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Network Topology Towards Energy-Efficient IP-Networks

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Abstract—Operating the Internet infrastructure in an energy-efficient manner becomes a challenging issue in most recent years with the recognition of significant energy consumption due to its large scale. Yet a limited number of contributions are available to address the issue mainly through putting idle routers and links into sleep mode, at the price of low global resource utilization efficiency and degraded network performance.

The same line of research but investigates an optimal solution of configuring IP network topology to minimize the number of active routers and links, and hence energy consumption, whilst keep the interference on network operation minimal. An optimal energy-efficient network model along with a heuristic algorithm is proposed for identifying the network elements in sleep mode to attain approximately the best trade-off between the energy-efficiency and performance degradation. Numerical experiments are carried out to assess the solution for a range of network and load scenarios and the results clearly demonstrate its effectiveness and Analysis of the Parameters of QoS.

Index Terms— energy efficiency, topology control, power saving.

I. INTRODUCTION

Internet becomes a global infrastructure with the enormous proliferation in the past few decades and its current energy consumption becomes extremely significant. It is indicated that the energy consumed by the Internet infrastructure is approximately 350 billion kWh in the US and 868 billion kWh globally. It is also show that the consumption of network equipments (access routers, backbone routers and links) represents about a quarter of the total Internet energy consumption. The Internet becomes a notable contributor of cardon emissions, e.g. the Information and Communication Technology (ICT) systems cause about 2% of the global carbon emissions.

In recent years, many research efforts are made from various aspects towards the energy-efficient networks in the literature. In a pioneering idea of reducing Internet energy consumption by putting idle network devices to sleep is proposed. It also highlights that the network energy efficiency can be improved at different network levels (individual device, network level and network topology) by adopting appropriate solutions.

A set of energy-saving approaches are available on operating individual devices by implementing various device-level mechanisms. In [4], [5], the authors suggest to operate certain network interfaces into sleep mode assuming that the devices can accurately estimate the time of packet arrivals. A policy of optimizing device power consumption is presented in [6] enabling individual devices to dynamically switch to their most suitable working frequencies based on the awareness of traffic load at network interfaces.

Very recently, the investigation has focused on reducing energy consumption in the scope of the overall network, instead of individual network devices or components. The fundamental idea behind the solutions is as simple as follows: when the network load is moderate, traffic demand on the under-utilized links can be shifted to the highly-utilized links and the former links can be put into sleep mode.In [7], an algorithm of obtaining the maximum number of nodes and links which can be switched off is proposed. The approach is further improved in [7] by presenting a new algorithm and assessment with a realistic ISP topology. However, there are some critical limitations with this approach which can be summarized into two-fold:(1) topology adjustment is constrained by a condition that the link utilization after adjustment is below 50%,which restricts the topology configuration flexibility and global resource efficiency; and (2) the access routers at network boundary in general cannot be selected to be in sleep mode as the connected end users will no longer have access to network services. A modified OSPF algorithm is proposed by using selected nodes and links to route packets. Nevertheless, this approach only considers improving energy-efficiency by manipulating links and keeping all routers in operation. The authors also pointed out that this modified OSPF algorithm is inappropriate for heavy-load network scenario as it may result in large load variation across links, and hence severe transition of network performance. This paper attempts to take a further step following the same strategy and resolve the highlighted drawbacks by explicitly incorporating the performance degradation constraint into the energy-efficiency optimization.

II. PROBLEM DEFINITION

In the current Internet infrastructure, the routers can be simply classified into two categories: backbone routers and access routers. In general, only the backbone routers can be operated in the sleeping mode as appropriate by shifting the traffic passed them to other nodes. Nevertheless, the access routers at the network boundary are in most of the case kept active as they are directly connected with the end users or required application resources. The network is modeled with both energy-efficiency and network performance in mind.

