Novel Packet Switching for Green IP Networks

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A green technology for reducing energy consumption 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. Here, we propose a novel energy-efficient packet switching method for use in an IP network for reducing unnecessary energy consumption. As a green networking approach, we first classify the network nodes into either header or member nodes. The member nodes then put the routing-related module at layer 3 to sleep under the assumption that the layer in the OSI model can operate independently. The entire set of network nodes is 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, a tag. To investigate the impact of the proposed scheme, we conducted a number of simulations using well-known real network topologies and achieved a more energy-efficient performance than that achieved in previous studies.

Keywords: Green network, Power consumption, IP network, Network node clustering, Packet switching.
such as Network Function Virtualization [11], the purpose of which is the use of IT virtualization-related technologies to virtualize entire classes of network node functions into building blocks that may be connected together to create a communication service.

This study may be considered as a green networking approach to energy-efficient packet switching. Specifically, we propose an algorithm to minimize the power consumption of a network during off-peak periods in an IP network. Assuming that the functions of each layer in a network node can be independently controlled, the proposed algorithm first selects header nodes (HNs) to manage general IP packet processing and manages subordinate member nodes (MNs) that will temporarily suspend IP packet processing at layer 3. In addition, instead of IP routing, each MN will conduct packet switching using a specially designed tag.

The reminder of this paper is organized as follows. Section II provides an overview of related works, and the problem formulation is presented in Section III. Section IV provides the network configuration and packet switching algorithm. A performance analysis using a simulation is developed in Section V, and the results and conclusions are presented in Section VI.

II. Related Works

Energy efficiency is not a new concept, and it has been an important topic of wireless environments such as sensor networks, IoT, and mobile communication. A significant amount of research has been expended to extend the battery life of various devices. The authors in [12] 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. In the area of MWSN, the authors in [13] designed a clustering algorithm to optimize the energy efficiency of mobile sensor nodes; this algorithm is employed to find the near-optimal threshold for residual energy and to reconfigure clusters. However, due to the recent exponential growth in the volume of network traffic, the spread of access to the Internet, and the expansion of new ICT services offered by service and network providers, energy efficiency has also become a high-priority goal of wired networks.

To analyze green technologies in a wired IP network, the authors of [14] introduced base approaches such as re-engineering, dynamic adaptation, and sleeping/standby. A large amount of research related to these issues has been performed during the last several decades.

As a re-engineering approach focusing on designing energy-aware elements, the authors in [15] introduced an investigation of the potential savings through power-aware network design and routing. The authors measured the power consumption of various configurations of widely used routers. Based on measurement results, they then created a general model for router power consumption to explore the potential impact of power-awareness in a simple space of example networks.

To achieve a dynamic adaptation, approaches have been formulated with an objective to modulate the capacities of packet processing engines and a network interface to satisfy actual traffic loads and requirements. The authors in [16] proposed a novel algorithm that involved switching off some portions of the Universal Mobile Telecommunication System core networks while still guaranteeing full connectivity and maximum link utilization. As an extension of [16], the authors of [2] proposed a simple algorithm to power off the links and full routers while maintaining the QoS constraints, such as maximum link utilization. As an example of dynamic adaptation, the GreenOSPF algorithm, presented in [17], extended the existing OSPF protocol slightly to share the shortest path tree of a specific node with neighboring nodes, and it solves the above problem by switching off network elements that are excluded by the shared shortest paths. The authors in [18] proposed reducing the router power consumption using a machine-learning technique to identify and quickly adapt to the changing traffic characteristics.

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 [19] investigated the effect of network connectivity proxy on energy saving by allowing idle hosts to enter a low-power sleep state while maintaining a full network presence.

Some interesting methods, focused on specific applications such as content delivery, have recently been proposed to reduce the power consumption in networks. The authors in [20] proposed an energy-efficient framework for content delivery in networks to support multicast transport and in-network caching. In [21], the authors also provided a survey of energy-efficient caching techniques in an information-centric network from the place, content placement, and request-to-cache routing aspects for a green ICN.

