Green Routing using Renewable Energy for IP Networks

Seng-Kyoun Jo
Lin Wang
and Max Mülhäuser
Department of Computer Science
Technische Universität Darmstadt
Germany
Email: sengkyoun.jo@tk.informatik.tu-darmstadt.de,
{wang, max}@tk.tu-darmstadt.de

Young-Min Kim
KSB Convergence Research Lab
ETRI
Korea (Republic of)
Email: injesus@etri.re.kr

Jussi Kangasharju
Department of Computer Science
University of Helsinki
Helsinki
Email: jussi.kangasharju@cs.helsinki.fi

***Abstract*—Green technology for not only reducing energy consumption but also environmental pollution has become a critical factor in ICT industries. However, for the telecommunications sector in particular, most network elements are not usually optimized for power efficiency. In this work, we propose a green routing method in an IP network for the reduction of unnecessary energy consumption. In addition, it can encourage the use of power generated by renewable energy sources instead of using traditional fossil energy. As a green networking approach, we first classify the network nodes into either header or member nodes according to the quantity of the available renewable energies. The member nodes then put the routing related module at layer 3 to sleep based on the assumption that this layer in the OSI model can operate independently. All of the network nodes are then partitioned into clusters consisting of one header node and multiple member nodes. Then, only the header node in a cluster conducts IP routing and its member nodes conduct packet switching using a specially designed identifier, referred to as a tag. To investigate the impact of the proposed scheme, we conducted a number of simulations using real-world renewable energy statistics and results show that our approach outperforms the existing solutions in terms of energy efficiency to a large extent.**

I. Introduction

Recently, energy consumption has become a key factor in performance evaluation in the ICT industry. In telecommunication networks, according to the Cisco Visual Networking Index 2015 [1], global IP traffic will reach 1.1 zettabytes per year or 88.4 exabytes (one billion gigabytes) per month in 2016. By 2019, it will pass a new milestone figure of 2.0 zettabytes per year, or 168.0 exabytes per month. However, most elements in current networks are not usually optimized for power efficiency as described in [2]. Consequently, network elements should always be powered on for the connectivity regardless of the network status or traffic volume. According to [3], the network load proportional to traffic volume is quite various between peak and off-peak period. To avoid wasting energy consumption in different period, differentiated strategies in network operation are strongly required in the aspect of energy efficiency. In [4] and [5] researchers propose sleeping and standby approaches according to network status. However, it sometimes requires additional components such as a proxy or can consume more power for nodes to switch back and forth between normal and power-saving modes.

978-1-5386-0728-2/17/$31.00 © 2017 IEEE

It is not easy to measure exactly how much power can be consumed per each component of router architecture because it depends on vendors and manufactures of router. However, according to [6], [7], [8], [9] and [10], we can estimate the power consumption at layer 3, used in routing engine and packet forwarding engine as a control and forwarding plane respectively, occupies more than 30∼60% of total power consumption in current IP router architecture. Thus it is expected to reduce the total power consumption of the network if operation of each layer in OSI model can be manageable independently according to network conditions such as peak and off-peak period, etc. This assumption has become realized with the development of cloud (or virtualization) related technologies such as Network Functions Virtualization (NFV) [11], [12], which propose to use IT virtualization related technologies, to virtualize entire classes of network node functions into building blocks that may be connected, together to create communication service.

Recently, there have been growing demand to consider environmental factors in the ICT industry. Accordingly, eco-friendly energy generated by sunlight, wind, or geothermal heat, etc. is getting more attention in the effort to reduce CO_2 emissions and to protect the environment. Much research has been focused on green solutions for not only reducing the consumption of power generated by traditional fossil but also utilizing power from various renewable energy sources. In order to reduce the carbon footprint of communication networks, for example, the authors of [13] propose greener solutions for content delivery that utilize renewable energy and a content caching concept. In particular, the authors consider the joint routing and caching problem from the point of view of minimizing the consumption of power generated from fossil energy source while satisfying users' requests.

