_DISC (MED) is a common attribute that used to discriminate the multi entry/exit to the same AS. When there is more than one link to the same AS, BGP prefer the link with lower MED value. Compared to the LOCAL_PREF attribute, MED is an inter-AS attribute that transmits from one AS to another AS. Another common attribute is the NEXT_HOP which defines the IP address of next hop. Though the BGP next hop is not directly connected, a reachable next hop address is necessary. The BGP route selection algorithm makes use of these path attributes to determine what the best path is. This algorithm consists of several routing policies, and it uses the policies to compare the path attributes sequentially. The general routing algorithm is summarized as follow: (1) The route with highest LOCAL_PREF value is preferred. (2) The route with shortest AS_PATH list wins. (3) BGP prefers the route with lowest MED value. (4) The external route has higher privilege than the internal route. (5) Lowest iBGP metric to BGP next hop is preferred [13]. BGP uses the sequential comparison method to decide the current best route. If a new route is received, it compares the newest candidate route with the current best route to determine the new best route.

2.3 Renewable Energy Resources

Popular energy resources can be divided into three categories: fossil fuel resources, nuclear resources and renewable resources. The renewable energy resources are considered as clean and sustainable energy which has minimal impact on the environment. Most of the energy resources have a negative impact on the environment whether short time or long term. Fossil-based resources, such as oil and gas, produce energy by burning, which emits a large amount of GHG into the atmosphere. The inevitable GHG emission will aggravate the global warming and air pollution issue.

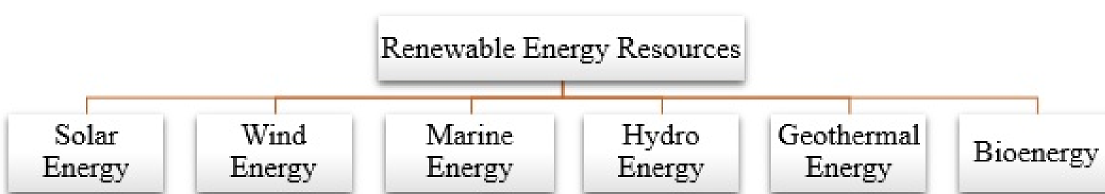

Figure 2.1: Overview of renewable energy resources

However, the renewable resources are natural energy resources, such as sunlight, wind and geothermal energy, which emit zero GHG into the atmosphere. Figure 2.1 shows an overview of renewable energy resources [24]. Renewable energy technology turns these natural energy resources into an available form of energy, such as electrical energy, heats or fuels. In this thesis, we will focus on solar and wind energy since the technology is relatively mature and also easy to aggregate with a large scale smart grid. The most common technology that is used to produce electrical energy from solar energy is the solar photovoltaic (PV) system. The solar PV system consists of numbers of PV cells which are the basic block of the PV system. Each of the PV cells is a semiconductor device that directly transfers the solar energy to electricity [24]. PV cell generates electricity from sunlight without emission, noise, and vibration [25]. The current best PV cell generation efficiency is about 30%, which depends on the various cell types, for example, the crystalline silicon cell has the highest efficiency, and the lowest is amorphous silicon cell [26]. Though the solar energy resource is clean and has potential, it is limited by the weather condition and the day time. Wind energy has a higher efficiency of electricity generation than the solar energy. It is a relatively mature technology for electricity production, which is widespread in many countries. Wind energy technology uses wind turbines to converts the available wind energy into electrical energy. To be more specific, the wind turbine turns the kinetic energy into mechanical energy when the wind passes through the blades. Then the mechanical energy converts into electrical energy through the generator. It is worth to note that only a fraction of available energy can be captured and converted to electrical energy. The design of a wind turbine mainly decides the energy capture from the wind [26]. The electricity generation from wind resources is inexhaustible in the long term. Moreover, the use of electricity produced by wind turbines avoids million tons of carbon or other emissions. Similar to the solar resource, the wind resource is also influenced by the local climate and weather.

Moreover, the renewable energies regenerate on a relatively short period and also beneficial over the whole life cycle [5]. Sunlight and wind are natural resources which can be seen as inexhaustible in a long period, but they also fluctuate according to the weather and the time of day. Renewable energy resources are great alternative energy resource to the traditional primary energy resources. Nonetheless, renewable energy resources also have their uncertainty and variability. The electrical energy generated by solar energy and wind energy is fluctuating continuously since the solar irradiation and the climatic condition is changing. At the level of large-scale grids, generator aggregation helps to decrease the variability. So energy storage and backup are also necessary, which helps to balance the fluctuations. Another way to address the variability in renewable energy resources is to make use of more than one renewable energy resources. In this concept, we may use both solar and wind energy in the same grid. This method smoothes the variability in renewable energy generation when no solar or wind energy can be utilized. The total energy production by solar and wind resource stays in a relatively stable situation.

Though renewable energy generators, such as PV systems and wind turbines, produce clean and green energy, integrating current electrical power system with renewable energy is still a big challenge. It is because the amount of produced electrical energy by renewable energy resources is fluctuating according to the weather condition of the day. One possible solution is the use of energy storage technology to improve the power quality to the loads in a smart grid structure [27]. Smart grid technology is an available solution to integrate energy storage systems to solar energy system and wind energy system [27]. Also, the next-generated smart grid provides real-time and reliable information about the energy network. The dynamic choice of energy supply is provided by the smart grid interfaces in order to operate with multiple energy resources [5]. The communication network can select the route with more devices powered by renewable resources using the power related information.

Chapter 3

Energy Power Consumption Model

In order to achieve the primary objective of maximizing the renewable energy usage, an energy power consumption model is necessary to estimate the power consumption of different candidate paths in the energy-aware network. Aiming at describing the relationship between the power consumption and the traffic load, a linear energy power consumption has been presented in this thesis [10]. With this particular measurement, we can obtain the traffic information and use it to calculate the power consumption of the whole network. More importantly, if we know the energy supply of one node which contains renewable and non-renewable energy, the estimated bandwidth from renewable energy is possible to be obtained using the linear model. So this linear model is also used to assess the bandwidth supplied by renewable energy which plays a significant role in our new metric.

Based on real measurements of a core router it was determined in [11, 12], that the power consumption of a router or switch consists of two main parts. One is the constant consumption which is not influenced by the traffic load, and other is the part that varies depending on the traffic load [11]. The constant power consumption is the fixed power consumption of devices whether there is traffic or not and includes, for example, the power consumption of chassis internal cooling. Also, the load-dependent component represents additional power consumption when carrying traffic in order to process more header and packets. Therefore, the router is considered as having two states. One is the idle state which means the router is on but carries no traffic and consume a fixed value of power. The other one is the active work state which is the normal state, and its power consumption is depending on the traffic that passes through it. It is worth to note that, the idle state power consumption is based on the energy efficiency of the devices with a newer device expected to have better energy efficiency. Following the energy model in [10], we assume that idle state power consumption of a router cost half of the total maximum power consumption than when it is fully loaded. According to the load-dependent component consumption, the estimated power consumption of a backbone router is increased linearly with the increasing traffic load from the idle to a working state. Accordingly, the power consumption of a router is

$$C = SF \cdot R_{load} + C_{idle} \tag{3.1}$$

where SF is the scaling factor of the device, R_{load} is the traffic going through the device and C_{idle} is the idle state power consumption. The C_{idle} in this model is half of the full load power consumption. Note that the traffic here is aggregated bandwidth since we consider the backbone network scenario as our object. The scaling factor measured in W/Gbps shows that processing 1 Gbps of traffic need 1W power. This traffic to energy measurement shows the energy efficiency of the network devices. With this specific energy efficiency metric, the network devices will be evaluated in power per gigabits which gives an equivalent measurement of different devices. In this linear model, the scaling factor can be seen as the slope of power consumption function which describes how power consumption growths according to the traffic load increasing from the idle to the working state. More specifically, the router with large scaling factor consumes less power per bits than the router with a small scaling factor, which also means router with large scaling factor has a higher energy efficiency suitable to run larger traffic. In other words, a router with a large scaling factor is more suitable to be deployed in the backbone network, because the traffic flow in backbone network is more massive. As we get the power consumption information from the datasheet or other data resources, the scaling factor of the router is also known while using this linear function. For example, a router with maximum aggregated bandwidth 100 Gbps and power consumption 1000 W at full load will have an idle state power consumption is 500 W which is half of the maximum power consumption. As a result, the scaling factor of this router is 5 W/Gbps, shown in Fig-1. Similarly, a router with 40 Gbps maximum capacity have maximum power consumption 640 W with a scaling factor of 8 W/Gbps.

