Computer Communications 55 (2015) 69–79

Contents lists available at ScienceDirect

Computer Communications

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

Cross-layer design with optimal dynamic gateway selection for wireless mesh networks

Anfu Zhou [a,*], Min Liu [a], Zhongcheng Li [a], Eryk Dutkiewicz [b]

[a] Institute of Computing Technology, Chinese Academy of Sciences, Beijing 100190, China
[b] Department of Electronic Engineering, Macquarie University, Sydney 2109, Australia

ARTICLE INFO

Article history:
Received 23 February 2014
Received in revised form 3 June 2014
Accepted 22 August 2014
Available online 30 August 2014

Keywords:
Cross-layer design
Dynamic gateway selection
Network utility maximization
Delay differentiation

ABSTRACT

The existence of multiple gateways, as is a common case in Wireless Mesh Networks (WMNs), brings the possibility to improve network performance. However, previous studies, including both heuristic-based gradual-optimization work and theory-driven cross-layer design work, cannot guarantee an optimal exploitation of multiple gateways. In this paper, we first extend the current framework of cross-layer design to incorporate a dynamic gateway selection strategy, and propose a novel joint traffic splitting, rate control, routing and scheduling algorithm called CLC_DGS, which distributes traffic of a flow into multiple gateways in an optimal way so as to guarantee maximum network utility. Secondly, based on CLC_DGS, we propose an enhanced CLC_DGS_DD algorithm which in addition takes into account the delay requirements for network flows. CLC_DGS_DD provides a flexible framework for adjusting delays among different flows, and thereby achieves as low as order-optimal delays for preferential flows while simultaneously guaranteeing maximum network utility. Through theoretical analysis and simulation experiments, we demonstrate that compared with previous studies, CLC_DGS and CLC_DGS_DD significantly improve performance of WMNs.

1. Introduction

As an important form of network architecture, Wireless Mesh Networks (WMNs) provide a convenient and economical way for Internet access, and are widely used in many environments such as enterprise, campus and rural places [1,2]. However, despite the wide use of WMNs, they often confront severe performance degradation, such as low throughput, unfairness and large delays [3–6,9,12].

To improve network performance of WMNs, research efforts in the literature recognize one key characteristic of WMNs that often more than one gateway are deployed in WMNs, and realize that the existence of multiple gateways provides a new possibility for improving performance. For example, one can reduce the delay of a preferential flow by assigning a near and low-congested gateway for the flow.

Based on this realization, plenty of work is devoted to exploit the potential of multiple gateways to enhance performance of WMNs. For example, Lakshmanan et al. in [15] and Lenders et al. in [16] propose anycast routing schemes in which wireless mesh nodes simultaneously associate with multiple gateways and forward packets to low-congested gateways. Laufer et al. in [17] advances the study to combine both anycast and anypath routing to further exploit multiple gateways. Although these studies can improve network performance to a certain extent, they are based on heuristics and do not necessarily lead to optimal utilization of multiple gateways.

In parallel, there are many works (later referred to as cross-layer design works) that address the issue of optimally utilizing a network. In contrast to heuristic-based approaches, cross-layer design provides a systematic theory-driven framework to develop performance-optimal data transmission control mechanisms for wireless multihop networks including WMNs. Following the seminal work of Tassiulas and Ephremides in [18], significant progress has been made on cross-layer control algorithms (see [19–26] and the references therein). It has been proven that cross-layer control algorithms can fully explore the capacity region of a network so as to guarantee maximum network utility,[1] that is, cross-layer control algorithms can achieve maximal overall throughput and at the same

---

* Corresponding author. Tel.: +86 10 62600705; fax: +86 10 62533449.
E-mail addresses: zhouanfu@ict.ac.cn (A. Zhou), liumin@ict.ac.cn (M. Liu), zcli@ict.ac.cn (Z. Li), eryk.dutkiewicz@mq.edu.au (E. Dutkiewicz).

[1] Network utility is a widely-used performance metric that can measure both aggregated throughput and fairness in a network. More explanation is given in Section 3.

http://dx.doi.org/10.1016/j.comcom.2014.08.011
0140-3664/

time ensure throughput fairness among different flows. However, previous works on cross-layer design are limited to a specific packet delivery model where the forwarding destination of a flow is one and only one pre-determined node, and ignore the advantage of multiple gateways in WMNs. As we will show in Section 5, this causes much performance loss, in terms of both network utility and delay.

In this paper, we seek to extend the framework of cross-layer design to incorporate dynamic gateway selection, so as to improve network performance as far as possible through the optimal use of multiple gateways in WMNs. We have two objectives in terms of network performance improvement. The first is to achieve maximum network utility in presence of multiple gateways. In previous cross-layer design works without the consideration of multiple gateways, control mechanisms at different network layers (i.e., rate control, routing and scheduling) are carefully designed to cooperate and interact with each other tightly to guarantee maximum network utility. The existence of multiple gateways, as a new issue, will further complicate cross-layer design. For example, we need to consider how to optimally split the traffic of a flow among different gateways, and how to integrate this traffic splitting strategy and rate control, routing, and scheduling into a unified framework. More importantly, we need to prove that this integration can indeed guarantee maximum network utility for WMNs with multiple gateways, in contrast to previous heuristic-based works [15–17].