As a green networking approach, the main contributions of this paper are summarized as follows: i) We define the network energy consumption problem and analyze its complexity; ii) We propose a green routing algorithm which can reduce energy consumption by clustering network nodes. Also the availability of renewable energy sources is taken into consideration; iii) We perform a number of simulations to evaluate the proposed green routing mechanism by using real renewable energy statistics under the NSFNET topology. The experimental results reveal that the proposed routing mechanism can achieve up to 37% more energy savings compared to existing solutions.

The rest of the paper is organized as follows. Section II presents the related work. Section III gives an overview of green network architecture and Section IV describes the network min-energy problem to be solved. Section V provides the design of green routing and the performance analysis using simulation is introduced in Section VI. Finally, Section VII summarizes the paper.

II. Related Work

Energy efficiency has been a common topic in wireless environments such as sensor networks, IoT, and mobile communication, and a significant amount of research has sought ways to extend the battery life. The authors in [14] analyzed the trade-off between spectrum efficiency and energy efficiency and introduced various studies within a framework of energy-efficient resource allocation in a 5G wireless network. However, triggered by the recent exponential growth of network traffic volume, 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 goal in the area of wired networks. To analyze green technologies in a wired IP network, the authors of [15] categorized base approaches into re-engineering, dynamic adaptation, and sleeping/standby. Related to these issues, a number of researches have been undertaken during the last decades. As a re-engineering approach focusing on designing energy-aware elements, the authors in [16] introduced an investigation of the potential savings achievable through power-aware network design and routing. The authors measured the power consumption of various configurations of widely used routers. They then created a general model for router power consumption based on measurement results to explore the potential impact of power-awareness in a set of example networks. To achieve a dynamic adaptation, approaches have aimed at modulating the capacities of packet processing engines and a network interface to satisfy the actual traffic loads and requirements. The authors in [17] proposed a novel approach to switching off some portions of the UMTS core networks while still guaranteeing full connectivity and maximum link utilization. As an extension of [17], the authors of [2] proposed a simple algorithm to power off the links and even full routers while still satisfying the QoS constraints, such as the maximum link utilization. As an example of dynamic adaptation, the GreenOSPF algorithm in [25] extended the existing OSPF protocol slightly to share the shortest path tree of a specific node with neighbor nodes, and solves the above problem by switching off those network elements that are excluded by the shared shortest paths. Finally, sleep/standby approaches are used to selectively drive network equipment into low standby modes, and to wake them up only when necessary. The authors in [18] investigated how a network connectivity proxy can enable significant energy saving by allowing idle hosts to enter a low-power sleep state and still maintain a full network presence.

Some interesting methods using renewable energy have recently been proposed to take our environment into account. The authors in [19] focused on the way how to minimize fossil fuel consumption in large Internet Service Provider (ISP) networks, by proposing new gradient-based routing protocol, which favors forwarding packets along routers powered by the highest quantity of renewable energies. Also the authors in [20] proposed green Internet routing using renewable energies by clarifying the model of how routers can distinguish renewable and non-renewable energies. Then, they reformulated an energy consumption problem, setup special cases based on the clarification, and proposed optimal and sub-optimal algorithm while guaranteeing QoS requirements. Datacenter is also one of the potential target to reduce carbon footprint and energy cost using renewable energy. Through the actual power trace experiments, the authors of [21] proposed a case that it is actually possible for a distributed Internet Data Center (IDC) system to exploit the geographical and temporal diversity of wind power in order to achieve green cloud service. The idea is to leverage the front-end load dispatching server to send work to the location where wind power is available. Then they proposed a wind-power-aware (WPA) algorithm which routes jobs considering both the current states of workloads and wind power availabilities in the data centers.

III. Overview of Green Networking

As a green networking approach, we propose a green networking solution for minimizing the power consumption in an IP network as illustrated in Figure 1. Assuming that the functions of each layer in a network node can be controlled independently, the proposed solution defines two kinds of network nodes: header node (HN) and member node (MN). An HN is a general IP router for IP packet processing, and an MN is a special node (or router) that can perform packet switching using a tag whenever its function at layer 3 is in the sleep mode. Then the solution partitions a whole network into clusters with one HN and more than one MN. After partitioning, the links between MNs belonging to the same cluster are switched off because the routing function of MNs is in sleep mode and traffic can be rerouted to the HN.