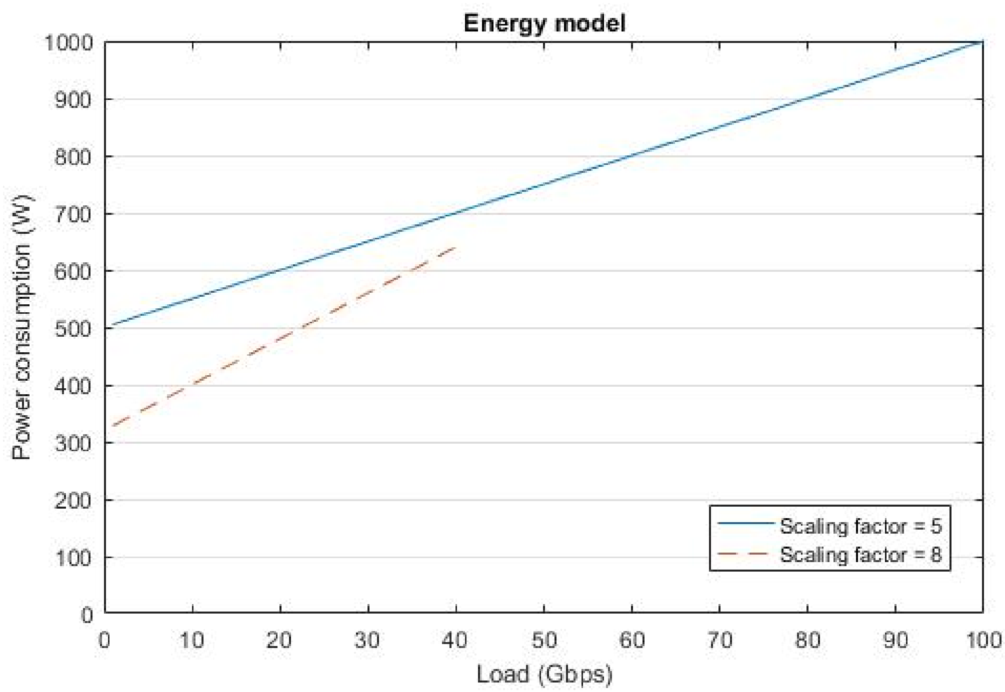

Figure 3.1: Energy model example

With this metric, the power consumption of each router can be estimated. The power consumption, measured in W, is a function of traffic load measured in Gbps. An energy-aware network is established by using this energy model and scaling up an individual router to the whole network. Nonetheless, in this thesis, the objective is more concerned with increasing the effectiveness of renewable energy power consumption. In this concept, we consider the combination of linear model and renewable energy availability to achieve a renewable energy-aware routing in the network. Both renewable and non-renewable energy is considered as the power resources of each node. Once we have the traffic information, the renewable power consumption can be calculated. Similarly, we also know the bit rate when we obtain the renewable power consumption information.

In conclusion, we can estimate the power consumption and bit rate of routers at any time slot based on the scaling factors which are calculated from the routers power consumption information in the data sheets.

Chapter 4

Renewable Energy-Aware Load Balancing Routing Algorithm

In this chapter, we will present a renewable energy-aware load balancing routing algorithm based on a load balancing idea which works with BGP after being modified to operate with a new routing metric. The basic idea of our renewable energy-aware routing algorithm is that route selection mainly depends on the renewable energy availability of each candidate route, which means that the route that has higher level of renewable energy availability will be chosen. This renewable energy-aware routing strategy selects the route with the highest bandwidth that can be powered by renewable energy. Note that this bandwidth is the modified routing metric used in the BGP route selection process. The new routing metric comes from the weighting function which is a significant part of the routing algorithm. To maximize the renewable energy usage, we also consider a load balancing mechanism which combine with the renewable energy-aware routing mechanism, so that routers can share their traffic load over each candidate routes according to the different weights of each route. Therefore, the nodes that have more renewable energy will carry more traffic and hopefully become a hot spot of the network. The next two sections introduce the two main functions of our algorithm.

4.1 Renewable Energy-Aware Weighting function

The renewable energy-aware load balancing routing algorithm is a BGP-based routing algorithm which works between ASs. According to the route selection process, it compares all the candidate paths with path attributes and chooses the best valid routes. To adjust for the available renewable energy at different routers, we consider modifying the weight attribute. The weight attribute has great flexibility to the energy-aware routing metric. After calculating the probability of selecting each possible route, the load balancing algorithm randomly selects a route according to this probability and assigns the weight values to the node on the chosen path. The original weight attribute is configured on the local router, and it has the highest privilege when determining the best route through the BGP best path selection algorithm.

Consider the network as a graph $G = (V, E)$, where V is the node which represents routers or switches and E is the link between nodes. Each node $v \in V$ in the graph has associated a weight W_v calculated by the metric weighting function in our routing algorithm. This metric weighting function works at the BGP route selection process, in order to calculate the weight of each node which will be advertised to all the neighbors. In detail, this metric is dynamic because it is based on the renewable energy availability at each node which depends on the time of day and weather conditions at the different geographic locations. For example, the weather of one node maybe sunny and at the same time cloudy at another node. The weight of these two nodes will be different because the weather conditions result in different solar and wind energy supplied to the nodes. Moreover, different time of day at different geographical location gives different renewable energy generation so that there will be various energy profiles during day and night. As a consequence, the route weights vary according to the changing renewable energy availability. Because of the metric to be used in the load balancing algorithm, it is necessary to consider several renewable energy availability situations when balancing the traffic. Therefore, the renewable energy availability is divided into three energy levels which are associated with the energy availability. The first level corresponds to the case when the renewable energy availability of all the nodes exceeds the energy demand of the idle state power consumption. In this situation, the power consumption of the node can be partially or wholly covered by the renewable energy generated at this node and all of the idle state power consumption driven by the renewable energy. The weighting function in this level is,

$$W_v = \frac{C_v - C_{idle}}{SF_v}, C_v \geq C_{idle}, \tag{4.1}$$

where C_v is the available renewable power at node v, C_{idle} represents the power consumption when node v is in the idle state, which means that there is no traffic go through to it. This metric is based on the linear energy model which uses the bandwidth to calculate the power consumption of a backbone router or switch. The renewable power availability measures in W which means how much renewable power is available at this node. So in this equation, the weight W_v represents the capacity to consume renewable energy. In other words, the metric we use at this level measures the bandwidth that can be powered by renewable energy. It is worth noting that this metric converts the available energy to bandwidth, which makes the renewable energy-awareness feasible in the data communication network. Furthermore, this bandwidth also works with our load balancing mechanism, which determines the probability that a node will be selected during the route selection process. Each candidate route has a probability depending on its weight so that traffic load is properly distributed to these routes. The weight determines the transmission capacity of the route. Packets will be assigned to the candidate routes according to the probability. Higher weight as a consequence of more renewable energy availability increases the probability to go through that route.

According to the linear model, the power consumption is linear related to the traffic load. The scaling factor describes the power per gigabits ratio of each router. Moreover, this linear relationship is also considered as the metric to estimate the available renewable power. When we obtain the renewable power information of each node, the transmission capacity can be calculated using the linear model. The renewable energy availability is considered as the available bandwidth that powered by renewable resources, and it works as a routing metric in BGP. Note that the equation (4.1) works when the renewable energy availability is more than the demand of idle state power consumption because the weight calculated by this equation needs to be a non-negative value. In addition, the idle state power consumption becomes the lower bound of the renewable power availability, which changes the weighting metric. It is because the weight will get negative value when the renewable power availability is lower than the idle state power consumption of the node.

