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Optimization architecture for joint multi-path routing and scheduling in wireless mesh networks

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ABSTRACT

In Wireless Mesh Networks (WMN), the optimal routing of data depends on the link capacities which are determined by link scheduling. The optimal performance of the network, therefore, can only be achieved by joint routing and scheduling optimization. Although the joint *single-path* routing and scheduling optimization problem has been extensively studied, its *multi-path* counterpart within wireless mesh networks has not yet been fully investigated. In this paper, we present an optimization architecture for joint multi-path QoS routing and the underlying wireless link scheduling in wireless mesh networks. By employing the contention matrix to represent the wireless link interference, we formulate a utility maximization problem for the joint multi-path routing and MAC scheduling and resolve it using the primal–dual method. Since the multi-path routing usually results in the non-strict concavity of the primal objective function, we first introduce the Proximal Optimization Algorithm to get around such difficulty. We then propose an algorithm to solve the routing subproblem and the scheduling subproblem via the dual decomposition. Simulations demonstrate the efficiency and correctness of our algorithm.

1. Introduction

Wireless mesh networks (WMNs) [1] have emerged as a key technology for next-generation wireless networking. In general, WMNs are built up in a hierarchical manner and comprise two types of nodes: mesh routers and mesh clients. Other than the routing capability for gateway/bridge functions as in a conventional wireless router, a mesh router contains additional routing functions to support mesh networking. Through multi-hop communications, the same coverage can be achieved by a mesh router with much lower transmission power. In addition, quite often some mesh routers in WMNs are also equipped with a gateway capability through which backhaul services are provided instead of the traditional T1 leased line. A typical wireless mesh network is depicted in Fig. 1.

In essence, WMNs are multi-hop wireless networks. However, different from conventional Ad hoc wireless networks, mesh routers in WMNs are rarely mobile and may not have power constraints. In most scenarios, WMNs behave almost like wireline networks in having infrequent topology changes, limited node failures, etc. Moreover, the service traffic of WMNs is mainly routed by the wireless mesh backbone between the mesh clients and the wired Internet and goes through the gateway nodes. Consequently, instead of being another type of Ad hoc networking, WMNs diversify the capabilities of Ad hoc networks. As such, the two major concerns, namely node mobility and power consumption in Ad hoc networks, are not significant in WMNs. Instead, capacity and QoS provisioning become the main topics in mesh networking.

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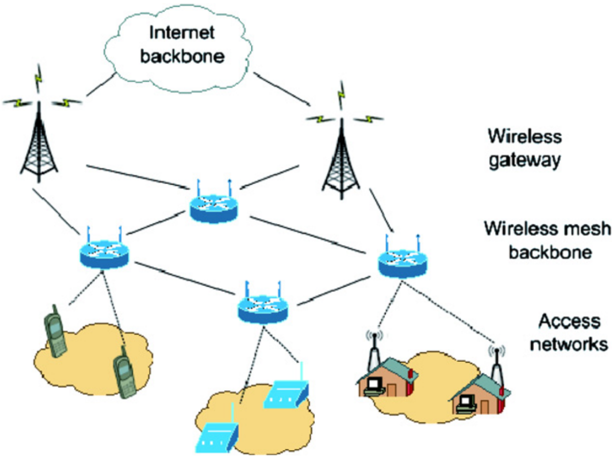

Fig. 1. The typical scenario of wireless mesh network.

QoS routing is an important component of QoS provisioning in wireless mesh networks. The objective of QoS routing in such networks is two-fold: to find feasible paths for each incoming connection in the presence of the underlying link interference; and to optimize the usage of the network by balancing the load. Since the optimal routing of data depends on the link capacities which, in turn, are determined by link scheduling, the optimal network performance can only be achieved by the joint optimization of both the routing and link scheduling. Although the QoS routing has been addressed considerably [2–5], they all focus on the construction of routing path under the impact of link scheduling while neglecting the performance optimization of the whole network. Recently, on the other hand, there have been substantial advances demonstrating that wireless resources across multiple layers can be incorporated into a unified optimization framework [6–9]. This dramatically enlarges the space for us to investigate the QoS-related issues by taking advantage of these existing techniques. However, the specific optimization architecture for joint routing and scheduling for wireless mesh network is still lacking. Further, although the *single-path* utility maximization problem, i.e., when each user (or class) has only one path, has been extensively studied [10–13], the *multi-path* utility maximization problem within wireless mesh network has not yet been fully investigated.

We address the problem of joint *multi-path* QoS routing and scheduling in wireless mesh networks in this paper. We view such joint control as a utility maximization problem. By employing the contention matrix representing the wireless link interference, we formulate our convex optimization routing problem under the impact of interference in wireless mesh networks and resolve it using the primal–dual method. To the best of out knowledge, it is the first optimization architecture for joint multi-path routing and scheduling in wireless mesh network. One disadvantage of this problem is that the objective function of *multi-path* routing primal problem is usually not strictly concave. Hence, the dual problem may not be differentiable. To circumvent this difficulty, we introduce the Proximal Optimization Algorithm, where the basic idea is to add a quadratic term to the objective function and therefore render it strictly concave. By applying the dual theory, we decompose our problem into a routing problem without link constraints and a scheduling problem where the MAC scheduling is implemented through scheduling link-layer flows according to the cost of routing along that link. The multi-path routing problem is thus solved via primal–dual method. We verify our proposal by a series of simulations. Simulation results have demonstrated the convergency and efficiency of our algorithm.