In current networks, most elements are usually powered by traditional fossil energy and this has an environmental impact as they consume more and more electricity, as described in Section I. Thus, green solutions which can improve energy efficiency in networks as well as minimize CO_2 emission are in the limelight. Assuming network elements are powered partially by renewable energy and partially by traditional

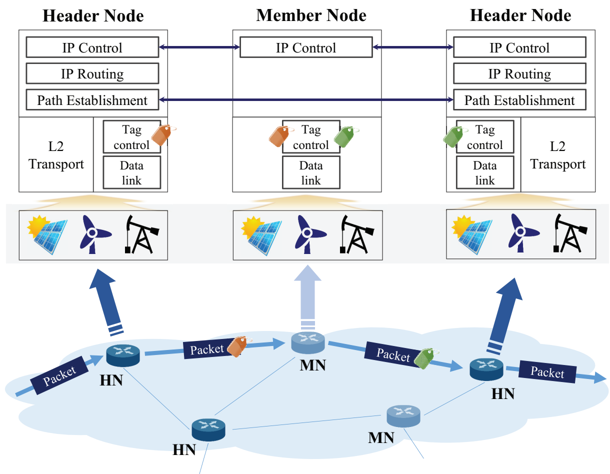


Fig. 1: The logic of green networking

fossil fuel-based energy, the proposed solution encourages network elements to be powered by the highest quantity of renewable energy sources instead of traditional fossil energy. The renewable energy could be a combination of multiple energy sources, such as geothermal heat, tides, and various forms of biomass, but in this paper we have considered wind and solar energy sources.

IV. Min-Energy Network Design Problem

The problem of minimizing the power consumption in a network satisfying a given traffic matrix can be formulated with a linear program [22]. However, our problem is different in the sense that we need to decide which nodes to be selected as HN and which links to be switched off accordingly such that the total power consumption of the network in terms of fossil energy is minimized, i.e., the renewable energy is maximally utilized.

Let us consider a network that is captured by 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 set N_i where $l_{ij} \in L$ for any $j \in N_i$. We consider the power consumptions from both the node and the link. The power consumption of a fully functional node (i.e., HN) $i \in V$ is characterized by $e^{HN}(i) : V \to \mathbb{R}^+$, while the power consumption of a MN with L3 functions disabled is characterized by $e^{MN}(i)$. Note that power consumption to manage hardware is not considered in $e^v(i)$ and $e^{MN}(i)$. The power consumption of a link $l_{ij} \in L$ is characterized by $e^l(l_{ij}) : L \to \mathbb{R}^+$. The power consumption of a link will be evenly distributed to the two endpoints of the link. For node i, we denote by $E_f(i)$ and $E_r(i)$ the available power from the fossil and the renewable energy respectively. We assume that both the node and the link can be turned into low-power mode to save energy by introducing decision variables $\alpha_i, \beta_{ij} \in \{0, 1\}$ for node, link respectively. Depending on the value of α_i and β_{ij}, the power consumption of node i from fossil energy can be represented by

$$P_f(i) = \min\{(\alpha_i e^{HN}(i) + (1-\alpha_i)e^{MN}(i) + \frac{1}{2}\sum_{j\in N_i} \beta_{ij} e^l(l_{ij}) - E_r(i)), 0\} \quad (1)$$

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; it is zero if the renewable energy is enough to support the total power consumption of the node 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, the min-energy network design problem can be formulated with the following integer program.