Note that in some scenarios, not all the nodes have the available renewable power that meets the idle state power demand, so we consider another power level. Thus, the algorithm will also use the weighting function shows in equation (4.1) to calculate the weight of each node. Moreover, we set the weights to zero for the nodes that have unsatisfied idle state power demand, since they will have negative value according to equation (4.1).

While all the nodes have not enough renewable energy to power the idle state of the nodes, the weight metric will no longer be effective to select the route and distribute the traffic load because the weight becomes negative. Therefore, in this renewable energy level, the renewable energy supply cannot satisfy the idle state power consumption, so we need to change the metric weighting metric that can adjust to this situation. For this consideration, the weighting function define as,

$$W_v = \frac{1}{SF_v}, C_v < C_{idle}, \tag{4.2}$$

where SF_v is the scaling factor of the node and this weighting function is to be applied when $C_v < C_{idle}$ which means that the available renewable power is lower than the idle state power demand. We use the reciprocal of scaling factor as weight in this power level, because it represents a power consumption trend of node and shows as the slope of the linear model. The larger the scaling factor is, the more the power consumption becomes. It also means that the backbone routers have lower energy efficiency when they have large scaling factor. Besides, because of the low renewable power availability in this situation, all of the nodes are under the minimum demand of renewable power consumption. In other words, there is not enough available renewable power for routes to deal with the incoming traffic. The renewable power consumption remains at a fixed value and becomes independent from traffic load. Hence, we use the reciprocal form of the scaling factor as the weight. This metric can help to improve route selection efficiency and reduce the congestion of the network.

4.2 Load Balancing Routing Function

Another important component of our renewable energy aware routing algorithm is a load balancing routing function which distributes the traffic to each route according to a routing probability. In the load balancing algorithm, each of the routes has a probability to be selected. Each incoming packet randomly picks a route between the list of candidate route according to the probability for each route. Generally speaking, this mechanism achieves a per-packet load balancing by distributing the traffic load depending on the probability calculated based on the renewable energy availability. First, we will introduce some notation uses in the calculation. Assume that there is n nodes in route i, notate as $i_1, i_2, \cdots, i_n$. Moreover, we define the node i_{j-1} as the previous hop of node i_j and node i_{j+1} as the next hop of node i_j. The probability of route i is defined as::

$$Pr_i = \prod_{j=2}^{n} p_{i_j}, \tag{4.3}$$

$$p_{i_j} = \frac{w_{i_j}}{\sum_{k=1}^{nb_{i_{j-1}}} w_k}, \tag{4.4}$$

$$w_{i_j} = \begin{cases} \sum_{q=1}^{nb_{i_j}} p_q w_q & , \quad nb_{i_j} > 1 \\ m_i & , \quad nb_{i_j} = 1 \end{cases} \tag{4.5}$$

$$m_i = min(W_{i_1}, W_{i_2}, \cdots, W_{i_n}), \tag{4.6}$$

where Pr_i is the probability that route i is selected, p_{i_j} is the probability of node i_j, nb_{i_j} is the number of neighbors at node i_j, w_{i_j} represents the minimum weight of node i_j and m_i is the minimum weight of route i, shows in Table 4.1. The probability that a route will be chosen is equal to the product of the probability that each node in the route will be selected. We can calculate the single node probability through the weight obtained from the weighting function. Note that if a node has more than one next hop, the weight of the node will change to the weighted average of its next hops. The weight represents the volume of data that can go through a node while consuming renewable energy. If there are more than one node in a route, we consider the weight of the route will not exceed the minimum weight of the nodes in this route. In other words, the transport capacity powered by the renewable energy of this route will be determined by the node with lowest such transport capacity. Therefore, the minimum weight is considered as the weight of the route and also assigned as the weight of each node in this route.

In our algorithm, each packet undergoes a route selection process based on the probability for each route. Higher probability there will be more traffic load assigned

Table 4.1: Parameters used in load balancing calculation

Parameter	Description
Pr_i	Probability of route i is selected
p_{i_j}	Probability of node i_j is selected
w_{i_j}	Minimum weight of node i_j
nb_{i_j}	The number of neighbors at node i_j
m_i	Minimum weight of route i
W_{i_n}	Weight of node i_n

to this route. This load balancing mechanism separates the traffic proportionally depending on renewable energy aware route metric. Moreover, the objective of our load balancing algorithm is to maximize the occupation of available bandwidth that is supported by renewable energy so that the renewable energy usage will be maximized. Different from the original best single path algorithm, our algorithm supposes that each route has a probability to be chosen instead of choosing only one best path. The traffic load will be distributed to each candidate routes proportionally to the renewable energy availability under this load balancing mechanism. It also makes an effort to avoid the network congestion and improves the working efficiency of the switches and routers. The incoming packets will be sent to several possible routes so that the traffic load on an individual router will be relatively small. Consequently, our renewable energy aware load balancing algorithm assigns the traffic load to each route to depend on renewable energy availability so that it can use as much as possible renewable energy and reduce the non-renewable energy utilization. The nodes with more renewable energy are made to carry more traffic which will reduces the unused renewable energy availability at each node.

4.3 Case Study

A simple toy example is presented in this section to explain the renewable energy-aware load balancing algorithm working mechanism. The network topology is shown in Figure 4.1, where R1 to R5 represents five IP backbone routers. These five routers use the configuration of a Cisco CR-3 single-shelf system model with a maximum bandwidth of 2240 Gbps (16 slots filled with 14 10-Gbps port cards). Assume that the source node is router R1 and the destination is R5, the data packets will choose two different routes, R1-R2-R3-R5 or R1-R2-R4-R5, depending on the probability related to the renewable energy availability at each node. We recorded the number of packets that go through each router and estimate the power consumption using the linear energy model. Also in this example, a constant renewable energy profile has been used as the renewable energy availability at each node and the total renewable energy availability at all the nodes is also a uniform distribution. Assume that the renewable energy storage of R1, R2 and R5 is invariable, in order to focus on the load balancing process, we just collect the traffic information of node R3 and R4. In this experiment, we changed the availability on R3 and R4 but kept the combined power of this two nodes fixed at a certain value. The specific total available renewable power of R3 and R4 is 16000 W, $C_{R3} + C_{R4} = 16000W$, because this is the amount that can satisfy at the same time the power demand of a node carrying maximum throughput and a node in the idle state. In addition, the power consumption of each node was evaluated as a per port measurement. By changing the difference between the energy availability at R3 and R4, we evaluated the metric that distributes the traffic load. It also shows the performance of the algorithm when balancing the network with the different configuration of renewable energy availability. Moreover, a single best path algorithm which follows a simple routing policy that maximizes the renewable energy usage was used as a comparison benchmark. This algorithm is pursuing a route with highest renewable energy availability, which has the maximum available renewable power.

Figure 4.2 shows the renewable energy power consumption measured in per port for the two routing algorithms. The power consumption is shown as a function of