The variation of link utilization of all active links in the network W is used to evaluate the potential performance degradation due to network topology changes. The primary aim of the work is to promote the energy-efficiency in the IP networks. It is reported in [7] that the average resource utilizations of the Internet backbone and LAN are approximately 15% and 1%, respectively. This indicated that the majority of the consumed energy in the network is wasted. In addition, it is very often that multiple alternative end to end routing paths are available between sources and destinations. It implies that the low energy-efficiency links can potentially shift its traffic demand to alternative routing path and switch to the sleep

However, our solution highlights two constraints that (1) the end to end connection for each pair of access routers with traffic demand should be remained; and (2) the performance degradation in terms of link load variation should meet the predefined constraint.

In addition, the load balancing is incorporated in the decision of sleeping node and link selection. Through using the link utilization as the cost, data packets will be routed via the links with low utilization based on standard OSPF protocol. The optimization of network energy-efficiency can be mathematically formulated. The objective is to find the subset of routers and links that can be put into sleep so that the overall energy efficiency of the network is maximized, subject to a set of constraints: link utilization variation, connection of access routers, and load balancing. In order to obtain the optimal network topology configuration to maximize the network energy-efficiency, we need to determine the value of the array composed as x, y, z] to ensure that all boundary access routers are all connected (via single or multiple hops) and the utilization variation of the remaining active links is within a predefined range.

III. BACKGROUND

1. TOPOLOGY CONTROL

Quite informally, topology control is the art of coordinating nodes' decisions regarding their transmitting ranges, in order to generate a network with the desired properties (e.g. connectivity) while reducing node energy consumption and/or increasing network capacity. While this definition is quite general, we believe that it captures the very distinguishing feature of topology control with respect to other techniques used to save energy and/or increase network capacity: the network wide perspective. In other words, nodes make local choices (setting the transmit power level) with the goal of achieving a certain global, network wide property. Thus, an energy-efficient design of the wireless transceiver cannot be classified as topology control because it has a node wide perspective. The same applies to power-control techniques, whose goal is to optimize the choice of the transmit power level for a single wireless transmission, possibly along several hops; in this case, we have a channel wide perspective.

Note that our definition of topology control does not impose any constraint on the nature of the mechanism used to curb the network topology. So, both centralized and distributed techniques can be classified as topology control according to our definition.

Several authors consider as topology control techniques also mechanisms used to superimpose a network structure on an otherwise flat network organization. This is the case, for instance, of clustering algorithms, which organize the network into a set of clusters, which are used to ease the task of routing messages between nodes and/or to better balance the energy consumption in the network. Clustering techniques are more often used in the context of wireless sensor networks since these networks are composed of a very large number of nodes and a hierarchical organization of the network units might prove extremely useful.

In a typically clustering protocol, a distributed leader election algorithm is executed in each cluster, and cluster nodes elect one of them as the cluster head. The election is based on criteria such as available energy, communication quality, and so on, or combination of them. Message routing is then performed on the basis of a two-level hierarchy: the message originating at a cluster node is destined to the cluster head, which decides whether to forward the message to another cluster head (inter cluster communication) or to deliver the message directly to the destination (intra cluster communication). The cluster head might also perform other tasks such as coordinating sensor node sleeping times, aggregating the sensed data provided by the cluster nodes, and so on.

Although clustering protocols can be seen as a means of controlling the topology of the network by organizing its nodes into a multilevel hierarchy, a clustering algorithm does not fulfill our informal definition of topology control since typically the transmit power of the nodes is not modified. In other words, a clustering algorithm is concerned with hierarchically organizing the network units assuming the nodes' transmitting range is fixed, while a topology control protocol is concerned with how to modify the nodes' transmitting ranges in such a way that a communication graph with certain properties is generated.

2. TOPOLOGY CONTROL FOR ENERGY-EFFICIENCY

Besides connectivity guarantee, a good network topology should also be energy efficient, i.e., the total energy consumption of the least energy cost path between any two nodes in the final topology should not exceed a constant factor of the power consumption of the least energy cost path in the original network. First introduced the concept of energy spanner into topology control. A sub graph G0 is called an energy spanner of a graph G if there is a positive real constant t such that for any two nodes, the energy consumption of the least energy cost path in G0 is at most t times of the energy consumption of the least energy cost path in G. The constant t is called the energy stretch factor and G0 is called an energy t-spanner of G.