$$\begin{aligned} \min \quad & \sum_{i\in V} P_f(i) \\ \text{s.t.} \quad & \sum_{i \in V^k} x_i = 1, \ \forall k \in [K], && \text{(2a)} \\ & \cup_{k\in[K]} V^K = V, && \text{(2b)} \\ & V^{k_1} \cap V^{k_2} = \emptyset, \ \forall k_1, k_2 \in [K], && \text{(2c)} \end{aligned}$$

where constraint (2a) ensures that each cluster of nodes contains only one HN. Constraint (2b) and (2c) represents 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. 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 $\alpha_i = 1$, $\alpha_j = 1$, and there exists $k \in [K]$ such that $i, j \in V^k$. In addition, the following two constraints need to be satisfied in order to ensure that the traffic can be successfully routed on the derived network.

$$\sum_{j\in N_i} f_{ij}^{sd} - \sum_{\{j\in V | i \in N_j\}} f_{ji}^{sd} = \begin{cases} f^{sd}, & \forall s, d, i = s \\ -f^{sd}, & \forall s, d, i = d \\ 0, & \forall s, d, i \neq s, d \end{cases} \quad (3)$$

$$\sum_{s\in V}\sum_{d\in V} f_{ij}^{sd} \leq C_{ij} \quad \forall i, j, l_{ij} \in L \quad (4)$$

It can be easily verified that the general Capacitated Multi-Commodity Flow (CMCF) problem is actually a special case of the above problem, which is known to be NP-hard in general. Since the above problem is as hard as CMCF, we can obtain that our min-energy network design problem is also NP-hard. Therefore, we aim at developing efficient heuristics instead of searching for exact solutions.

V. Design of Green Routing

In this section, green routing algorithm as the objective of our research is presented with several procedures.

A. Partitioning of the Whole Network into Clusters

1) HN Selection: Now we start with simple method described in Algorithm 1 for how to select HNs and configure clusters with selected HNs and MNs. For the selection of HNs, various criteria can be considered selection policies

Algorithm 1 Pseudo code for header node selection

$E_f(i)$: Available power from fossil energy at node i
$E_r(i)$: Available power from renewable energy at node i

for node i = 1 to node i = N **do**
  Compute $savedE_f^{HN}(i)$ and $savedE_f^{MN}(i)$

$$\textbf{\textit{savedE}}_f^{HN}(i) = \begin{cases} E_r(i) & \text{if } E_r(i) < E_f(i) \\ E_f(i) & \textit{Otherwise} \end{cases}$$

  ▷ The amount of power consumption saved if the node operates as *HN*

$$\textbf{\textit{savedE}}_f^{MN}(i) = \begin{cases} E_f(i) & \text{if } E_r(i) \geq \rho E_f(i) \\ (1-\rho)E_f(i) + E_r(i) & \textit{Otherwise} \end{cases}$$

  ▷ The amount of power consumption saved if the node operates as *MN*
  sendToNeighbor $(node_{i \to j},\ savedE_f^{MN}(i))$
    ▷ node j is a neighbor node of node i
  receiveFromNeighbor $(node_{j \leftarrow i},\ savedE_f^{MN}(j))$
end for

Compute ***savedE***$_f(i)$ = $savedE_f^{HN}(i)+\sum_j^k savedE_f^{MN}(i)$

for node i = 1 to node i = N **do**
  sendToNeighbor $(node_{i \to j},\ savedE_f(i))$
  receiveFromNeighbor $(node_{j \leftarrow i},\ savedE_f(j))$
end for

if max $(savedE_f(i),\ \cdots,\ savedE_f(j))$ = $savedE_f(i)$ **then**
  node i is selected to be a *HN*
else
  node i is selected to be a *MN*
end if

such as node utilization, network nodality, end-to-end delay, etc. In this paper, we consider the availability of renewable energy sources in order to decide HNs selection and node clustering as explained in Algorithm 1. For HN selection procedure, each node first computes how much fossil energy is saved if node can be powered by renewable energy sources in case of HN and MN. Then each node sends information including $savedE_f^{MN}(i)$ to its neighbor nodes. On receiving information, each node compute $savedE_f(i)$ which means the amount of saved fossil energy if node itself operates as a HN and the other neighbor node operate as MNs. Finally each node exchanges the amount of saved fossil energy with neighbor nodes and the node which has maximum value of $savedE_f$ is selected to be HN.