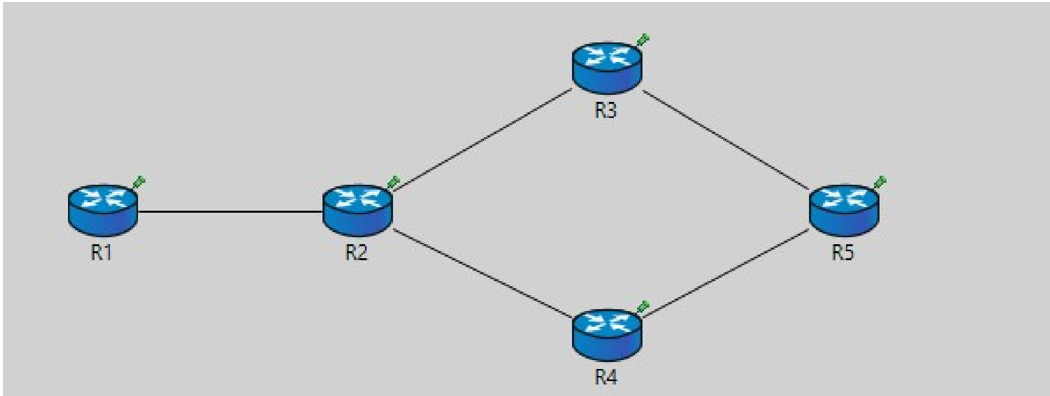

Figure 4.1: Topology of the example network

ΔC, $C = C_{R4} - C_{R3}$,where ΔC represents the difference of available renewable power between node R3 and R4. In other word, in this simulation example, we use ΔC as a variable and observe the behavior of R3 and R4. We also assume that the renewable energy availability on R4 is more than R3. Because we use the same router model and configuration in this simulation, the results will be similar when the renewable energy availability on R3 is more than R4. As the ΔC increases from 0 to 25 W, the renewable energy-aware load balancing algorithm consumes more renewable energy than the single path algorithm. In this stage, the total available renewable power of R3 and R4 is 71.5 W per port. The maximum power consumption of a port is 49 W, so the idle state power consumption of a port is 24.5 W. As ΔC equals 25W, the available renewable power on R3 is just 23.25 W. which means renewable power is insufficient to run any traffic. In all cases, the rest of the power use comes from non-renewable sources. The algorithm achieves its goal to increase the use of renewable energy. In Figure 4.2, the renewable energy power consumption of the single path algorithm linearly increases from 60.5 to 71.3 W. This is because the single path algorithm selects a route with the highest renewable energy availability, which will generate a single path with the most usage of available renewable power. The increasing ΔC makes the route pass through R4 consume more renewable power than the route pass through R3 since C_{R4} is increasing and C_{R3} decreasing at the same time. Renewable power consumption on R3 keeps the same value since no traffic pass through it. Note that all of the nodes are in working state. The renewable power consumption is a linear function of the traffic load that powered by renewable energy. According to this relationship, Figure 4.2 also shows the traffic distribution of each route. Different from the single path algorithm, the load balancing algorithm has a little variance while ΔC is lower than 25W. When sending a packet, the per-packet load balancing algorithm randomly selects a route, which is depending on the probability calculated for each node. According to this policy, the data flow distributes to every possible route, for example, R1-R2-R3-R5 and R1-R2-R4-R5. And because there is enough available renewable energy for each route, the load balancing algorithm keep balancing the traffic based on the renewable energy availability for each route.

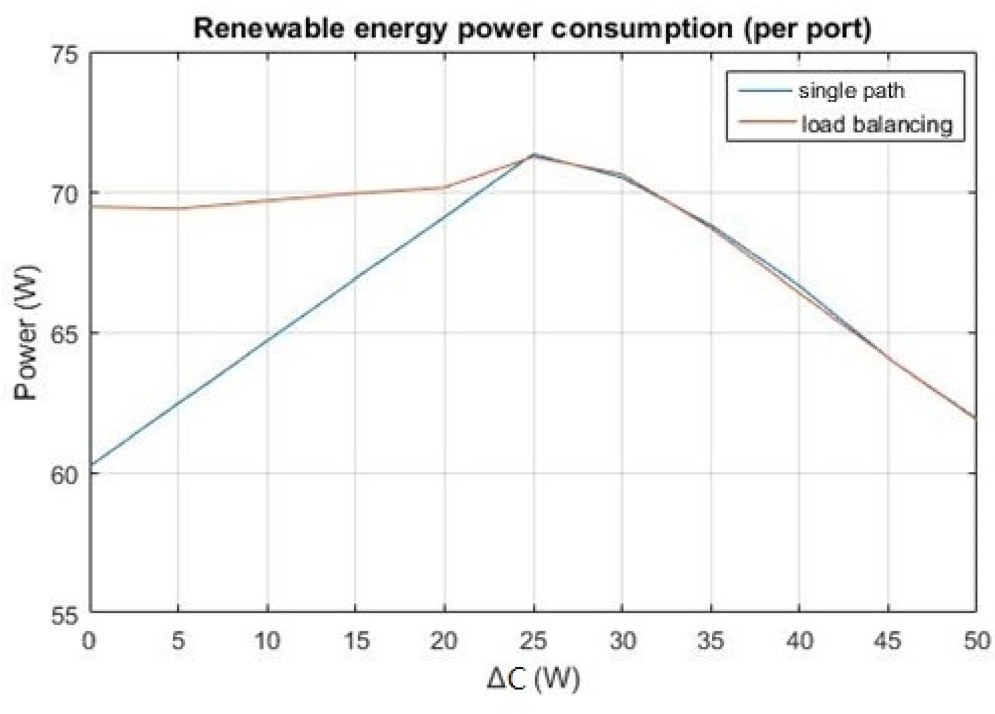

Figure 4.2: Renewable Energy power consumption between different algorithms

When ΔC equals 0, which means $C_{R4} = C_{R3}$, the available renewable power at node R3 and R4 have the same value, which results in a maximum difference between the two algorithms. This is because the setting assumes that the renewable energy availability cannot satisfy the power demand when all the traffic traverse through one node. It is worth to note that, although the single path algorithm just selects one best route, the routers on other routes still consume power since they are in the idle state. For example, while selecting the route R1-R2-R4-R5, router R3 still need to consume power. As R3 and R4 have the same renewable energy availability, each packet has the same probability to be sent to R3 or R4. The percentage of packets that go through R3 is near 50% when the number of incoming packets becomes larger. So we can consider that the traffic load has been distributed equally as it should be according to the design. Compared to the renewable power consumption of single path algorithm, the load balancing algorithm uses more renewable energy on R3 and less on R4. This behavior reduces the waste of available bandwidth supplied by renewable energy on R3. It also decreases the non-renewable energy power consumption on R4 at the same time.

With increasing ΔC, the renewable energy availability at R4 gradually becomes larger than R3. When ΔC reach 25 W, the single path algorithm achieve the maximum renewable energy usage. At this point, the available renewable power at R3 is 23.25 W, so it is lower than the idle state power demand of R3. The load balancing algorithm assigns all the incoming traffic go through R4 depend on the probability. The renewable power consumption of the single path algorithm linearly increases to the largest value when ΔC equals 25 W. Because the available renewable power on R4 achieves the value that all traffic pass through R4 can be powered by renewable energy. The two algorithms have roughly equivalent performance when ΔC is larger than 25 W. This is because the renewable power available in R3 is lower than the power demand in the idle state so that the load balancing algorithm distributes traffic to one path. As the ΔC continues to increase, the renewable energy availability on R4 becomes larger than R3 and the single path algorithm also selects the route that passes through R4. According to the weighting function, the weight of node

R3 becomes zero when renewable energy supply cannot satisfy the idle state power demand. Consequently, the probability that the route R1-R2-R3-R5 will be chosen decreases to zero. In this situation, all the traffic runs on only one path.

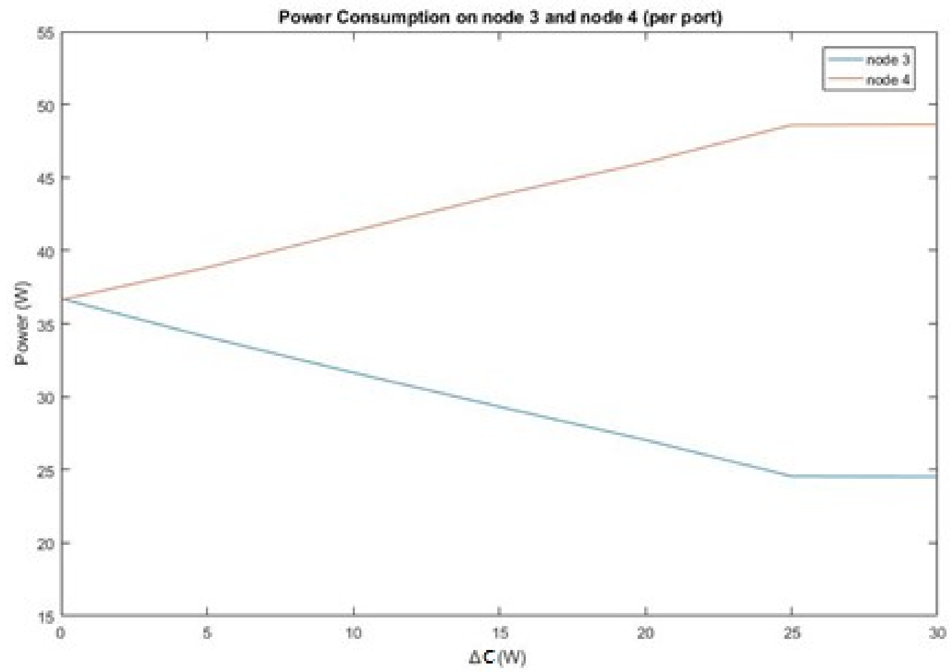

Figure 4.3: Power Consumption between node R3 and R4 (per port)