III. Problem Formulations

1. Network Energy Consumption Problem

An energy-consumption minimization network problem can be formulated using linear programming [22]. Let us consider a direct graph $G(V, L)$, where $V$ and $L$ are the set of nodes and directed links, respectively. A link that connects node $i$ to its neighbor node $j$ is denoted by $l_{ij}$. The set of neighbors of node
i is denoted by \( \{N_i \in V, l_i \in L\} \). Each node \( i \in V \) and link \( l \in L \) are characterized by the energy consumption \( e^l(i): V \rightarrow R^+ \) and \( \bar{e}^l(i) : L \rightarrow R^+ \), respectively. Note that the power consumption required to manage the hardware is not considered in the definition of \( e^l(i) \). Given the traffic matrix \( T_{\text{traffic}} = [f^i_{sd}]_{\text{traffic}} \), such that \( f^i_{sd} \) is the amount of traffic from source \( s \) to destination \( d \), the above problem to be solved is as follows,

\[
\min \left\{ \sum_{i \in V} e^l(i) + \sum_{i \in L} e^l(l_i) \right\},
\]

\[
\sum_{j \in N_i} f^i_{sd} - \sum_{j \in N_i} f^i_{sd} = \begin{cases} f^i_{sd}, & \forall s, d, i = s, \\ -f^i_{sd}, & \forall s, d, i = d, \\ 0, & \forall s, d, i \neq s, d, \end{cases}
\]

\[
f_{ij} \leq C_{ij}, \forall i, j, l_i \in L,
\]

where \( f^i_{sd} \) is the amount of traffic from \( s \) to \( d \) that is routed through link \( l_i \). Constraint (2) refers to the classical flow conservation constraints, whereas constraint (3) requires the total offered load transmitted on link \( l_i \) to be less than the link capacity \( C_{ij} \). The above energy consumption in a network has the typical form of a capacitated multi-commodity flow problem. Accordingly, solving this problem (that is, an NP-complete problem) is not viable for large-scale networks.

2. Reformulation of Network Energy Consumption Problem

In order to reformulate the original energy-consumption minimization network problem to be feasible, we introduce several primitives related to network clustering and a lemma. Our goal is to minimize the total power consumption of a network; we begin by comparing the power consumption before clustering. Prior to clustering, all nodes and links should be turned on, and in this case, the power consumption \( PC \) can be formulated as follows.

\[
PC = \sum_{i \in V} e^l(i) + \sum_{i \in L} e^l(l_i).
\]

On the other hand, based on the traffic change, several nodes and links can be switched off after clustering and the power consumption \( PC_{\text{clustering}} \) can be less than \( PC \). As a result, we can reduce the power consumption by reducing the difference between the power consumption before clustering and the power consumption after clustering. This implies that our goal can be referred to as “maximize the power consumption reduced by clustering;” which is defined as \( \max(\text{PC} - \text{PC}_{\text{clustering}}) \).

Let us now suppose that the network consists of \( K \) clusters and \( 1^K \) is a set of nodes that consists of one HN and one or more MNs.

\[
V^1 \cup V^2 \cup \ldots \cup V^K = V.
\]

Then, the number of HNs and the total power consumption of cluster \( k \) \( (PC_k) \) is as follows.

\[
n_{\text{HN}} = N - \sum_{k} n_{\text{MN}},
\]

\[
PC_k = e^l(i) + n_{\text{MN}} e^l(i) + \sum_{i \in V^k} \sum_{j \in N_i} \gamma e^l(l_j),
\]

where \( N \) is the number of nodes in the network and is equal to \( n_{\text{HN}} + n_{\text{MN}} \); \( e^l(i) : V \rightarrow R^+ \) is the power consumption of an MN in which the IP-routing related operation at layer 3 is temporarily put to sleep; \( n_{\text{HN}}, n_{\text{MN}} \) is the sum of the number of HNs in the network and MNs in cluster \( k \), respectively; and, \( \gamma \) is a binary variable \( \{0, 1\} \) if \( l_j \), which is initialized to 1, is powered on.

