The Journal of Systems and Software 104 (2015) 152–165

Contents lists available at ScienceDirect

The Journal of Systems and Software

journal homepage: www.elsevier.com/locate/jss

Network coding-based energy-efficient multicast routing algorithm for multi-hop wireless networks

Dingde Jiang [a,*], Zhengzheng Xu [a,b], Wenpan Li [a], Zhenhua Chen [a]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[b] School of Economics and Management, AnQing Normal University, AnQing 246011, China

ARTICLE INFO

Article history:
Received 24 September 2014
Revised 4 February 2015
Accepted 8 March 2015
Available online 12 March 2015

Keywords:
Multi-hop multicast
Network coding
Energy efficiency

ABSTRACT

Multi-hop multicast routing can provide better communication performance in multi-hop wireless networks. However, existing multi-hop multicast routing hardly take into account energy efficiency of networks. This paper studies the energy-efficient multicast communication aiming at multi-hop wireless networks. Firstly, we analyze energy metric and energy efficiency metric of multi-hop networks. Then the corresponding models are given. Secondly, network coding is used to improve network throughput. Different from previous methods, we here consider that network nodes are satisfied with a certain random distribution. In such a case, it is a challenge to construct the network structure that network coding requires. For the above random network topology, we propose three basic structures of network coding to overcome this problem. Thirdly, we present a flexible energy-efficient multicast routing algorithm for multi-hop wireless networks to extensively exploit the network structure proposed above to maximize network throughput and decrease network energy consumption. Finally, we perform numerical experiments by network simulation. Simulation results indicate that our approach is significantly promising.

1. Introduction

Multi-hop wireless networks are used widely in current wireless communications such as multi-hop sensor networks, multi-hop ad hoc networks, multi-hop mobile networks and so forth. In such multi-hop wireless networks, network nodes often have limited energy supply (Irwin et al., 2012; Khreishah et al., 2009; Jiang et al., 2014a; Jiang et al., 2011). How to improve network energy efficiency and decrease network energy consumption is still a main challenge. Compared to unicast communication, wireless multicast can effectively exploit network resource (Chen et al., 2010; Guo and Yang, 2004; Jiang et al., 2014b; Guo and Li, 2007). However, due to dynamic topologies and time-varying network links in multi-hop wireless networks, energy-efficient wireless multi-hop multicasts have received extensive attention from academic and industrial circles.

Although multicast communication plays an important role in multi-hop wireless networks, energy consumption and efficiency are still a challenge. To reduce network energy consumption, researchers used the cross layer design technology (Khreishah et al., 2009) and the cognitive network architecture (Chen et al., 2010) to improve network performance. The directional antenna was also exploited to improve energy utilization of multi-hop wireless networks (Guo and Yang, 2004). Ahlswede et al. (2000) considered network coding for solving energy consumption in multi-hop wireless networks. But they did not give a specific network coding implementation. In multi-hop wireless networks, COPE is one of the most practical network coding schemes (Katti et al., 2006). As mentioned as Katti et al. (2006), COPE is a new forwarding architecture that inserts a coding shim between the IP and MAC layers to raise the throughput of wireless networks. Liu et al. proved that network coding could reduce the transmission number of wireless ad hoc networks (Liu et al., 2007). They also found that the upper bound of energy gains is 3. For energy-constrained wireless sensor networks, network coding scheme could decrease energy consumption (Kasireddy and Wang, 2011). Random and scalable network coding could implement energy savings from 13% to 50% (Philipp et al., 2011). Generally, network coding has the potential abilities to improve network throughput, robustness and load balancing. Network coding is employed to put forward new coding algorithms (Wang and Shroff, 2010), optimize network performance (Sengupta et al., 2007; You et al., 2009), and minimize the transmission cost (Wu et al., 2005; Cui et al., 2008; Lun et al., 2006), while it can achieve the maximum multicast rate theoretically (Chen et al., 2010). However, these methods focused on energy consumption of nodes or components in wireless networks. The energy efficiency for multicast routing in multi-hop wireless networks does not receive sufficient attentions.

Different from previous methods, this paper takes into account the energy-efficient multi-hop multicast routing to improve the

* Corresponding author. Tel.: +86 24 83684219.
E-mail address: jiangdingde@ise.neu.edu.cn, jiangdd99@gmail.com (D. Jiang).

http://dx.doi.org/10.1016/j.jss.2015.03.006
0164-1212/

performance of multi-hop wireless networks. Firstly, we discuss the minimum network energy consumption, analyze the energy efficiency of networks, and propose the corresponding models. Secondly, network coding is used to reduce network energy consumption and raise network throughput. Accordingly, we can improve energy efficiency of networks. We randomly deploy the locations of network nodes to raise the robustness of our approach. In such a random network topology, the special network structure is constructed to perform network coding. We propose three basic network coding structures to adapt to different network topologies. Thirdly, an energy-efficient multicast routing algorithm for multi-hop wireless networks, which flexibly exploits the network structure proposed above to maximize network throughput and decrease network energy consumption, is proposed to attain better network performance. Finally, simulation results show that our approach is promising.