Figure 4.3 shows the total power consumption of node R3 and R4 while using the load balancing algorithm. The power consumption includes renewable energy and non-renewable energy. The total power consumption on R3 and R4 reflects the traffic load distribution of the network. R4 runs more traffic than R3 depending on the increasing renewable energy availability. On the contrary, R3 keeps decreasing until there is no traffic that pass through it. Then node R3 goes into the idle state because there is no traffic directed to R3 as there is not enough renewable energy to supply the idle state demand. As ΔC keeps increasing, R4 reaches its maximum power consumption since all the incoming traffic passes through R4. In this stage, the power consumption on R3 and R4 will not change even though ΔC keeps increasing. This is because all of the traffic load assigned to router R4 according to the renewable energy distribution. Note that the sum of the power consumption on R3 and R4 maintains almost the same value when ΔC is over 25W. The different performance on R3 and R4 show that the incoming traffic is assigned to each possible routes based on the renewable energy availability.

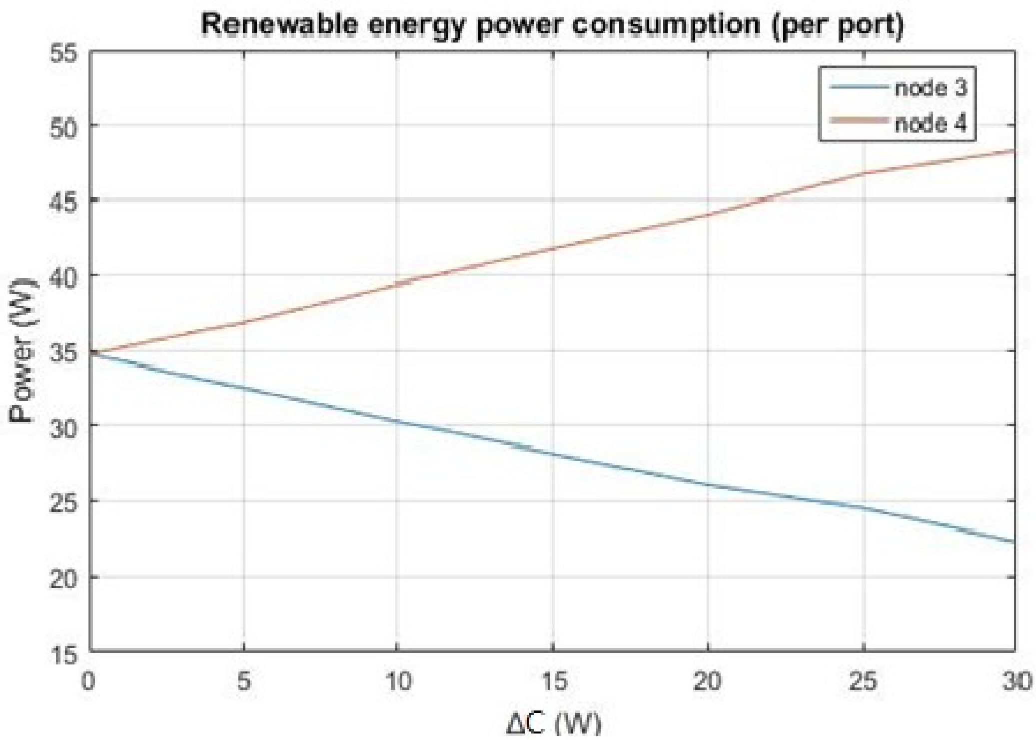

Figure 4.4: Renewable Energy Power Consumption between node R3 and R4 (per port)

Moreover, Figure 4.4 presents a linearly increasing trend on the renewable energy power consumption at R4. As ΔC becomes large, there is more available renewable energy stored or generated at R4. This increment at R4 enhances the probability that R4 will be selected. The probability that packets go through router R4 becomes larger so that more traffic load will be assigned to it. Meanwhile, the renewable power consumption at R4 also increases because of increasing incoming traffic. Similarly, the renewable power consumption at R3 has a linearly decreasing trend as a result of the reduction of renewable energy availability. Note that when ΔC is over 25 W, which means the renewable power at R3 is lower than the idle state power consumption, the increasing renewable power consumption at R4 slightly reduces since the availability is over the maximum power consumption of the router. It also means router R4 gradually turns into the full use of renewable energy. However, the renewable energy power consumption at R3 also gradually gets down to zero because the power consumption of R3 is a constant when it is in the idle state. The available renewable power at R3 is insufficient, so that rest of the idle state power consumption is compensated by the non-renewable energy. Both Figure 4.3 and Figure 4.4 show that our renewable energy-aware load balancing algorithm distributes the traffic load depending on the renewable energy availability at each node.

Chapter 5

Result Analysis

In order to evaluate the proposed renewable energy-aware load balancing routing algorithm, we conducted routing simulations to measure the effectiveness of using renewable energy. The simulations were based on implementing a network where each node has a power consumption model and a setting for renewable energy availability. In this chapter, different configurations of renewable energy availability have been considered. We calculated the renewable power consumption of routing nodes when using the load balancing algorithm and compared with the single best path algorithm.

The simulated backbone network topology is presented in Figure 5.1. The network has 7 nodes which represent 7 ASs (AS 65001 to AS 65007). We assume that each AS has one border router, which uses the Cisco CR-3 single-shelf system chassis backbone router as its border router in this simulation. Each backbone router has 16 lots which can plug in 14 10-Gigabit port cards so that the total maximum aggregated bandwidth is 2240 Gbps [12]. The power consumption parameters of CR-3 shows in Table 5.1 [12]. The packets randomly generated from the source node and followed an

Table 5.1: Power consumption parameters of router CR-3

Parameter	Value
Bandwidth	2240 Gbps
C_{full}	10984 W
C_{idle}	5492 W
SF	2.45

exponential distribution. The packets arrivals follow a Poisson process determined by the specific mean arrival rate. Because the primary purpose of this simulation is to evaluate the performance of renewable energy-aware load balancing routing algorithm, we needed to focus on specific variables and avoid the influence of other factors. We assumed that the mean arrival rate and renewable energy availability are variables under uniform distribution. In this way, we focused on measuring the impact of certain variables, for example, renewable energy availability and traffic load. We also assumed that all the nodes have renewable energy resources, such as solar or wind power. In the simulation, it was considered node R1 as the source node and node R7 as the destination node.

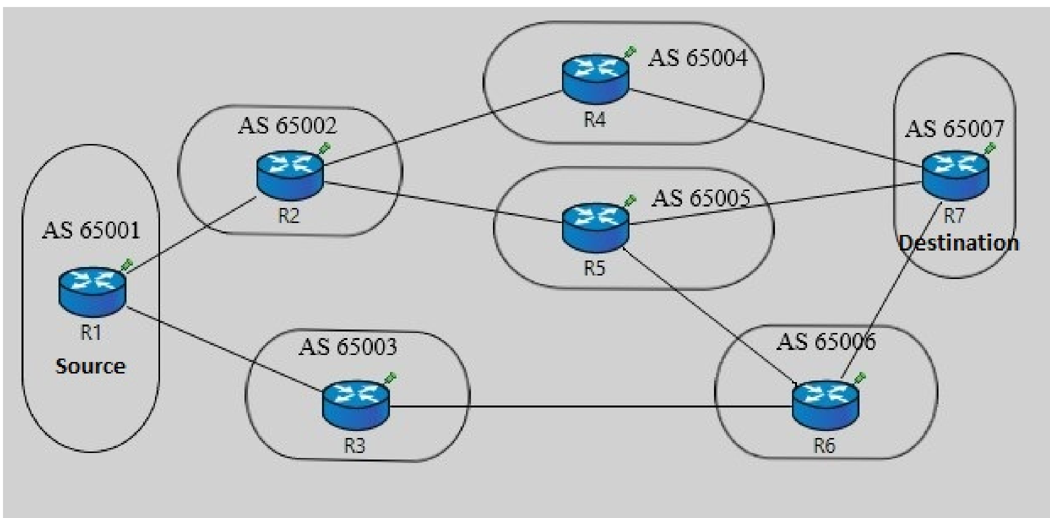

Figure 5.1: The simulated backbone network topology

5.1 Scenario 1

This set of experiments use the configuration that each node has the same renewable energy availability. It is aiming at showing the impact of renewable energy availability and traffic load.