A power spanner of the original communication graph is usually energy efficient for routing, since it guarantees that there is an efficient path between each pair of nodes. Several geometrical topologies are energy spanners of unit disk graph (where every node uses its maximum transmission power) while others are not. Wang and Li introduced a new topology control problem: the minimum power energy spanner problem, which aims to find the optimum transmission power of each individual node such that 1) the induced communication graph is an energy t-spanner of the original communication graph; and 2) the total power level of all nodes is minimized.

They first proved that the problem is NP-complete and then presented two heuristics for the construction of a low cost power assignment with an energy spanner property for unit disk graphs. Recently, Shpungin and Segal provided the first approximation algorithm for this problem. They first presented a basic method to construct an energy t-spanner such that the total power consumption is at most n times of the optimal solution, for any t > 1 . Then, they generalized the basic method for a randomly distributed network to build an energy t-spanner with high probability such that the total power is at most of the times of the optimal, for any a > 1, , and any positive integer m n. Abu-Affash et al. [39] presented a constant approximation algorithm for the minimum power energy spanner problem. Their method can build a planar energy t-spanner such that the total power is at most of the times of the optimal when the underlying communication graph is a completed graph or a unit disk graph.

3. TOPOLOGY CONTROL AND MAC LAYER

The MAC (Medium Access Control) layer is responsible for regulating the access to the wireless, shared channel. Medium access control is of fundamental importance in ad hoc/sensor networks in order to reduce conflicts as much as possible, thus maintaining the network capacity to a reasonable level. To better describe the interaction between the MAC layer and topology control, we sketch the MAC protocol used in the IEEE 802.11 standard (IEEE 1999).

In 802.11, the access to the wireless channel is regulated through RTS/CTS message exchange. When node *u* wants to send a packet to node *v*, it first sends a Request To Send control message (RTS), containing its ID, the ID of node *v*, and the size of the data packet. If *v* is within *u*'s range and no contention occurs, it receives the RTS message, and, in case communication is possible, it replies with a Clear To Send (CTS) message. Upon correctly receiving the CTS message, node *u* starts the transmission of the DATA packet, and waits for the ACK message sent by *v* to acknowledge the correct reception of the data.

In order to limit collisions, every 802.11 node maintains a Network Allocation Vector (NAV), which keeps trace of the ongoing transmissions. The NAV is updated each time a RTS, CTS, or ACK message is received by the node. Note that any node within *u*'s and/or *v*'s transmitting range overhears at least part of the RTS/CTS/DATA/ACK message exchange, thus obtaining at least partial information on the ongoing transmission.

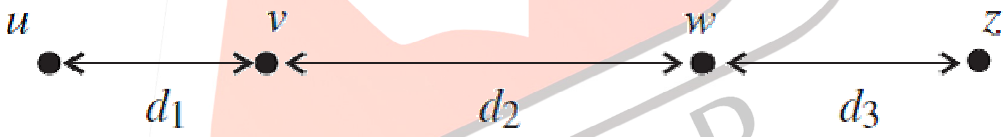

Figure 2.1 The importance of appropriately setting the transmit power levels.

As outlined, for instance, in (Jung and Vaidya 2002), using different transmit power levels can introduce additional opportunities for interference between nodes. On the other hand, using reduced transmit powers can also avoid interference. To clarify this point, consider the situation depicted in Figure 3.7. There are four nodes *u*, *v*, *w*, and *z*, with $\delta(u, v) = d1 < d2 = \delta(v,w)$ and $\delta(w, z) = d3 < d2$. Node *u* wants to send a packet to *v*, and node *w* wants to send a packet to *z*.