In summary, our contributions of this paper are (1) we focus on the optimization of the multi-path routing policy in the presence of underlying wireless interference and formulate a novel optimization architecture for joint routing and scheduling in wireless mesh networks; (2) we introduce the Proximal Optimization Algorithm to get around the non-strict concavity in the utility optimization problem and resolve our problem in a cross-layer manner via the dual decomposition.

The remainder of this paper is organized as follows. In Section 2, we introduce the system model and formulate our problem afterwards. In Section 3 we derive the algorithm for computing the optimal routing ratios and obtain the proposed algorithm. We present the simulation results in Section 4 and then conclude the paper in Section 5.

2. The system model

Without loss of generality, consider a wireless mesh network with N nodes and L links. We model it as a directed graph $\mathcal{G}(\mathcal{N}, \mathcal{L})$, where $\mathcal{N} = \{1, 2, \ldots, N\}$ represents the set of nodes and $\mathcal{L} = \{1, 2, \ldots, L\}$ represents the set of links. Each link corresponds to a pair of transmitting node and receiving node, via which those two nodes can have a conversation. We assume a static topology and each link l has a fixed finite capacity c_l packets per second when active, i.e., we implicitly assume a power control algorithm that maintains a constant data rate in the presence of fading and other channel imperfections.

It is well known that the wireless medium is an inherently multi-access medium where the transmissions of users interfere with each other. This causes interdependencies across links and network layers that are simply not present in

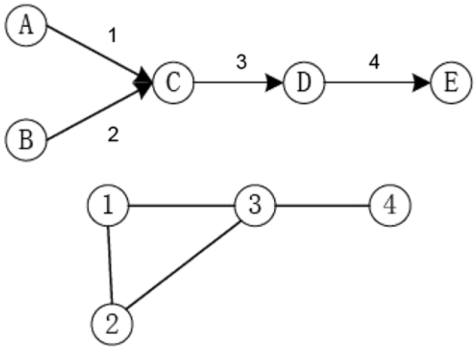

Fig. 2. An example of a wireless mesh network and its corresponding contention graph.

their wireline counterparts. Network layer routing and MAC layer scheduling are thus highly correlated and interact with each other: the selection of a route largely depends on how much bandwidth the underlying MAC layer can provide along its path while route selection affects the traffic density in the wireless mesh backbone, thus further affecting MAC performance. In this work, we will focus on the routing policies while introducing the impact of MAC scheduling as a major resource constraint and characterizing the link interdependency relations using contention graph and contention matrix.

2.1. MAC link constraints and contention graph

A fundamental difference between wireline and wireless networks lies in the interference among wireless links. Traffic flows or packet transmissions in a wireless network mentioned above are subject to location-dependent contention. In theory [14], there exist two models for packet transmission in wireless networks, generally referred to as the *protocol model* and *the physical model*. Roughly speaking, the protocol model mainly focuses on the relative position and the distance between nodes while the physical model is directly related to the physical layer characteristics and concerned with the signal-to-noise ratio. In this work, we concentrate our attention on the MAC layer constraint based on the protocol model, leaving the physical model as a future research direction.

Based on the protocol model, link flows mutually interfere with each other whenever either the sender or the receiver of one link is within the interference range of the sender or receiver of the other. Among a set of mutually contending links, only one of them may transmit at any given time. Under these assumptions, we can construct a flow contention graph that captures the contention relations between the links of the network (see, e.g., [15,16]). In a contention graph, each vertex represents an active link, and an edge between two vertices denotes the contention between the corresponding links: two links interfere with each other and cannot be active at the same time. Fig. 2 shows an example of a wireless mesh network and its corresponding contention graph.

According to the graph theory [17], a clique is a subset of vertex set in which vertices are pairwise-connected. It also denotes a complete subgraph in a graph. A maximal clique is defined as a clique that is not contained in any other cliques. Given a wireless link contention graph, the vertices in a maximal clique represent a maximal set of mutually contending wireless links, across which at most one link may transmit at any given time. To this end, we observe that each maximal clique in the contention graph represents a "channel resource" with links in the clique contending for exclusive access to the resource. The links within the same clique share the "capacity" of the clique [18]. Therefore, compared with the capacity of links within a wireline network which represents the constraint on flows contending for its bandwidth and is independent from each other, the capacity of a wireless link in the case of wireless mesh networks is interrelated with other wireless links in its vicinity. So as far as the "capacity" is concerned, wireless links usually have more restricted capacity regions than its wireline counterpart due to the unique characteristics of location-dependent contention in wireless mesh networks.

We proceed to consider the problem of capacity region of wireless links such that every link flow is achievable or feasible, i.e., whether a schedule can be found to achieve all this set of link flows [19,20]. This will be the constraint imposed by the MAC layer. There are two types of constraints that are imposed upon the capacity of wireless links, namely, (1) the link constraint and (2) the time constraint. The link constraint (usually considered in wired networks) corresponds to the fact that the sum of flow rates of all sessions that traverses through link is not greater than c_l, the capacity of link l. The time constraint means that at any instant of time, there can be only one instance of communication at a given clique. Due to the wireless characteristics we have mentioned above as well as the fact that the link constraints are subsumed by the time constraints claimed by [21], we henceforth focus on the time constraint in this work.

Assume that we are given a L-dimensional vector $\mathbf{y}$ with each component y_l representing the desired flow on link $l \in \mathcal{L}$, in packets per second. Give a link flow y_l, note that y_l/c_l denotes the fraction of time required to send this amount of flow. Since flows within the same clique cannot transmit simultaneously, we obtain a necessary scheduling constraint:

$$\sum_{l \in L(m)} \frac{y_l}{c_l} \leq 1, \tag{1}$$

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