Figure 5.2 shows the renewable power consumption percentage under different renewable energy availability conditions. The single path algorithm route packets to the only route that has the most available renewable power. The renewable power consumption percentage is measured as the ratio between the available renewable power to the total power consumption which includes renewable and non-renewable power consumption of the routing nodes. In this experiment, we consider the renewable energy availability ratio as the ratio of available renewable power to the total power demand of the nodes. This means that when the ratio is 0.5, half of the consumed power comes from the renewable source and the other half from non-renewable. When the renewable energy availability ratio is less than 0.5, the two algorithms have almost the same performance. The main reason is the renewable energy generated at each node cannot power the backbone routers to transmit any traffic data. As the renewable energy availability does not achieve the lowest power demand of each node, all the renewable energy has been used to power in part the router in the idle state. The routers consume all of the renewable energy as their basic power consumption. The rest of the power demand is compensated by non-renewable energy. In other words, there is not enough renewable energy to supply the traffic dependent component of the routers. The renewable power consumption keeps the same value no matter if the traffic data is aggregated in one path or distributed to several paths. Moreover, the weight of each node is also invariant according to the weighting function. This is because they have a fixed scaling factor which is determined by the hardware configuration of routers. The routes also have the same probability to be selected at this renewable energy availability level since they have the same configuration. Therefore, the single path algorithm and the multi-path load balancing algorithm have almost the same percentage of the renewable energy power consumption when the renewable energy availability ratio is below 0.5.

When the renewable energy availability ratio is over 0.5, the performance of the two algorithms begins to diverge. The load balancing algorithm has a higher percentage of renewable energy power consumption than the single path algorithm which

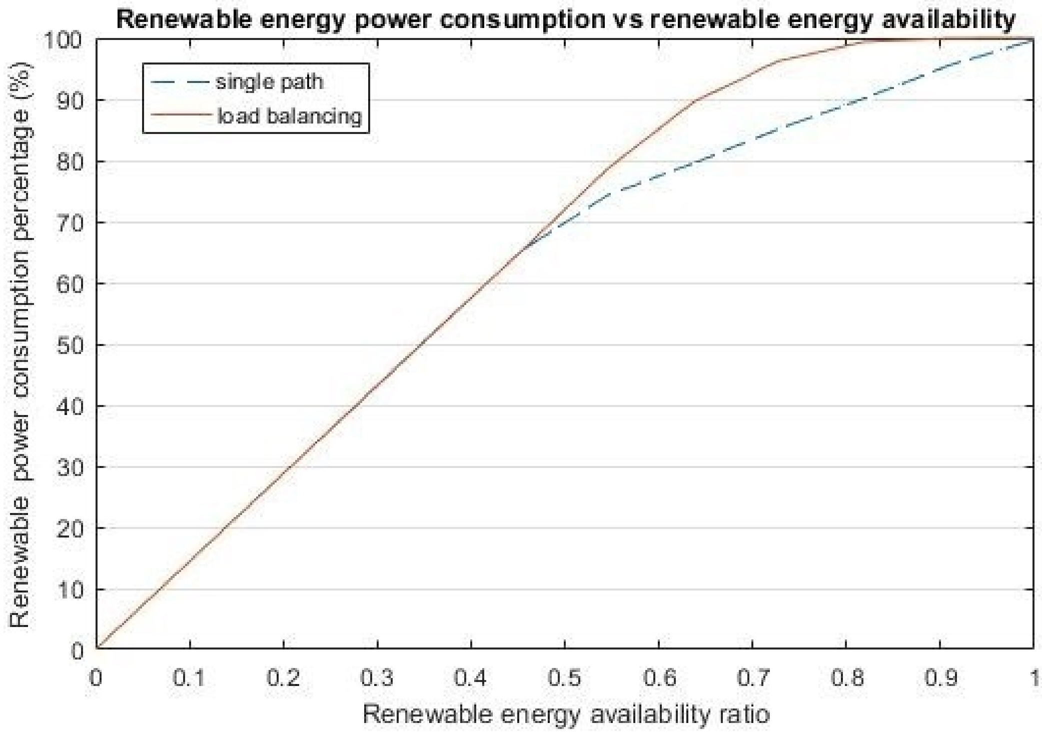

Figure 5.2: Renewable energy power consumption vs renewable energy availability with scenario 1

selects the route with maximum renewable energy availability. The maximum improvement between load balancing algorithm and single path algorithm is 11% when the renewable energy availability ratio is around 0.7. At this point, the available renewable power is still insufficient for single path algorithm to carry all the traffic load. The single path algorithm selects the best path with the highest weight so that all the traffic will pass through the nodes with more available renewable energy. If there is not enough renewable energy at the node, the router will switch to use non-renewable energy. However, the load balancing algorithm distributes the traffic loads that consumed non-renewable energy to the other candidate routes, which have available renewable power to carry these traffic loads. Consequently, the renewable power is responsible for 95% of the total power consumption when renewable energy availability ratio is around 0.7. The load balancing algorithm routes most of the traffic that used non-renewable power to other routes with available renewable power and the two algorithm achieves the maximum difference. Though single path algorithm just selects one best path, the nodes that have not been chosen to route still need to consume power to satisfy the idle state demand. They have full use of renewable energy when the renewable availability ratio is lower 0.5. For this reason, the total renewable power consumption percentage is over 70% when the availability ratio is just 0.5. As the renewable energy availability increases, the single path algorithm begins to have a lower increasing rate. This is due to the algorithm decides to transmit data only in one best route which has a low percentage of renewable energy usage. However, the other routers have full use of renewable energy at the same time, since they are in the idle state. Therefore, the percentage grows slowly when the renewable energy availability is over 0.5.

Different from the single path algorithm, the load balancing algorithm has a better performance. The load balancing mechanism makes each node achieve a higher percentage of renewable energy usage. The overall incoming traffic has been assigned to each candidate route according to the renewable aware metric, which makes each of them to carry proper traffic load. The load balancing algorithm makes use of the free available renewable power to run the traffic. Therefore, the total percentage keeps a relative high increasing rate until the percentage reaches near the upper bound. As a consequence, the total renewable power consumption percentage under load balancing algorithm is higher in this situation. It is worth to note that, the two algorithms have the same amount of total power consumption for the whole network. In other words, the load balancing algorithm consumes less non-renewable energy when transmitting the same traffic.

Figure 5.3 shows the renewable energy power consumption percentage at different traffic load conditions. The traffic load has been normalized as the variable in this simulation (note that the normalized traffic load is depending on the maximum bandwidth of a single path because the routers have the same maximum bandwidth). In