Assume all the nodes have the same transmit power, corresponding to transmitting range *r*, with $r > d2 + \max\{d1, d3\}$. Then, the first between nodes *v* and *z* that sends the CTS message inhibits the other pair's transmission. In fact, nodes *v* and *z* are in each other's radio range, and overhearing a CTS from *v* (respectively, *z*) inhibits node *z* (respectively, *v*) from sending its own CTS. Thus, with this setting of the transmitting ranges, no collision occurs, but the two transmissions cannot be scheduled simultaneously.

Assume now that nodes *u* and *v* have radio range equal to *r*1, with $r1 = d1 + \varepsilon < d2$ and that nodes *w* and *z* have range *r*2, with $r2 > d2$. In this situation, *w* and *z* cannot hear the RTS/CTS exchange between nodes *u* and *v* and they do not delay their data session. However, when node *w* transmits its packets, it causes interference at node *v*, which is within *w*'s range. Thus, in this case, using different transmit powers *creates* an opportunity for interference.

Finally, assume nodes *u* and *v* have radio range *r*1, and nodes *w* and *z* have range equal to *r*3, with $r3 = d3 + \varepsilon < d2$. With these settings of the radio ranges, the two transmissions can occur simultaneously, since node *v* is outside *w*'s radio range and node *z* is outside *u*'s radio range. Contrary to the example above, in this case, using different power levels *reduces* the opportunities for interference, leading to an increased network capacity.

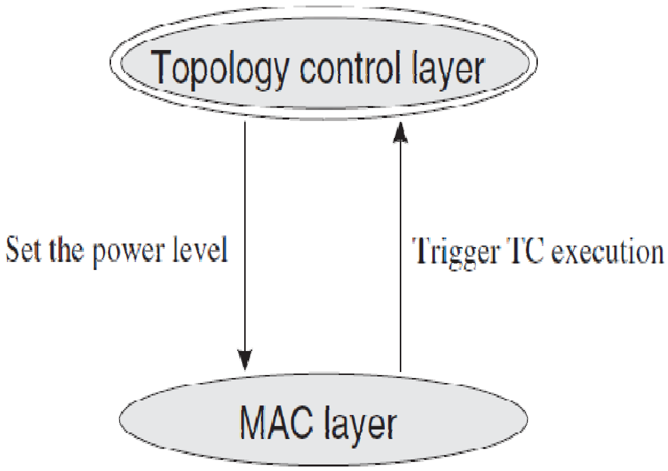

Figure 2.2 Interactions between topology control and MAC layer.

The example of Figure 2.1 has outlined the importance of correctly setting the transmit power levels at the MAC layer. We believe this important task should be performed by the topology control layer, which, having a networkwide perspective, can take the correct decisions about the node's transmitting range. On the other hand, the MAC layer can trigger re execution of the topology control protocol in case it discovers new neighbor nodes. The MAC level can detect new neighbors by overhearing the network traffic and analyzing the message headers; this is by far the fastest way to discover new neighbors, and a proper interaction between MAC and topology control (which, we recall, is in charge of maintaining the list of efficient neighbors) ensures a quick response to changes in the network topology. The two-way interaction between topology control and the MAC layer is summarized in Figure 2.2

IV. LITERATURE REVIEW

1. RELATED WORK

In cooperative networks, transmitting and receiving nodes recruit neighboring nodes to assist in communication. We model a cooperative transmission link in wireless networks as a transmitter cluster and a receiver cluster. We then propose a cooperative communication protocol for establishment of these clusters and for cooperative transmission of data. We derive the upper bound of the capacity of the protocol, and we analyze the end-to-end robustness of the protocol to data-packet loss, along with the tradeoff between energy consumption and error rate. The analysis results are used to compare the energy savings and the end-to-end robustness of our protocol with two non-cooperative schemes, as well as to another cooperative protocol published in the technical literature. The comparison results show that, when nodes are positioned on a grid, there is a reduction in the probability of packet delivery failure by two orders of magnitude for the values of parameters considered. Up to 80% in energy savings can be achieved for a grid topology, while for random node placement our cooperative protocol can save up to 40% in energy consumption relative to the other protocols. The reduction in error rate and the energy savings translate into increased lifetime of cooperative sensor networks.[4]

