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Energy efficient management framework for multihop TDMA-based wireless networks

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ABSTRACT

Green networking has recently been proposed to reduce energy cost as well as carbon footprint of computer networks. However, the application of green networking to multihop wireless networks has seldom been reported in the literature. This paper presents an energy-efficient framework for joint routing and link scheduling in multihop TDMA-based wireless networks. Our objective is to find an optimal tradeoff between the achieved network throughput and energy consumption. To do so, we first propose an Optimal approach, called Optimal Green Routing and Link Scheduling (O-GRLS), by formulating the problem as an integer linear program (ILP). As this problem is $\mathcal{NP}$-Hard, we then propose a simple yet efficient heuristic algorithm based on Ant Colony, called AC-GRLS. Through extensive simulations, we show that both approaches can achieve significant gains in terms of energy consumption, flow acceptance ratio and achieved throughput, compared to the Shortest Path (SP) routing, and the Minimum link Residual Capacity (MRC) based routing. In particular, we show that the same performance as SP or MRC in terms of average network throughput can be attained with up to 20% energy saving. On the other hand, with the same energy cost, our approaches enhance the flow acceptance ratio by up to 35% in average. This leads to a throughput increase of approximately 50% and 52% compared to SP and MRC routing, respectively.

1. Introduction

The Information and Communication Technology (ICT) consumes alone 3% of world wide energy consumption, and its CO_2 emission is around 2%, which is equivalent to airplanes emission and a quarter of cars emissions [1]. Combined with the fact that the cost of energy continues to rise, and the need for broadband expansion to rural areas, green networking has become one of the most important research directions in the ICT industry. To realize this goal, energy efficient communication has emerged as a promising solution to achieve sustainable and cost effective operations of communication networks.

The application of green networking to multihop wireless networks, in particular Wireless Mesh Networks (WMN), has seldom been reported in the literature. Typically, a WMN [2] comprises wireless mesh routers, also called access points (APs). Each AP serves multiple mobile users and connects them through multihop wireless routing to the wired network. The mesh nodes connected directly to the wired network (i.e., connecting the WMN to the wired network) are called gateways. They represent, respectively, the sources and sinks of downlink and uplink traffic in the WMN. Since such networks are expected to proliferate in the next few years, their energy consumption will impact the overall energy consumption of the Internet [3].

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In this paper, we focus on TDMA-based wireless multihop networks since TDMA-based channel access facilitates the use of Quality of Service (QoS)-aware link scheduling and routing [4,5]. Indeed, while the IEEE 802.11 protocol is the de facto standard for multihop wireless networks, its MAC protocol (Carrier Sense Multiple Access with Collision Avoidance, CSMA/CA) performs poorly in WMNs and it is almost impossible to guarantee QoS [5,6]. To guarantee QoS, packet collisions must be avoided by scheduling interfering links to transmit in non-overlapping frequency or time intervals [5]. This is why several developments were provided using multihop MAC protocols based on TDMA, such as the IEEE 802.16 mesh protocol (e.g., WiMAX) [7], the 802.11s mesh deterministic access (MDA) protocol [8], and the software-based 802.11 overlay TDMA MAC protocol [5].

In this context, novel green and energy efficient routing and link scheduling strategies are needed to take into account energy consumption of wireless nodes when powered on. In this case, important questions arise: how many APs need to be active to route a traffic within a WMN and what is the optimal tradeoff between the achieved network throughput and energy consumption?

To answer these questions, we propose in this paper a holistic management framework that provides the WMN administrator with a parameterized objective function to achieve the desired tradeoff between network throughput and energy consumption. Specifically, we first propose an Optimal Green Routing and Link Scheduling, called O-GRLS, that aims at finding the optimal tradeoff. Here, we formulate the problem as an integer linear program (ILP). As this problem is known to be $\mathcal{NP}$-Hard [9,10], we then propose a simple yet efficient algorithm based on Ant Colony, called Ant Colony Green Routing and Link Scheduling (AC-GRLS) to solve it. The Shortest Path (SP) routing strategy and the Minimum link Residual Capacity (MRC) routing metric, are used to develop baselines to which AC-GRLS and O-GRLS are compared. Through extensive simulations, we show that our proposals can achieve significant gains in terms of energy consumption, flow acceptance ratio, and achieved throughput, compared to alternative solutions (i.e., SP and MRC). Specifically, we show that the same performance as SP or MRC in terms of average network throughput can be attained with minimum energy consumption. In this case, the energy saving is up to 20%. On the other hand, with the same energy cost, our approaches enhance the flow acceptance ratio by up to 35% in average. This leads to a throughput increase of approximately 50% compared to SP and MRC routing.

The reminder of this paper is organized as follows. Section 2 presents an overview of related works, followed by a description of the system model and the problem statement in Section 3. Section 4 describes our proposed framework for energy management through green joint routing and link scheduling. First, we introduce the O-GRLS method with the associated ILP formulation, then we present the AC-GRLS algorithm. Simulation results are presented in Section 5. Finally, Section 6 concludes this paper.

2. Related work

Energy management has been an active research area in the last few years. Numerous proposals have been made in the literature, essentially in the context of wired networks. The energy consumption metric in these works is either the number of shut down nodes or the shut down interfaces. A proposal in this direction is [11], where the authors propose to shut down nodes one by one and verify that the network still route the required traffic. Authors in [12] present results from a testbed of routers with multiple network interface cards. In [13], the authors address the online admission and flow-based routing problem in wired networks. Their approach uses the depth-first search method and a path length to find, for every flow, a feasible path (i.e., satisfying the required QoS) that requires the least number of nodes and links to be turned on.

Clearly, these schemes are not suitable for multihop wireless networks since the problem of interference between links limits the possibility to aggregate all traffic to reuse the same nodes.

On the other hand, an important body of work on energy-efficiency in cellular and WLAN systems has been reported in the literature. A survey on energy-efficient protocols for such networks can be found in [14].

In WLANs, authors in [15] present a centralized strategy that decides on which nodes (WLAN APs) to power on or off, according to users' demands. The obtained results show an important energy saving, which can attain 46%. In [16], authors proposed an analytical model to assess the effectiveness of the concept of Resource on Demand in WLANs and authors in [17] show management strategies for energy savings in solar powered 802.11 WMNs by turning off some APs. Similarly, authors in [18] proposed a theoretical framework based on queuing theory for energy saving in WLANs.

In cellular access networks, Masran et al. [19] propose to shut down some base stations during low traffic demands to reduce the overall energy consumption. Similarly, authors in [20] investigate energy saving procedures by turning off both transmission components during signal-free symbols and cells during low traffic periods. In [21], the authors propose a framework for green communications in wireless heterogeneous networks. This framework is cognitive in the holistic sense and aims at improving energy efficiency of the whole system.

In the context of WMNs, classical routing and link scheduling algorithms focus on the performance in terms of network throughput and delay. A survey of some of the existing works in literature is presented in [22]. However, these works did not address the energy consumption issue. Relevant works on energy-efficiency are reported in [23–28]. Specifically, authors in [23] present an energy saving approach in hybrid wireless-optical broadband access networks. They propose to reduce the energy consumption in the optical part of the network by shutting down an optical node whenever its load is below a threshold. At the same time, the traffic in the wireless part of the network is routed using the minimum residual capacity as a routing metric.