2) Clustering with one HN and multiple MNs: After the HN selection procedure, nodes selected as HNs send advertising messages to the adjacent nodes. Once neighbor nodes receive a message from the HNs, they compare $savedE_f(i)$ from multiple HNs and select the HN has the maximum $savedE_f(i)$. If nodes receive an advertising message from other HNs, they then discard the advertising message. The clustering procedure is described in Algorithm 2.

Algorithm 2 Pseudo code for clustering

for header node i = 1 to i = n^{HN} **do**
  for member node j = 1 to j = n^{MN} **do**
    sendToNeighbor $(node_{i \to j},\ savedE_f(i))$
    receiveFromNeighbor $(node_{j \leftarrow i},\ savedE_f(i))$
  end for
end for

MNjoinsHN (node j, node i)
    ▷ node j selects node i which has the maximum $savedE_f(i)$ as HN

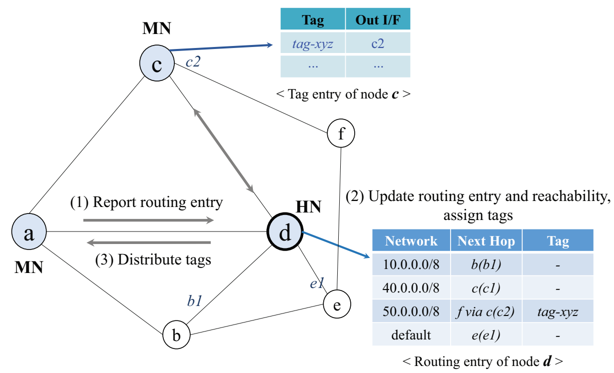


Fig. 2: Tag allocation and distribution

B. Green Packet Routing

1) Tag Allocation and distribution: After clustering, the MNs send routing information to their HN, and the HN adds this routing information to the routing entry for identifying the arrival reachability through the MNs. In this step, there can be several routing entries for the same next hop. 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 cluster the MNs, as illustrated in Figure 2. A tag is a specially designed identifier within a cluster for switching instead of IP routing, and includes the outgoing node interface. Even though label defined in MPLS architecture [23] can have similar feature and used for packet switching, we propose a simple identifier in order to focus on the solution of given problem in Section 1 rather than traffic engineering concerns. Upon receiving tags from an HN, the MNs temporary 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.

2) Packet Routing using Tag: To demonstrate the operation of packet switching from a source to a destination, we consider a simple network topology with 3 clusters $\{a,\ c,\ \boldsymbol{d}\}$,$\{\boldsymbol{b}\}$, $\{e,\ \boldsymbol{f}\}$ as shown in Figure 3, wherein each HN of cluster is expressed in bold. When node a receives packets without tags and forwards them to node d, as an operating assumption, the

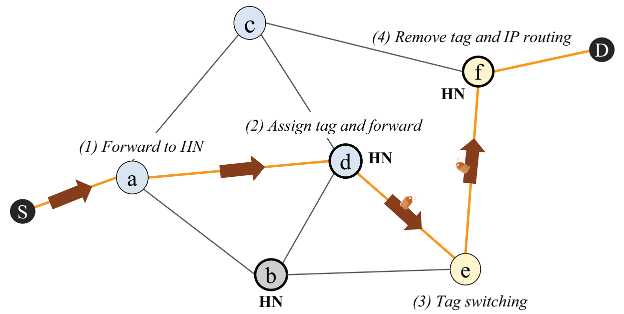


Fig. 3: Green routing operation

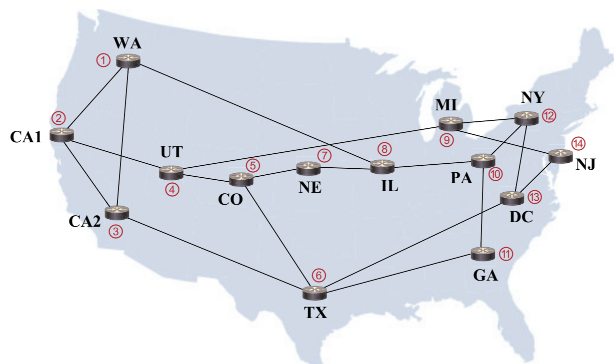


Fig. 4: NSFNET topology in US

MN (i.e., 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 e. Node e forwards the packets to the next hop, node f, after tag switching. Finally, packets with a tag arrive at node f, which removes the tag and routes the packets to the destination.