In [1], the authors formulate an optimization problem to determine the network topology based on a demand matrix. Due to its NP-hard property, the optimization model is solvable only for small networks. For large scale backbone networks, Chiaraviglio et al. [6] develop two heuristic approaches, named Least-Flow and Ransom. To reduce the computational complexity, Least-Flow sorts overall links in increasing order according to its carried flow, while Ransom treats all links in random order. Each of the two approaches shuts down the sorted links one by one according to the order until the network connective constraint is violated or one of active links becomes overflow. The two approaches were performed in the practical backbone network [7]. The results show that more than 23% of the energy could be saved per year.

However, these power-saving approaches only determine the on/off states for the network equipment. They don't provide the required link metric for link state routing protocols. An Energy-Aware Algorithm (ERA) for OSPF protocol was presented. ERA selects some routers as Exporter Routers (ERs) and some routers as Importer Routers (IRs). The ERs compute their own shortest path trees (SPT) by Dijkstra algorithm, while the IRs modify their SPTs to match the SPTs of ERs so as to turn off the redundant links. However, the link capacity constraint is not considered in it. Thus, authors indicate the ERA algorithm can be used only if the traffic load is low. Otherwise, the network would suffer the risk of link overflow.

In our design, the network control and management system is responsible to collect historical demand matrix for different time periods. Based on the demands, our algorithm determines the energy-aware network topology and link metric for each period. The computational results are downloaded to each router. As a time period ends, each router performs topology changes by itself in a distributed manner.

The contribution of the paper is two-fold. First we model the optimal link weight assignment problem as an integer linear programming problem. In the model, not only minimizing energy consumption but also physical capacity constraints are considered. We propose a mixed solution approach (called LR&HS) that combines the Lagrangean relaxation and the harmonic series based algorithm to tackle the problem. In the solution procedure, we take Lagrangean relaxation technique to transform the original problem into its dual form and apply subgradient method to obtain a set of Lagrangean multiplier. This set of multiplier is used as an initial link weight to become the input to the harmonic series based approach. Although both approaches solely can provide a solution to the green network design problem, interestingly combining these two approaches together reaches a solution that outperforms those two methods individually.

The second contribution comes from our proposal of a loop free packet forwarding mechanism during the transient period of network topology changes. This issue comes from the synchronization problem among the routers. As we have mentioned, changing network topology is performed in a distributed manner at the end of each time period. Without stringent synchronization among routers, routing loops would be formed and result in a lot of packet loss and traffic congestion. We therefore proposed a Multi-Topology Routing (MTR) based loop-free packet forwarding scheme to resolve this problem.

We perform simulations on benchmark networks and compare the proposed LR&HS algorithm to the Lagrangean Relaxation (LR) algorithm, the Harmonic Series (HS) algorithm, and a Simulated Annealing-based (SA) algorithm [10]. Through numerical results, we delineate that the proposed LR&HS algorithm can provide the best solution.

V. CONCLUSION AND FUTURE WORK

1. CONCLUTION

In this report relate to optimize the energy-efficiency of IP networks. A heuristic network topology configuration algorithm is proposed and assessed for a range of network and traffic load scenarios, which takes a further step based on recent relevant work. The solution could optimize the network-. wide energy efficiency, whilst keep the resulted performance degradation minimal and load balanced across the network. Numerical experiments are carried out to assess the suggested solution for a range of network and load scenarios and the results clearly demonstrate its effectiveness.

2. FUTURE WORK

Envisage the work in two directions: (i) obtain more accurate prediction of network dynamics with advanced mechanisms to minimize the potential network interruption due to topology configuration; and (ii) further assess the proposed EET algorithm in a set of large-scale ISP networks with more realistic characteristics in terms of network topology, traffic dynamics and power consumption.

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