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Ant colony based self-adaptive energy saving routing for energy efficient Internet

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ABSTRACT

According to recent research, the current Internet wastes energy due to an un-optimized network design, which does not consider the energy consumption of network elements such as routers and switches. Looking toward energy saving networks, a generalized problem called the energy consumption minimized network (EMN) had been proposed. However, due to the NP-completeness of this problem, it requires a considerable amount of time to obtain the solution, making it practically intractable for large-scale networks.

In this paper, we re-formulate the NP-complete EMN problem into a simpler one using a newly defined concept called 'traffic centrality'. We then propose a new ant colony-based self-adaptive energy saving routing scheme, referred to as A-ESR, which exploits the ant colony optimization (ACO) method to make the Internet more energy efficient. The proposed A-ESR algorithm heuristically solves the re-formulated problem without any supervised control by allowing the incoming flows to be autonomously aggregated on specific heavily-loaded links and switching off the other lightly-loaded links. Additionally, the A-ESR algorithm adjusts the energy consumption by tuning the aggregation parameter β , which can dramatically reduce the energy consumption during nighttime hours (at the expense of tolerable network delay performance). Another promising capability of this algorithm is that it provides a high degree of self-organizing capabilities due to the amazing advantages of the swarm intelligence of artificial ants. The simulation results in real IP networks show that the proposed A-ESR algorithm performs better than previous algorithms in terms of its energy efficiency. The results also show that this efficiency can be adjusted by tuning β .

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1. Introduction

Energy conservation is becoming a key issue for the Internet because its energy consumption is remarkably high and may exponentially grow [1,2]. According to several studies [3], the global amount of energy consumed by the Internet has been approximately 900 billion kWh, which represents 5.5% of the total global electricity

consumption; this consumption is estimated to increase by around 20–25% annually. Furthermore, the energy efficiency of the current Internet is very low, approximately 8–10 times lower than that of wireless networks [4], which arises from the fact that, as indicated in [5], the network elements, such as routers and switches, in the current Internet are not optimized for energy saving; they tend to consume the maximum energy even though the carried traffic occupies only a small portion of their capacity, and their capacity is usually over-provisioned for accommodating future growth. Experiments in [6] found this energy inefficiency in current network elements, where is little or no difference in the energy consumption between peak and off-peak periods.

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To cope with this energy inefficiency, two types of approaches, classified as system-level and network-level, have been proposed. The system-level approaches [2,5,6] are based on the following observation: if network elements can predict the idle periods of their outgoing links, they could reduce energy consumption by switching off their relevant interfaces during the predicted idle periods. However, they intrinsically require the redesign or replacement of the existing network elements to be capable of this foresight.

The network-level approaches [4,7–9] use a slightly different method; rather than developing intelligent network elements, they try to minimize the active network elements, such as nodes or links, while still guaranteeing network connectivity. The authors in [8,9] formulated an integer linear programming (ILP) of the above problem and proposed some methods for its solution. Although these methods can reduce the active network elements quite effectively, solving the ILP problem is unfortunately not viable in large-scale networks because it is a variant of multi-commodity flow problems (i.e., NP-complete). The GreenOSPF algorithm in [4] set out to reduce the active network elements by sharing the shortest path tree of a specific node with neighbors of the node, rather than solving the time-consuming ILP problem. This algorithm can accomplish its task within a finite time; however, it may waste energy under dynamic network conditions because it only considers the topological information without the knowledge of the network's status, such as the traffic demand.

In this paper, we propose a novel network-level approach referred to as A-ESR to produce energy efficient networks. The proposed A-ESR algorithm exploits the ant colony optimization (ACO) method, which is a promising technique in solving combinatorial optimization problems [10,11] and has been applied in many communication areas [12–14]. In A-ESR, a single artificial ant colony is employed in the networks, in which a number of artificial ants in the colony gather information about the network's status and deposit pheromone trails based on the gathered information in real-time. The novel contributions of the A-ESR algorithm are as follows:

- A-ESR defines a new concept named traffic centrality and re-formulates the aforementioned NP-complete ILP problem into a simpler one using the defined traffic centrality.
- The re-formulated problem can be gradually solved by letting incoming flows be autonomously aggregated on specific links.
- A-ESR promptly learns the current changing network status by exploiting the pheromone trails deposited by artificial ants, in real-time. Accordingly, under the learned status, this algorithm can reduce the energy consumption more efficiently.
- A-ESR adjusts the energy consumption by tuning the aggregation parameter β . It intuitively teaches us that when network traffic load is low, the proposed algorithm dramatically reduces the energy consumption by increasing β .
- Due to the inheritance from the advantages of swarm intelligence [11], A-ESR provides a high degree of self-organizing capabilities.

The remaining part of this paper is organized as follows. In Section 2, we formulate the energy consumption minimized network problem, review some related works to solve the problem, and re-formulate the original problem into a new one using the newly defined traffic centrality. We then explain the proposed A-ESR algorithm, focusing on how to solve the re-formulated problem in detail in Section 3. The computational complexities of the proposed scheme and related works are analyzed in Section 4. In Section 5, we compare the performance of the previous schemes with respect to their energy efficiency under the real network topologies provided by the Rocketfuel [15] project. Finally, we conclude the whole paper and briefly describe future research directions for this project.

2. Problem definitions

2.1. Energy consumption minimized network problem

An energy consumption minimized network (EMN) problem can be formulated using integer linear programming [8,9]. Let us consider a directed 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 $\{N_i | i \in V, l_{ij} \in L\}$. Each node $i \in V$ and link $l \in L$ is characterized by the energy consumption functions $e^v(i) : V \rightarrow R^+$ and $e^l(l) : L \rightarrow R^+$, respectively. Given the traffic matrix $\mathbf{TM} = [f^{sd}]_{N \times N}$, where f^{sd} is the amount of traffic from source s to destination d , the EMN problem to solve is as follows:

$$\text{minimize} \left(\sum_{i \in V} e^v(i) + \sum_{i \in V} \sum_{j \in N_i} e^l(l_{ij}) \right), \quad (1)$$

$$\text{C1) } \sum_{j \in N_i} f_{ij}^{sd} - \sum_{j \in N_i} f_{ji}^{sd} = \begin{cases} f^{sd}, & \forall s, d, i = s \\ -f^{sd}, & \forall s, d, i = d \\ 0, & \forall s, d, i \neq s, d \end{cases} \quad (2)$$

$$\text{C2) } f_{ij} \leq c_{ij} \quad \forall i, j, l_{ij} \in L \quad (3)$$

where f_{ij}^{sd} is the amount of traffic from s to d that is routed through link l_{ij} , and f_{ij} is the total amount of traffic on link l_{ij} . Eq. (2) states the classical flow conservation constraints, while Eq. (3) requires the total offered load on link l_{ij} to be smaller than the link capacity c_{ij} . As we already know, the above problem has the typical form of a capacitated multi-commodity flow problem; accordingly, solving the problem (i.e., NP-complete) is not viable in large-scale networks.

The authors in [8,9] proposed some heuristic methods to solve this problem. The basic operation principle of these methods takes the brute-force approach: initially, all network elements start with the on state; then, they try to temporarily switch off a network element (either a node or a link), and check the network connectivity (C1) and maximum link utilization constraints (C2). If no violation is present, the network element can be switched off. In this manner, they iteratively try to switch off all other network elements. Although these authors significantly reduce the computational complexity of the original ILP

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