VI. Evaluations

This section describes the comprehensive simulations we carried out to evaluate the energy saving performance of our proposed algorithm.

A. Experimental Settings

To investigate the performance of the proposed algorithm, we conducted several simulations using an NS-2 simulator under the well-known NSFNet topology with 14 nodes and 42 links, as shown in Figure 4. To evaluate of the energy consumption, we assumed the power consumption of a node is 700W; 490W is used for IP routing (i.e., ρ = 0.3), with the residual being used for tag switching. In addition, the power consumption of a link is 235 W according to [13].

In order to consider the effect of renewable energy, we used the meteorological data which is available from the *National Solar Radiation Data Base*, available in [24] and got the real weather dataset of 14 nodes including (i) *Global Horizontal Irradiance(GHI)*, a widely used metric to estimate how much solar power could be achievable from photovoltaic solar panels; (ii) wind speeds for every hour in a year. [19] provides the distribution of available renewable energy in the U.S using the average annual wind speed and *GHI*.

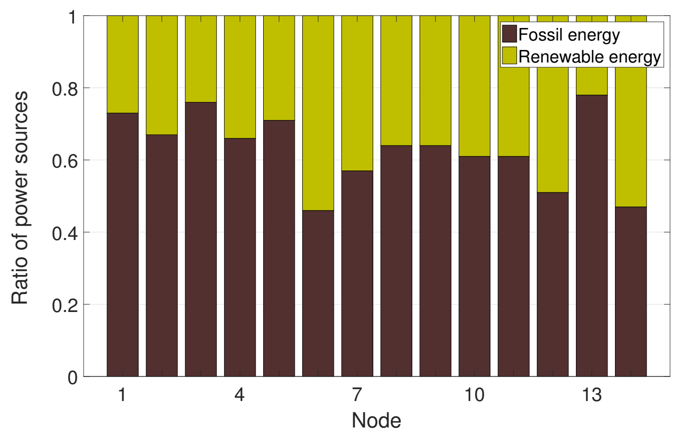


Fig. 5: Ratio of power sources used in 14 nodes

B. Energy Efficiency of Green Routing

Under these conditions, we measured the energy efficiency, which is defined as the rate of reduced power consumption. In particular, we compared the energy efficiency of the proposed algorithm with those of the GreenOSPF [25], ILP [2] and tag switching algorithm [26].

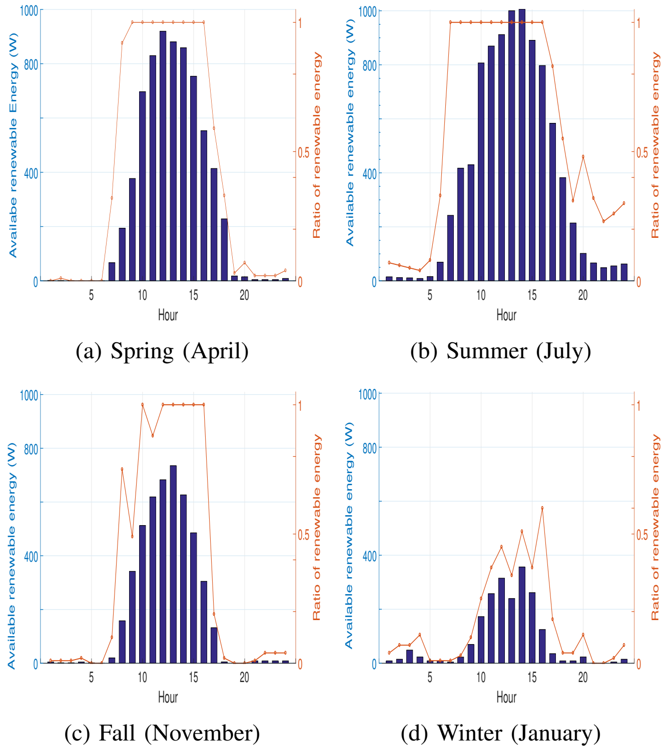
Figure 5 shows the ratio of power sources in 14 nodes after network node clustering. Overall, power consumption from fossil energy can be reduced by 37% and replaced by renewable energy sources.

