Available online at www.sciencedirect.com

ScienceDirect

Computer Communications 31 (2008) 1318–1328

computer communications

www.elsevier.com/locate/comcom

Statistical delay budget partitioning in wireless mesh networks

Najah A. Abu-Ali *, Hossam S. Hassanein

School of Computing, Queen's University, 52 Rosemund Cres., Kingston, Ont., Canada K7M 6Z4

Available online 2 February 2008

Abstract

Wireless Mesh Networks (WMNs) are currently attracting strong attention due to their great potential in supporting multimedia applications with real-time transport with last-mile Internet access. Multimedia end-to-end transmission requires Quality of Service (QoS) guarantees. Mapping end-to-end QoS requirements into link QoS requirements is an important step for providing QoS in WMNs. Despite the importance of this functionality, it is yet to be addressed in WMNs or, more generally, in multihop wireless networks. Such mappings, however, have resulted in several algorithms being proposed for connection-oriented wired networks. The algorithms proposed, nevertheless, are either near-optimal or heuristics, and provide solutions for only one end-to-end requirement.

In this paper, we propose a partitioning algorithm that is capable of partitioning multiple end-to-end QoS requirements simultaneously. We define QoS as the pair of the required end-to-end delay and the violation probability of meeting the required end-to-end delay. Our approach is motivated by experiments decisively showing that the delay probability distribution can be accurately characterized by a gamma or logistic distribution, thus there is not a specific one distribution that can characterize the delay. This conclusion is used to formulate a mathematical linear program that optimally partitions the end-to-end delay and the violation probability into link delays and link violation probabilities without imposing any specific delay distribution. Extensive simulation verified the effectiveness of the algorithm compared to two representative QoS partitioning algorithms. The proposed algorithm outperforms the other algorithms for loose and stringent QoS requirements, and over different path lengths.

Keywords: Wireless mesh networks; End-to-end QoS; Delay budget partitioning; IEEE 802.16j; IEEE 802.11s; Radio resource management

1. Introduction

Wireless Mesh Networks (WMNs) are multihop wireless networks that are integrally different from mobile ad hoc networks as the former are aimed at backhauling service networks. Mesh routers provide gateway/bridge functionality to integrate heterogeneous networks, i.e., comprising wired and wireless connectivity. Accordingly, a mesh router is usually equipped with multiple wired and wireless interfaces, possibly of different technologies, and are characterized by little to know mobility.

Interest in WMNs is currently growing strong as they are expected to support multimedia and mission critical applications with real time transport for last mile Internet access. Multimedia applications require QoS guarantees for end-to-end delay, jitter, packet loss and flow rate. Different multimedia applications also have different QoS requirements. For example, certain real-time applications, e.g., tele-medicine, require hard bounds on end-to-end delay. Thus, a deterministic guarantee is required from the network, where the delay bound of any packet is not allowed to be violated. In other words, the delay violation probability for such applications must be guaranteed by the network to be zero. Other real time applications, like streamed multimedia, require soft bounds on the end-to-end delay. This means that the delay of small number of packets is allowed to violate delay bound. Such bounds are called stochastic delay bounds. Supporting real time applications over backhaul WMNs (for example, IEEE 802.16-2004-mesh mode, IEEE 802.16j, and IEEE 802.11s) is not a trivial task because of the wide variation of QoS requirements of real time applications and the incapability of certain standards, such as

* Corresponding author. Tel.: +1 613 544 6917.
E-mail addresses: najah@cs.queensu.ca (N.A. Abu-Ali), hossam@cs.queensu.ca (H.S. Hassanein).

0140-3664/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.comcom.2008.01.050

IEEE 802.16 and IEEE 802.11s, of supporting end-to-end QoS requirements. However, in the emerging IEEE 802.16j, it is possible each user can have more than one connection or service type with pre-defined QoS requirements and different traffic models. Traffic models support four service types for QoS including UGS, rtPS, nrtPS, and BE. This classification distinguishes requirements for video, audio and data services.

The standards IEEE 802.16j and 802.16-mesh as a backhaul WMN are based on Time Division Multiple Access/ Time Division Duplex (TDMA/TDD) technology and operate under distributed control or centralized control, i.e., distributed scheduling or centralized scheduling. Mesh nodes are required to reserve periodic time slots for their data transmissions and according to the QoS requirements. Thus to have a successful scheduling, mesh nodes need to be synchronized for TDMA operation. The reserved time slots are used to transmit packets from a source mesh node to a destination mesh node over a multihop wireless route in TDD mode. The traffic slots reserved by the mesh nodes are done on hop-by-hop basis, with each one-hop link operating independently.