In order to calculate the effect of clustering, we divide the power consumption of the network into the power consumption of the nodes and links. First, from the node energy perspective, the power consumption of nodes \( (PC') \) before clustering is as follows.

\[
PC'_n = n e^l(i).
\]

The power consumption of the nodes after clustering \( (PC'_{\text{clustering}}) \) is as follows.

\[
PC'_{\text{clustering}} = \sum_{k} \left( e^l(i) + n_{\text{MN}} e^l(i) \right) = n_{\text{HN}} e^l(i) + n_{\text{MN}} e^l(i).
\]

Accordingly, the amount of power consumption of the nodes reduced by clustering can be obtained as follows by using (5), (7), and (8).

\[
Ne^l(i) - \left( n_{\text{HN}} e^l(i) + n_{\text{MN}} e^l(i) \right) = n_{\text{MN}} (e^l(i) - e^l(i)).
\]

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

\[
PC'l = \sum_{i \in L} e^l(l_i).
\]

Using (6), the total power consumption of links within cluster \( k \) after clustering is

\[
PC'^{clustering}_k = \sum_{i \in V^k} \sum_{j \in N_i} \delta e^l(l_j),
\]

where \( \delta \) is also a binary variable \( \{0, 1\} \), the value of which specifies whether \( l_j \) is powered on or off. Note that (11) includes only links within the cluster. In order to consider the power consumption of the link after clustering, we need to consider the links that connect the clusters; this can be expressed as follows:

\[
PC'^{clustering}_k = \sum_{k} \left( PC'_k + \sum_{i \in V^k} \sum_{j \in N_i} \delta e^l(l_j) \right).
\]
where $\delta$ is a binary variable $\{0, 1\}$ set to a value of 1 if node $i$ and node $j$ belong to different clusters and $l_{ij}$ is powered on. The amount of power consumption of the links reduced by clustering can be defined as follows by using (10)–(12).

$$\sum_{i,j} \sum_{l_{ij}} e'(l_{ij}) = \sum_{i} \{ PC_i + \sum_{j, l_{ij} \in N_i} \delta e'(l_{ij}) \}. \quad (13)$$

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

$$\sum_{i>j} \sum_{l_{ij}} \delta = n^N_{MN}, \quad \sum_{i} \{ \sum_{j, l_{ij} \in N_i} \delta \} = n^N. \quad (14)$$

Then, (13) can be rewritten using (14) as follows:

$$\sum_{i,j} \sum_{l_{ij}} e'(l_{ij}) = \left( n^N \cdot e'(l_{ij}) + \sum_{j} \{ \sum_{l_{ij} \in N_i} \delta e'(l_{ij}) \} \right). \quad (15)$$

In conclusion, our goal is to maximize (9) and (15) from the point of view of the total power consumption of the nodes and links, respectively. According to the measurement study in [6], $e'(i) - e'(i) \geq 0$.

Thus, maximizing (9) is the same as maximizing the number of MNs (that is, minimizing the number of HNs) in the network, which is the general purpose of our proposed algorithm in this paper. Accordingly, we focus on maximizing (15) (that is, minimizing the links among clusters). To solve (15), we introduce a new concept referred to as "link centrality among clusters."

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

$$C^i(i) = \sum_{\varphi_j} \sum_{l_{ij} \in N_i} \varphi_j,$$

where $\varphi_j = \max_{l_{ij}} e'(l_{ij})$ and $C^i(i) \leq 1$ defines how densely the traffic of node $i$ centralizes on a specific link $l_{ij}$ to other clusters. All links in the network are assumed to have the same capacity and the same energy consumption.

**Lemma.** As $C^i(i) \rightarrow 1$ (that is, maximizes), the energy consumption of links among clusters is minimized and the number of active links among clusters (that is, the number of active links among clusters, $\sum_{i} \{ \sum_{l_{ij} \in N_i} \delta \}$ in (15)) can be also minimized.