Figure 6 summarizes the results obtained in evaluating how renewable energy can be used to support power consumption per season at node 3, which is located in California where there is plenty of sunshine in daytime hours with little wind and so large amounts of power can be generated from solar panels.

Figure 7 illustrates the energy efficiency (i.e., how much fossil energy can be saved) under various routing algorithms according to the change in offered load. As the offered load increases, energy efficiency is reduced in most algorithms except for our proposed one. Such behavior is caused by traffic congestion of nodes and links and the constraint (4) cannot be satisfied. In order to solve a hot spot problem, it is necessary to turn MNs into HNs and switch on unused links. Even though the energy efficiency of the proposed algorithm differs according to time and season, it encourages the consumption of available renewable energy first. Thus, the proposed algorithm using renewable energy shows better performance regardless of the offered load.

VII. Conclusions

Energy efficiency is becoming a key factor for a greener ICT industry. Our study of a green network provides an algorithm to reduce the consumption of power generated from fossil energy, and instead, encourages the use of renewable energy in IP networks. The proposed algorithm first configures



(a) Spring (April) (b) Summer (July)

(c) Fall (November) (d) Winter (January)

Fig. 6: The available renewable energy and its ratio at node 3

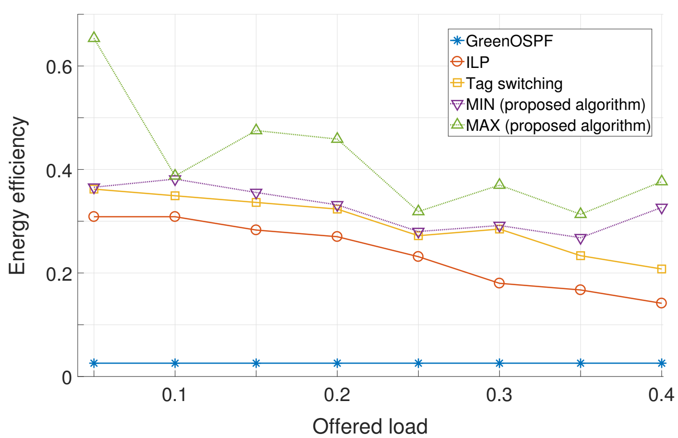


Fig. 7: Energy efficiency w.r.t. the algorithms

clusters consisting of one HN and multiple MNs according to the HN selection method using the availability of renewable energy of nodes, and conducts green routing using tags. The results obtained show that the proposed green routing scheme can exhibits a more energy efficient performance than previous works. In a future study, we will investigate network provisioning with respect to various renewable energies.

ACKNOWLEDGMENT

This work has been partially funded by the German Research Foundation (DFG) Collaborative Research Center (CRC) 1053 MAKI.

REFERENCES

[1] "Cisco visual networking index: Forecast and methodology, 2014-2019," tech. rep., Cisco, 2015.

[2] L. Chiaraviglio, M. Mellia, and F. Neri, "Reducing power consumption in backbone networks," in *IEEE ICC*, Jun. 2009.

[3] Y.-M. Kim, E.-J. Lee, and H.-S. Park, "Ant colony optimization based energy saving routing for energy-efficient networks," *IEEE Communications Letters*, vol. 15, Jul. 2011.

[4] ITU-T REC. Y.3022, "Measuring energy in networks," Aug. 2013.