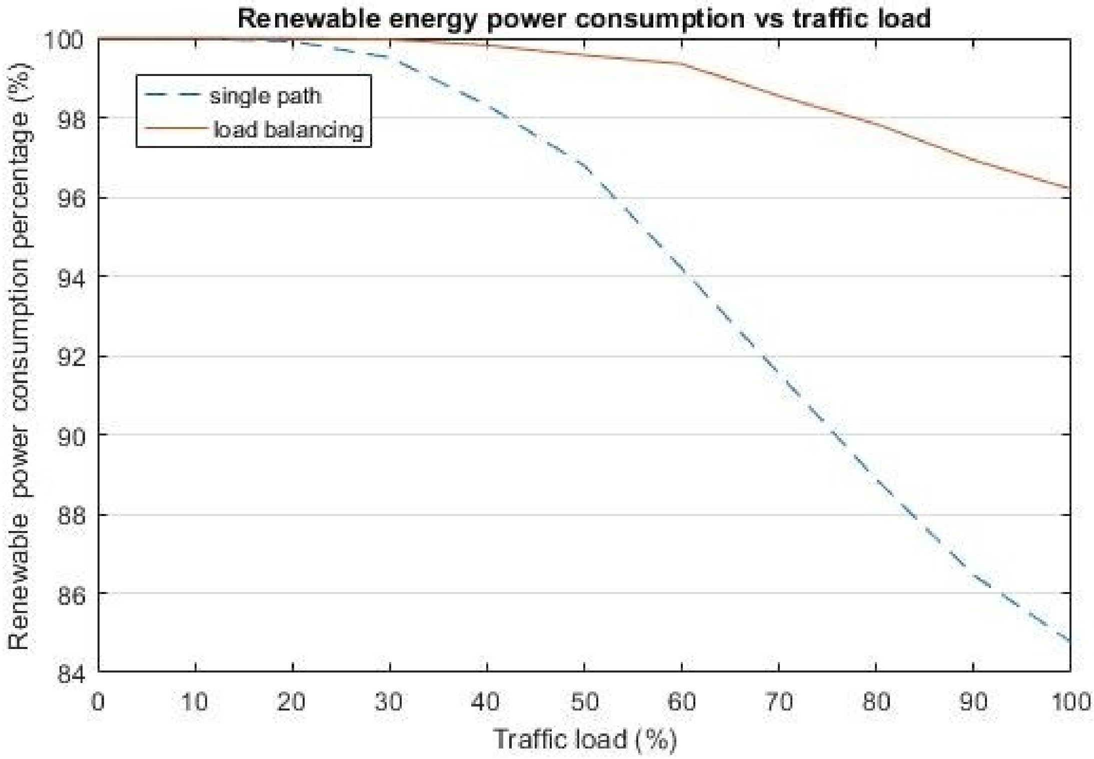

Figure 5.3: Renewable energy power consumption vs traffic load with scenario 1

this simulation, the renewable energy availability ratio is set to 0.75 which achieves a distinct difference in renewable power consumption between the two algorithms. When the traffic load is lower than 20%, the two algorithms almost have the same percentage of renewable energy power consumption. This is because the traffic load is low, and the total power consumption is also small, close to the idle state, according to the linear power model. At this time, all the nodes achieve 100% usage of renewable energy.

When the traffic begins to grow larger, the performance of the two algorithms shows a distinct difference. The load balancing algorithm increases 13% of renewable energy power consumption when the load is 100% compared with the single path algorithm. The renewable power consumption percentage decreases 4% as the traffic load increase from 0% to 100% using the load balancing algorithm. However, the single path algorithm reduce about 15%. The single path algorithm wastes some of the available renewable power at the route that has not been selected. Most of the routers stay in the idle state except for the routers in selected route. The renewable energy availability on these routers exceeds the fixed idle state power consumption so that some of the available renewable power is not used. Nonetheless, the renewable energy availability of the selected route is not enough to power all the traffic demand, so part of the traffic need to consume non-renewable energy. Therefore, the percentage of renewable energy usage has a visible reduction when the traffic load becomes larger. Compared to the single path algorithm, the load balancing algorithm maintains a high percentage of renewable energy consumption as the traffic load grows. While the traffic load is increasing, the total power consumption also increases. Consequently, the overall renewable power consumption percentage slightly decreases. Thus, the load balancing algorithm has a notable increase in renewable energy utilization than the single path one.

5.2 Scenario 2

The simulation experiments in this scenario are to show the performance of load balancing algorithm while having uneven renewable energy availability distribution at each node. In this scenario, the available renewable power on each node is proportional to the total renewable energy availability.

Figure 5.4 shows the renewable power consumption percentage with different renewable energy availability configuration. It has no appreciable difference while the renewable energy availability ratio is lower than 0.5. When the available renewable power is insufficient, all the renewable power will be used as the part of the idle state power consumption. So the renewable energy usage is a fixed as no available renewable power can be utilized to power the load-dependency component. When the availability ratio is higher than 0.5, the load balancing algorithm has inconspicuous difference against to the single path algorithm in scenario 2. Compared to the

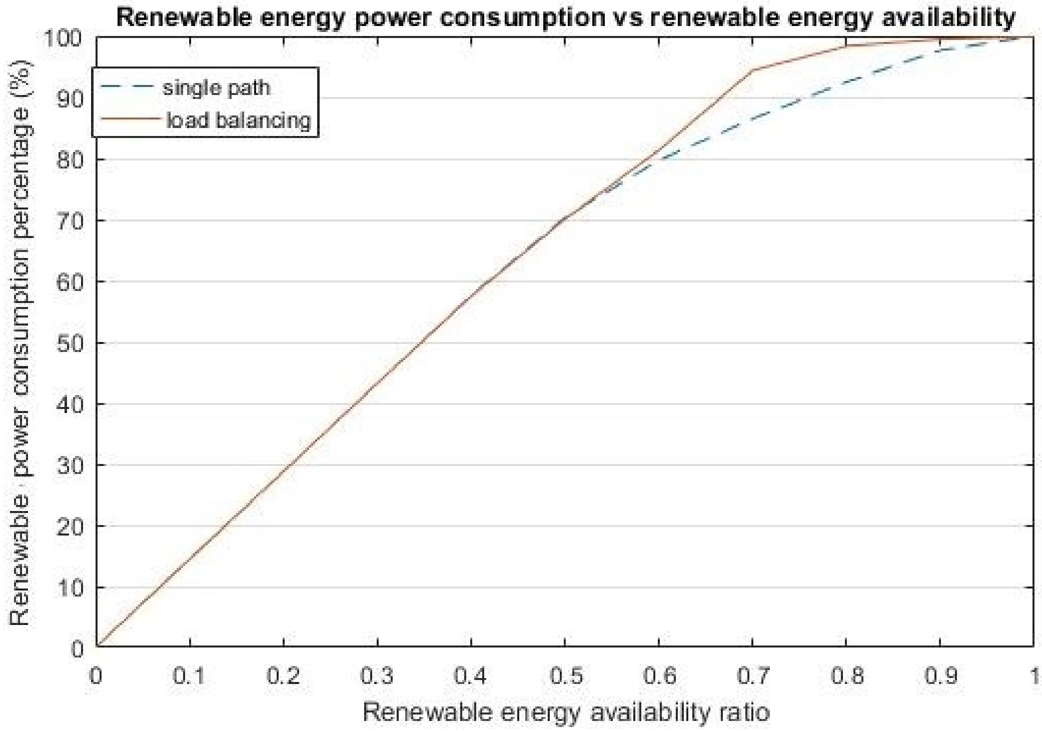

Figure 5.4: Renewable energy power consumption vs renewable energy availability with scenario 2

scenario 1, the load balancing algorithm almost achieves the same percentage of renewable power consumption. Note that the single path algorithm consumes a higher percentage of renewable energy in this configuration. This difference is due to the renewable energy availability distribution used in these simulations. The renewable energy availability used in this scenario is uneven on all nodes while the previous scenario used equal renewable energy availability. Since the load balancing algorithm distributes traffic load according to the weight, the route that has more renewable energy availability will carry more traffic load. However, the single path algorithm chooses the best route with highest renewable energy availability so that it consumes more renewable energy in this scenario. Note that the load balancing algorithm performs a little difference in this two scenarios, but the single path algorithm has a higher percentage of renewable power consumption in scenario 2. In conclusion, the load balancing algorithm balances the network depending on the renewable energy availability and maximizes the renewable energy usage at different renewable energy distribution.