**Proof.** For $C^i(i) \rightarrow 1$, $\varphi_j = \sum_{l_{ij} \in N_i} \sum_{j, l_{ij} \in N_i} \delta$ must be satisfied. This implies $l_{ij}(j \in N_i, j \notin V^K) \rightarrow 0$ holds except for the link with the highest traffic volume; that is, there exists little traffic on the links $l_{ij}(i \notin l_i)$. Accordingly, node $i$ in cluster $k$ can minimize the energy consumption by allowing

the traffic carried on $l_{ij}(\neq l_i)$ to be aggregated on the link $l_{ij}(i \in V^K)$ first, and then switching off the other links, $l_{ij}(\neq l_i)$. Then, the number of links among the clusters can be reduced by switching off $l_{ij}(\neq l_i)$.

Accordingly, our goal to minimize the original problem in (1) is to reduce the number of active links among clusters that maximizes (15) while satisfying the flow conservation constraints described in (2) and (3).

**IV. Network Node Clustering and Packet Switching Algorithm**

1. **Partitioning of an Entire Network into Clusters**

   The objective of our research—the creation of a packet switching algorithm—is presented in this section along with several detailed procedures. First, we classify all network nodes into either HNs or MNs. An HN is a general IP router for IP packet processing, and an MN is a special node (or router) that can perform IP packet switching using a tag whenever its function at layer 3 is in the sleep mode. Routing-related functions at layer 3 include routing and packet forwarding engines, such as IP header processing and quality of service queueing. Figure 1 illustrates the logic for energy-efficient packet switching, including the node architecture of the HNs and MNs.

   **A. Header Node Selections**

   We will begin with the simple method described in Algorithm 1 that describes the selection of HNs and configuration of clusters using the selected HNs and MNs. Regarding the selection of HNs, various criteria can be considered to define the selection policies, such as the power consumption of the network node, the network nodality, and end-to-end delay. In this study,
we assume that the utilization of network nodes is applied to the HN selection and node clustering, as shown in Fig. 2.

Algorithm 1 describes the HN selection procedure. First, each node sends a message including the utilization information of a node and link to its neighbor nodes. Upon receiving this message, each recipient node inserts the neighbor information into the neighbor table. After sending and receiving a message, each node calculates the difference in utilization between nodes. Finally, nodes are selected to be either HNs or MNs through a comparison with the threshold. The threshold is a predefined value determined by the network operator and is used as the basis for an HN decision. A lower value of the threshold will result in a greater number of HNs among multiple HNs. Once the nodes receive an advertising message from some HN, they then discard subsequent advertising messages. The clustering procedure is described in Algorithm 2.

Algorithm 2. Pseudo code for clustering
1: for header node \( i = 1 \) to \( i = N \) do
2: \( \text{sendToMN} \ (\text{node}_{i-j}, u_i, u_{ij}) \)
3: \( \text{receiveFromNeighbor} \ (\text{node}_{j-w}, u_j, u_{wj}) \)
4: \( \text{insertNeighborTable} \ (\text{node}_{i-j}, u_i + u_{ij} - u_j + u_{wj}) \)
5: end for
6: \( \text{MNs} \ (\text{node}_i, \text{node}_j) \)

Member node \( j \) selects the least utilized header node \( i \).

C. 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 to identify the arrival reachability through the MNs. In this step, there can be several routing entries that support the same next hop. After adding the MN information, the HN selects the shortest and non-overlapping next hop among multiple paths targeted for the same destination, and it 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 Fig. 3.

Rather than using IP routing, we use a tag, which is a specially designed identifier within a cluster, for switching that includes the outgoing node interface. Even though the label defined in the Multi-Protocol Label Switching (MPLS) architecture [23] can be used for packet switching, we propose a new and simple identifier in order to solve the problem defined in Section I. Upon receiving tags from an HN, the MNs temporarily put the routing-related function in layer 3 to sleep and perform packet switching using a tag. If the MNs receive packets without a tag, the packets are directly forwarded to the cluster HN.
2. Packet Switching Using a 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, d\}, \{b\}, and \{e, f\}, as shown in Fig. 4. Each HN of each cluster is expressed in bold. When node a receives packets without tags and forwards them to node d, as an operating assumption, the MN (that is, 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. After tag switching, node e forwards the packets to the next hop, node f. Finally, packets with a tag arrive at node f, which removes the tag and routes the packets to the destination.