[5] M. Andrews, A. Anta, L. Zhang, and W. Zhao, "Routing for energy minimization in the speed scaling model," in *IEEE INFOCOM*, Mar. 2010.

[6] A. M. Lyons, D. T. Nelson, and T. R. Salamon, "Energy efficient strategies for high density telecom applications," tech. rep., Alcatel-Lucent, Jun. 2008.

[7] "EU-ECONET project." http://www.econet-project.eu. Accessed: 2017-02-27.

[8] J. Wu, S. Rangan, and H. Zhang, *Green Communications: Theoretical Fundamentals, Algorithms and Applications*. CRC Press, 2012.

[9] V. Acharya *et al.*, "Energy Consumption of IP vs Ethernet," 2012.

[10] C. Lee, S. Jung, Y. Kim, and J.-K. K. Rhee, "Energy efficient network planning: Issues and prospects in wired/wireless network," in *ICT Convergence (ICTC), 2011 International Conference on*, pp. 132–135, IEEE, 2011.

[11] J. Matias, J. Garay, N. Toledo, J. Unzilla, and E. Jacob, "Toward an SDN-enabled NFV architecture," *IEEE Communications Magazine*, vol. 53, no. 4, 2015.

[12] C. Bu, X. Wang, M. Huang, and K. Li, "SDNFV-based dynamic network function deployment: Model and mechanism," *IEEE Communications Magazine*, 2017.

[13] A. Khreishah, H. B. Salameh, I. Khalil, and A. Gharaibeh, "Renewable energy-aware joint caching and routing for green communication networks," *IEEE Systems Journal*, vol. PP, no. 99, 2016.

[14] G. Wu, C. Yang, S. Li, and G. Y. Li, "Recent advances in energy-efficient networks and their application in 5G systems," *IEEE Wireless Communications*, 2015.

[15] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy efficiency in the future internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures," *IEEE Communications Surveys & Tutorials*, May. 2011.

[16] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright, "Power awareness in network design and routing," in *IEEE INFOCOM*, 2008.

[17] L. Chiaraviglio, D. Ciullo, M. Meo, M. A. Marsan, and I. Torino, "Energy-aware UMTS access networks," in *IEEE W-GREEN*, 2008.

[18] X. Wang, M. Veeraraghavan, T. Miyazaki, S. Okamoto, N. Yamanaka, and I. Popescu, "Dynamic layer-1 WAN access architecture for large enterprises," in *IEEE ICNC*, 2015.

[19] J. Mineraud, L. Wang, S. Balasubramaniam, and J. Kangasharju, "Hybrid renewable energy routing for ISP networks," *INFOCOM, 2016 Proceedings IEEE*, pp. 1–9, 2016.

[20] Y. Yang, D. Wang, D. Pan, and M. Xu, "Wind blows, traffic flows: Green internet routing under renewable energy," *INFOCOM, 2016 Proceedings IEEE*, 2016.

[21] Y. Gao, Z. Zeng, X. Liu, and P. Kumar, "The answer is blowing in the wind: Analysis of powering internet data centers with wind energy," in *INFOCOM, 2013 Proceedings IEEE*, pp. 520–524, IEEE, 2013.

[22] L. Chiaraviglio, M. Mellia, and F. Neri, "Minimizing ISP network energy cost: Formulation and solutions," *IEEE/ACM Transactions on Networking*, Apr. 2012.

[23] "IETF RFC 3031, Multiprotocol Label Switching Architecture," 2001.

[24] NREL, "National Solar Radiation Data Base." http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_USAFN.html.

[25] A. Cianfrani, V. Eramo, M. Listanti, M. Marazza, and E. Vittorini, "An energy saving routing algorithm for a green OSPF protocol," in *IEEE INFOCOM*, Mar. 2010.

[26] S.-K. Jo, Y.-M. Kim, H.-W. Lee, J. Kangasharju, and M. Muehlhaeuser, "A novel packet switching for green IP networks," *ETRI Journal*, vol. 39, no. 2, 2017.