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Approximate dynamic programming for link scheduling in wireless mesh networks

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Abstract

In this paper a novel interference-based formulation and solution methodology for the problem of link scheduling in wireless mesh networks is proposed. Traditionally, this problem has been formulated as a deterministic integer program, which has been shown to be $\mathcal{NP}$-hard. The proposed formulation is based on dynamic programming and allows greater flexibility since dynamic and stochastic components of the problem can be embedded into the optimization framework. By temporal decomposition we reduce the size of the integer program and using approximate dynamic programming (ADP) methods we tackle the curse of dimensionality. The numerical results reveal that the proposed algorithm outperforms well-known heuristics under different network topologies. Finally, the proposed ADP methodology can be used not only as an upper bound but also as a generic framework where different heuristics can be integrated.

Keywords: Approximate dynamic programming; Scheduling; Wireless mesh networks

1. Introduction

A wireless mesh network (WMN) consists of a collection of geographically distributed nodes that are equipped with a wireless interface and communicate through a shared radio channel. Mesh networks (also referred to as multi-hop radio networks) allow multi-hop communication, in the sense that transmitted packets can be relayed over one or several intermediate nodes before received by the destination node. The current growing interest in WMNs emerges from the fact that these networks can fulfill a number of different operational roles, which can vary from rapid deployable, low cost backhaul support to cellular networks and WLAN networks to first mile wireless connectivity to the Internet, or even to transient wireless networking [1]. Additionally, the IEEE 802.16 standard [2], which supports a mesh mode and the emerging ramifications of this standard, can be considered as a stepping stone towards the commercial realization of WMNs.

The major resource management issue in mesh networking is maximizing the transmission opportunities of active nodes in a pre-defined time window by taking into account the interference caused by simultaneously transmitting nodes. Such concurrent transmission can lead to erroneous reception at the receiver, if the level of the received signal is too weak compared to the aggregate interference (signal to interference ratio, SIR). Thus, transmission schedules

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in the mesh network that control access to the shared channel are of fundamental importance for efficient utilization of the scarce wireless resources. The medium access control scheme under consideration is based on time division multiple access (TDMA). In TDMA, time is divided into time slots and each node can transmit periodically only at pre-allocated time slots, thus collisions can be avoided. Since nodes are spatially distributed it is possible to reuse the time slots by nodes that are sufficiently far apart. Spatial reusing of time slots has been defined in the seminal work of Kleinrock [3] and is called spatial-TDMA (STDMA). Therefore in STDMA the efficiency of the spatial reuse of the time slots is dependent on the algorithm used to schedule links for packet transmission in the mesh network.

Optimization techniques have been extensively used in wireless networking (see [4] and references therein). This paper focuses on finding optimal link scheduling policies for STDMA wireless networks, that has proved to be an $\mathcal{NP}$-hard problem [5,6]. Column generation approaches have been used in [7,8]. Since these problems are generally hard, the majority of previous work is based on heuristics. In general, proposed algorithms can be categorized into interference or graph theoretic based.

Graph theoretical models assume circular pre-defined transmission ranges of the nodes and interference is limited within this radius. Thus, in such a model interference is indicated by an edge connecting two nodes if they are within each others' transmission range. Absence of an edge denotes that there is no interference between these nodes and therefore these nodes can potentially transmit at the same time slot. This formulation transforms the time slot allocation into a graph coloring problem, where both distributed and centralized algorithms can be deployed [3,5,6,9–12]. A review on the performance of different graph based scheduling algorithms can be found in [13]. The fundamental drawback of graph theoretic-based algorithms is that interference is not accurately modeled. These algorithms fail to take into account the aggregate interference levels within the wireless mesh network, having as a net effect that some transmitting link may not satisfy the SIR threshold, thus leading to erroneous packet reception. It has been previously shown that graph-based models can lead to poor SIR levels at the receiving node and therefore the whole system performance can deteriorate [14,15].

Interference-based algorithms on the other hand utilize information from the exact interference produced in the network, and therefore the SIR constraints are taken into account in the problem formulation [7,14,16,17]. Algorithms that utilize information of the SIR need more detailed information regarding channel condition between nodes within the wireless mesh networks and therefore are more complex than the graph-based algorithms.

In contrast to previous work that focus on integer programming (IP) formulations of the link scheduling problem [7,8,18], in this paper we provide an alterative formulation based on dynamic programming (DP). We temporally decompose the integer program into one-slot IPs, which are smaller in size, and we link them together using dynamic programming. Even though the size of the IP has been reduced, classical dynamic programming algorithms require the one-slot IPs to be solved a large number of times, which is exponential with respect to the number of links (curse of dimensionality). We tackle this problem using approximate dynamic programming (ADP) methods, where the number of times the one-slot IPs are solved is linear with respect to the number of links. The DP formulation with ADP methodology is scalable to larger instances of the problem as opposed to the IP formulation. Apart from reducing complexity, the DP formulation allows us to use dynamic objective coefficients in contrast to the IP formulation. Additionally, the IP formulations are deterministic in nature, whereas the proposed DP formulation incorporates stochastic information such as packet arrivals and channel conditions.

Approximate dynamic programming methodology used in this paper is closely related to algorithms used in [19,20]; other types of approximate DP algorithms have been discussed and developed in [21,22].

The rest of the paper is organized as follows. Our study launches in Section 2, where the link scheduling problem is formulated as an integer program. In Section 3 we provide a dynamic and stochastic formulation of the problem using dynamic programming. In Section 4 we propose an approximate dynamic programming methodology that provides a novel framework for the solution of the link scheduling problem. The performance of the ADP methods is evaluated in Section 5 under different wireless mesh network scenarios. Conclusions end the paper in Section 6.

2. Integer programming formulation

In this section we define the basic notation and formulate the link scheduling problem as an integer program.

A wireless mesh network can be represented by a graph of V nodes and L links (directed arcs). A link from node i to node j indicates that we want to schedule a wireless transmission from i to j. When node i transmits on link (i, j), we say link (i, j) transmits. We let $\mathscr{V} = \{1, \dots, V\}$ be the set of nodes and $\mathscr{L} = \{(i, j)$ for some $i, j \in \mathscr{V}\}$ be the set