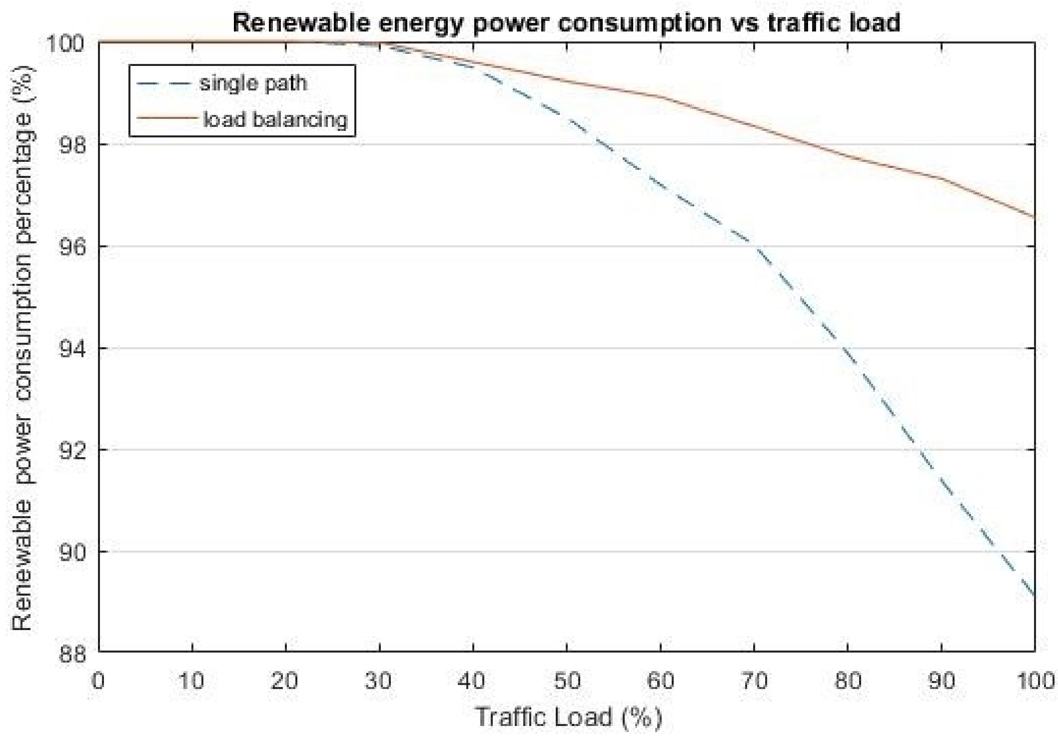

Figure 5.5: Renewable energy power consumption vs traffic load with scenario 2

In Figure 5.5, the two algorithms have a similar performance as in scenario 1. The load balancing algorithm keeps a high percentage usage of renewable energy in all traffic conditions and is close to the performance in the previous scenario. The renewable energy consumption is over 96% when the network is fully loaded since the renewable energy availability used in this scenario is the same as in previous one. The single path algorithm entirely uses the renewable energy resources as its power when the traffic load is lower than 30%. The load balancing algorithm presents a similar performance in this scenario. However, the renewable power consumption of the single path algorithm is higher than in the previous scenario. As the traffic load grows larger than 30%, the renewable energy power consumption begins to decrease. Though it shows the same trend, the single path algorithm uses more renewable energy during simulation. This is because the route that the single path algorithm selects has higher renewable energy availability than in scenario 1. The load balancing algorithm still performs well when the traffic increases. It shows a maximum 8% more renewable power consumption than the single path algorithm. The difference between two algorithms can be clearly seen when the traffic goes larger and it becomes close to the performance of scenario 1. While using the load balancing algorithm, the incoming traffic load prefers to choose the routes with higher available renewable power. Therefore, the network keeps balanced as the traffic is going larger.

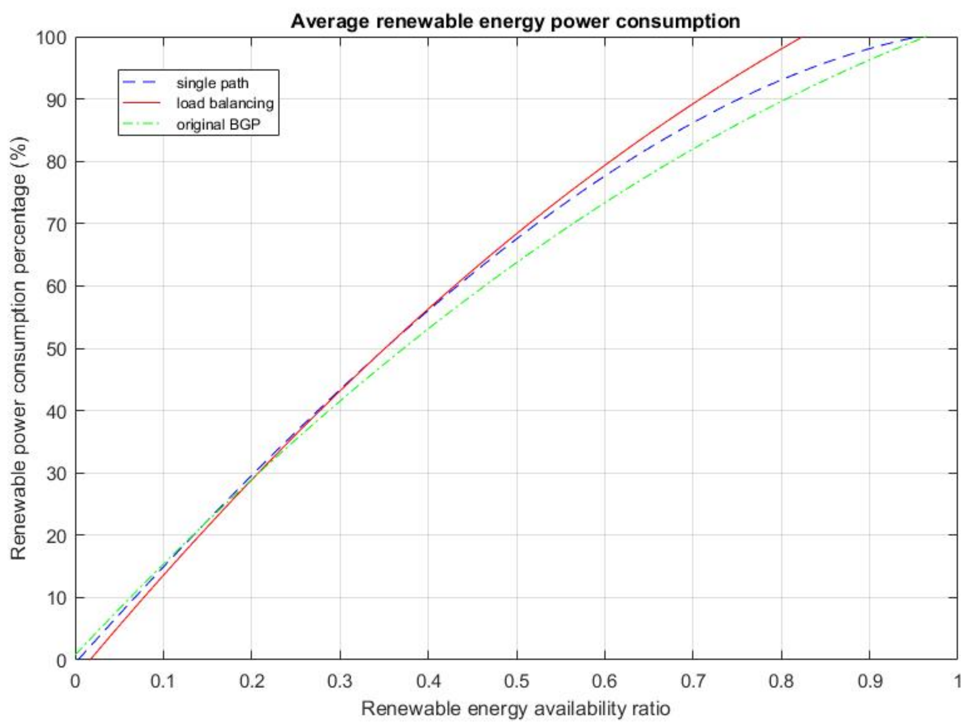

Figure 5.6: Average renewable energy power consumption

Figure 5.6 shows the average renewable energy power consumption of three algorithms. In this experiment, we randomly generate 50 sets of renewable energy availability at each routing node. Each of the nodes has different renewable energy availability. The original BGP routing algorithm selects the route with the minimum hops and has a comparison purpose only. According to this routing mechanism, the route decision will not vary based on the renewable energy availability. In Figure

5.6, we observe that our load balancing algorithm increase the renewable power consumption percentage compared with the single path and original BGP algorithm. Compared to the original routing algorithm, our load balancing algorithm increase the usage of renewable energy as renewable energy availability grows. This is due to the use of renewable energy-aware routing metric, which makes the routing decision depending on the renewable energy availability. Note that the load balancing algorithm has 100% usage of renewable energy when the ratio is about 0.82. This result shows that our load balancing algorithm can make use of the available renewable energy on several routes to increase the use of renewable energy. The results in Figure 5.6 also show that the load balancing algorithm has a higher percentage of renewable power consumption when the ratio larger than 0.5. The ratio larger than 0.5 means half of the total power demand of the network can use the available renewable power. This also indicates that the average available renewable power on each node is over the routers idle state power demand. Therefore, the load balancing algorithm utilizes the available renewable power of the nodes on each possible route to the destination.

In summary, the load balancing algorithm improves the renewable energy usage in both scenarios that have equal and unequal renewable energy availability distribution. It maintains a balanced network according to the renewable energy availability that more traffic is routed to the routes with higher renewable energy availability. The first scenario achieves a better renewable energy utilization using the load balancing algorithm when the renewable energy availability ratio is over 0.5. The reason is there is more available renewable power on the route that can be used by the load balancing algorithm. It is worth to note that, as the renewable energy is lower the idle state power demand, the balanced network has almost the same renewable power consumption as the original network. We observe that the load balancing algorithm balances the traffic loads to maximize the renewable power consumption and it also reduces the bandwidth that is powered by the non-renewable energy.

Chapter 6

Conclusion

In this thesis, we presented a renewable energy-aware load balancing routing algorithm for the backbone network which adapts renewable energy resources. This BGP-inspired routing algorithm operates based on a new routing metric and incorporate with a load balancing mechanism, which prefers the routes with more available renewable energy. The load balancing routing algorithm improves the renewable energy usage and also reduces the non-renewable consumption of the whole network. Simulation results show the load balancing algorithm distributes the traffic load to candidate routes depending on the renewable energy availability. The proposed algorithm has better performance than a single path algorithm which selects the only one route with maximum renewable energy availability. The average results also show our algorithm use more renewable energy than the original BGP routing algorithm and the single path routing algorithm. Compared to different renewable energy availability configurations, our load balancing algorithm has higher percentage utilization with the same availability scenario. The traffic load is also considered as an essential factor that influences the efficiency of the load balancing algorithm.

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