For mesh networks based on IEEE 802.11s, mesh routers follow the IEEE 802.11e standard to provide QoS by allocating more resource to the traffic with higher demands. End-to-end communications in multihop network involve several radio links in tandem, and as discussed in [1], 802.11e can not support QoS services well in multihop networks. Thus, offering QoS guarantees using 802.11e over multiple hops requires a mechanism above traditional MAC in order to make end-to-end flow based assignments and to guarantee allocated service assignments.

To provide end-to-end QoS guarantees over link-based standards, such as IEEE 802.16 and IEEE 802.11s, end-to-end QoS bounds have to be optimally and correctly mapped into link QoS bounds. The mapping process is a very subtle step in QoS provisioning as it impacts routing and link resource allocation. Consequently, mapping plays a major role in balancing the load in a WMN and optimizing the utilization of network resources. In this paper, we address end-to-end statistical delay mapping over backhaul wireless mesh networks, also known as the delay budget partitioning problem, which is an important network optimization problem. We introduce a novel delay partitioning algorithm to solve the delay budget optimization problem for stochastic delay requirement. The algorithm maps the end-to-end QoS requirements denoted by the pair (D_r, P_r) into link QoS requirements denoted by the pairs $\{(d_i^r, p_i^r)\}_{i=1}^{M}$. The value d_i^r is the required link delay over the ith link, p_i^r is the required link violation probability and M is number of links, while D_r is the end to end delay and P_r is the end to end violation probability.

The proposed algorithm solves a linear programming problem to find the optimum link QoS pairs (d_i^r, p_i^r) using (D_r, P_r) and the probability density function (pdf) of the link delays. Section 3 presents our work in studying the delay distribution of homogenous and heterogenous traffic in a testbed wireless mesh network. The results of the experiments for identifying the delay distribution indicate that the empirical distribution of the delay can be fitted to well known distributions. We are able to identify two well known distributions, namely the gamma and logistic distribution. Our algorithm is accordingly designed to be independent of the type of the delay distribution. To the best of our knowledge, this algorithm is the first algorithm capable of optimally partitioning end-to-end stochastic QoS pair simultaneously in wireless mesh networks.

In designing the proposed delay budget partitioning algorithm, we are attempting to meet two contradicting objectives. The first is aimed at user satisfaction by meeting the user application's QoS requirement. The second objective is concerned with the service provider satisfaction by balancing the load over the connection path. The load is balanced over the path by allowing heavy loaded or in deep fading wireless links to have larger delay and violation probability portions than the lightly loaded or good channel quality links. Consequently, the proposed algorithm avoids generating future bottleneck links that results in rendering the whole path unusable.

The remainder of this paper is organized as follows. In the following section we review related work. We proceed by presenting the mesh testbed and characterizing the probability density function (pdf) of the delay in Section 3. The mathematical solution of the delay partitioning problem is formulated in Section 4. We compare the performance of the proposed algorithm with two existing algorithms in Section 5. We finalize the paper with the conclusions in Section 6.

2. Related Work

To the best of our knowledge, proposals addressing QoS provisioning in wireless communication networks focus on satisfying the link delay bound at a node or satisfying the end-to-end delay bound in general as the summation of the link delays along a path. Wang et al. [2] extend the Proportional Delay Differentiation (PDD) service model in wired networks into the Neighborhood PDD (NPDD) in wireless LANs. The objective of NPDD is to assure equal delay for the same class of service at each link along the path. The NPDD algorithm considers end-to-end delay as the summation of link delays. Draves and Padhye [3] proposed a new metric called the Weighted Cumulative Expected Transmission Time (WCETT) to find a route between static mesh routers based on estimating the delay at each node. The delay in [3] is calculated as a function of packet loss rate and available bandwidth. The packet loss is measured using the algorithm described in [4]. In [5], the authors estimate the end-to-end delay in wireless ad hoc networks by using a mobility model based on a discrete time Markov chain. The end-to-end delay is estimated by knowing a priori the random position of every node using the mobility model. Narlikar and Wilfong [6] propose a framework for activating wireless links in a backhaul net-