The rest of the paper is organized as follows. Section 2 is about related work. In Section 3, we make problem statement and propose the corresponding system model. Section 4 derives our algorithm. Section 5 is simulation analysis. Finally our work in this paper is concluded in Section 6.

2. Related work

With all kinds of network traffic quickly increasing, energy efficiency in wireless networks is becoming an important metric. To improve energy efficiency of wireless networks, network throughput should be maximized while network energy consumption should be minimized. Network coding has the potential abilities to improve network throughput, robustness and load balancing. Kasireddy and Wang (2011) checked the network coding performance on energy consumption of the grid wireless sensor network where sensors are placed in a square pattern. Philipp et al. (2011) proposed exploited network coding to optimize data gathering and data communication in the wireless sensor network and discussed the energy saving of their approach. Wu et al. (2005) studied the minimum-energy multicast problem in mobile ad hoc networks and proposed using network coding to attain the minimum energy-per-bit. However, most of these methods use the fixed network topologies to validate their algorithms. In our energy-efficient approach, we randomly place network nodes and construct as many network coding structures as possible to improve networks' energy efficiency.

Additionally, Cui et al. (2008) proposed an energy-efficient opportunistic network coding approach in wireless networks. They divided the unicast communication into a combination of unicast and multicast communications and then built network coding within each session. Lun et al. (2006) discussed the minimum-cost multicast over wired and wireless coded packet networks and found that network coding could always lead to the significant improvement of network performance. Ding and Wu (2011) analyzed the lifetime maximization of energy constrained wireless networks. They exploited network coding to improve network performance for energy savings. Vahid (2008) investigated the multicast in wireless sensor networks and they used network coding to increase network lifetime and decrease the number of packets. Although these use some approaches to save network energy, most of them do not consider energy efficiency performance of networks. In our work, we target energy efficiency in multi-hop wireless networks. We take into account maximizing network throughput and consider minimizing networks' energy consumption.

Mirghaderi and Goldsmith (2012) proposed a feedback optimization framework to perform energy-efficient communication in point-to-point wireless links. They considered the energy consumption of the forward and feedback links and found that using the feedback could improve the energy efficiency for large values of available energy. Athanassopoulos et al. (2013) studied the combinational optimization problems and minimized the network energy built the connectivity between nodes in multi-interface wireless networks. Luo et al. (2010) proposed a new scheme based on network coding to reduce energy consumption of wireless sensor networks. Xiong et al. (2011) used network coding to reduce network consumption and proposed a cooperative MIMIO transmission scheme. Hamini et al. (2011) proposed the ultra wide time concept and energy efficiency metric to evaluate the energetic performance of communication systems. Lee et al. (2011) thought that energy efficient research in information and communications technology was coming one of the most significant researches. They introduced the significance and energy efficient researches and reviewed energy proportionality index. Chen et al. (2010) overviewed the energy efficiency metrics in wireless networks. They thought that the new energy-efficient architecture and metric were the key for the energy consumption problem in wireless networks. Hasan et al. (2011) surveyed the approaches of improving the energy efficiency in cellular networks. Kouyoumdjieva et al. (2012) evaluated the performance of a dual-radio architecture in opportunistic communications and shown that this architecture could highly decrease the energy consumption while slightly dropped network throughput. Ehsan and Hamdaoui (2012) overviewed the state-of-the-art energy-efficient routing techniques in wireless multimedia sensor networks. Although some energy-efficient methods are proposed to improve network performance, most of these approaches do not consider multi-hop scenario. We study the energy-efficient networking problem for multi-hop wireless networks. Energy efficiency is taken as a metric to build the optimal multi-hop wireless networks. By constructing the appropriate network coding structure, we can achieve the higher energy efficiency.

Parker and Walker (2011) described an absolute energy efficiency metric. Wieselthier and Nguyen (2002) used energy efficiency to evaluate the constructed multicast tree in infrastructureless wireless networks. They proposed the broadcast incremental power (BIP) and multicast incremental power (MIP) and validated BIP and MIP could attain the better performance. Wieselthier et al. (2002) studied energy-aware wireless networking problem using directional antennas and proposed the directional multicast increment power (D-MIP) algorithm. Guo and Yang (2006) considered the advantages of power savings when using adaptive antennas and presented the directional multicast increment–decrement power (D-MIDP) algorithm (Guo and Yang, 2006). Our work is related with that in (Wieselthier and Nguyen, 2002; Wieselthier et al., 2002; Guo and Yang, 2006). In our method, we take the maximum energy efficiency as the optimal objective function to build the highly energy-efficient multicast routing. Moreover, we exploit network coding to improve energy efficiency of multi-hop wireless networks.

3. Problem statement and system model

3.1. Multicast problem in multi-hop wireless networks

In this paper, we consider a multi-hop wireless network without a center, which does not need the support of fixed basic devices. All the nodes in the network can send and receive data packets. The multi-hop wireless network meets the requirements of free communication in any circumstance. It provides solutions for the communications in the special environments such as military communications, disaster relief and temporary communications.

In our approach, when the signal-to-noise ratio of the received signal of each node is large enough, it can make correct communication. At the same time, the nodes can receive the right messages only when they are in the coverage range of transmission nodes. Our transmission channel is the white Gaussian noise one. Additionally, there are F frequencies available, which are orthogonal and are enough for