The second objective is to reduce flow delays. It is well-known that large flow delays in wireless multi-hop networks including WMNs is a long-lasting problem. Moreover, the delay performance further deteriorates under the traditional cross-layer control algorithms, as reported in many studies [31–34]. Recently there are also some new cross-layer control algorithms [35–37] proposed to reduce delay. However, to reduce delay for all flows, these algorithms [35,36] bring the adverse effect of sacrificing a lot of network utility. For example, the overall throughput achieved by the algorithm in [35] is only $\frac{1}{5}$ of the maximum throughput. Clearly, the sacrifice of network utility in these algorithms cannot be ignored, especially in consideration of the fact that one advantage, probably the biggest advantage, of cross-layer control algorithms is their utility-optimal property. Moreover, all these algorithms in [35–37] do not consider the existence of multiple gateways.

Motivated by the above objectives, in this paper we propose two novel cross-layer control algorithms for WMNs with multiple gateways to improve network performance, in terms of both network utility and delay. We first incorporate dynamic gateway selection into the cross-layer framework and design a novel cross-layer control algorithm called CLC_DGS that can exploit the full potential of multiple gateways so as to achieve maximum network utility. Then based on CLC_DGS, we propose an enhanced algorithm called CLC_DGS_DD that in addition takes into account different delay requirements of flows. CLC_DGS_DD solves the large-delay problem without the sacrifice of network utility using delay differentiation approach. The basic idea is to distribute delays among flows (i.e., to achieve low delays for delay-sensitive flows at the expense of increasing the delays of other flows), while simultaneously guaranteeing maximum network utility. In particular, the contributions of this paper can be summarized as follows:

- We propose a novel Cross-Layer Control algorithm with Dynamic Gateway Selection (CLC_DGS), which is a joint traffic splitting, rate control, routing and scheduling algorithm that takes the advantage of multiple gateways. We prove that the CLC_DGS algorithm can distribute traffic of a flow into multiple gateways in an optimal way so as to guarantee maximum network utility.
- Based on CLC_DGS, we propose an enhanced Cross-Layer Control algorithm with Dynamic Gateway Selection and Delay Differentiation (CLC_DGS_DD) which in addition considers different delay requirements for flows. Besides achieving maximum network utility, CLC_DGS_DD provides a flexible framework for adjusting delays among different flows, and thereby can achieves low delays for preferential flows.
- We validate the proposed algorithms through simulations. Simulation results show that compared with previous works, the aggregated throughput of all flows and fairness among flows are greatly improved by CLC_DGS and CLC_DGS_DD (the improvement ratio ranges from 19.9% to 87.1%), and delays of preferential flows achieved by CLC_DGS_DD can be as small as the delays achieved by the delay-order-optimal algorithm in [36].

The rest of the paper is organized as follows. Section 2 describes the system model. Sections 3 and 4 present the CLC_DGS and CLC_DGS_DD algorithms respectively. We give simulation results in Section 5 and discuss more related works in Section 6, and conclude in Section 7.

2. System model

2.1. Network model

Here we represent a wireless mesh network with a graph $G = (\Gamma, E)$, where Γ is the set of all mesh nodes ($N = |\Gamma|$) and E is the set of links ($L = |E|$). The set of mesh gateways is denoted by GW. To improve the readability of this paper, we gather all the notations and acronyms in Table 1.

Due to interference in wireless networks, neighboring links cannot be active simultaneously. Here we denote a feasible schedule by $\vec{S}$ where its l_{th} component $S_l = 1$ if link l is activated and $S_l = 0$ otherwise. The set of all feasible schedules is denoted by Φ. Note that Φ is decided by the underlying wireless interference model of the network. In this paper, the one-hop interference model is assumed for convenience (Note that our work could be extended to other interference models easily). Under the one-hop model, any two links with a common node cannot be active simultaneously. For example, in Fig. 1, link 1 and link 2 cannot be simultaneously active since they share the common node 2.

Table 1
Definitions

Γ	The set of mesh nodes
E	The set of links
GW	The set of gateways
F	The set of flows
$r_{s(f)}^{(f)}(t)$	The amount of traffic of flow f admitted into the network in time slot t, where $s(f)$ denotes the source node of flow f
$r_{s(f)}^{(f)}$	The long-term average amount of traffic of flow f admitted into the network
$y_d^{(f)}$	The fraction of traffic of flow f that has forwarding destination of gateway d
$Q_i^{(d)}(t)$	The queue length of packets with forwarding destination of gateway d on node i in time slot t
$\mu_{mn}^{(d)}(t)$	The number of packets with forwarding destination of d transmitted over from node m to node n in time slot t
$\mu_{mn}^{(d)}$	The long-term average number of packets with forwarding destination of d transmitted from node m to node n
Λ	The capacity region of a network