V. Performance Analysis

To investigate the performance of the proposed algorithm, we conducted several simulations using an NS-2 simulator configured with the well-known NSFNet topology with 14 nodes and 42 links, as shown in Fig. 5(a). Additionally, as described in Figs. 5(b) and 5(c) and Table 1, we include real network topologies from the Rocketfuel project given in [24]; the Exodus (3967) and Ebene (1755) networks are composed of 79 nodes and 294 links, and 87 nodes and 322 links, respectively.

For an evaluation of the energy consumption, we assume that the consumed power of the node is 600 W; 420 W are used for IP routing, whereas the residual is used for tag switching [6]. In addition, the power consumption of a link is 235 W according to [14].

Under these environments, we measured the energy efficiency, defined as the ratio of the number of links to be switched off to the total number of all links. In particular, we compared the energy efficiency of the proposed algorithm with those of the GreenOSPF [17] and ILP [2] algorithms.

Figure 6 shows the results obtained from the evaluation of the performance of the proposed algorithm under various topologies. As the offered load increases, energy efficiency is reduced in all network topologies. However, in the cases of Exodus and Ebene, both of which are scale-free networks, the energy efficiency rapidly decreases when the offered load is greater than 0.3. On the other hand, we observe less reduction in a random NSF network as the load increases. This behavior is caused by traffic congestion at hot spot nodes in the Exodus and Ebene topology with smaller offered load. In an NSF network, less congestion occurs because the nodal degree is uniformly distributed between 1 and 4. Thus, the proposed algorithm shows better performance in random networks than scale-free networks regardless of the offered load. Overall, the proposed algorithm can be applied to both random and scale-free network topologies as our objective is the reduction of power consumption during off-peak periods.

Figure 7 summarizes the energy efficiency when the offered load is 0.2. All previous algorithms attempt to reduce the energy consumption by turning off the nodes and links. Therefore, the energy efficiency of an ILP is much higher than GreenOSPF because the ILP determines the nodes and links to be turned off through a complicated optimization technique. Generally, turning off the network equipment allows incoming flows, passing by the elements, to be rerouted to other candidate paths, which results in paths that are much longer than the shortest paths.

The behavior described above causes the traffic to be
aggregated on the links that still turn on, and hence, the average link load for such links naturally increases, as shown in Fig. 7. If some of the nodes begin to experience congestion as a result of the rerouting, the algorithm may no longer support the energy consumption, which is why the energy efficiency of an ILP stops at 25%. Contrary to previous approaches, the proposed algorithm simply turns off the L3 routing function while maintaining the network connectivity to the HN. Accordingly, the candidate paths are no longer than the original shortest paths, thereby providing an opportunity to reduce the energy consumption much more than previous methods.

Figure 8 illustrates the energy efficiency under various network topologies according to the change in HN ratio by adjusting the threshold value in the HN selection procedure when the offered load is 0.4. As the number of HNs increases, the energy efficiency in an NSF also increases. As explained in Figs. 7 and 8, a random NSF network has fewer hot spot nodes and less congestion caused by rerouting after clustering. On the other hand, congestion can easily occur at several hot spot nodes in a scale-free network. We can therefore observe the optimal conditions that can maximize the energy efficiency under the given traffic load and HN ratio.

VI. Conclusions

Energy efficiency is becoming a key factor in the green ICT industry, in addition, it is essential to realize trusted network infrastructure as ICT industries continue to grow. Our research for a green network provides an algorithm to minimize the power consumption in IP networks during off-peak periods. The proposed algorithm first configures clusters consisting of one HN and multiple MNs according to the HN selection method, and conducts packet switching using tags. The results obtained show that the proposed packet-switching scheme can obtain more energy efficient performance than previous works. In a future study, we will investigate a trade-off between the HN selection method and performance, as well as research optimal network conditions to maximize energy efficiency.

References


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