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Multicast with cooperative gateways in multi-channel wireless mesh networks ☆

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ABSTRACT

Wireless mesh networks (WMNs) are emerging as a promising solution for pervasive and cost-effective broadband connections. In this paper, we target high-throughput multicast that combats the interference and bandwidth limitation of wireless channels, which are particularly severe with wireless meshes. We suggest that they can be addressed by introducing multiple cooperative mesh gateways and exploiting the diversity of wireless channels. We present a cross-layer design that jointly selects appropriate channels for each mesh node to use at judiciously tuned power, and computes the optimal multicast flows from multiple cooperative gateways. We show that this design can be iteratively optimized through Lagrange relaxation and primal–dual decomposition. A progressive channel assignment and power level adjustment heuristic is introduced in the MAC/PHY layer, together with a smart link capacity allocation for cooperative gateways in the network layer. Through extensive simulations, we demonstrate the effectiveness of the proposed solution framework and the sub-problem heuristics. In particular, a throughput improvement of up to 100% is observed compared to straightforward approaches of utilizing multiple wireless channels for multicast routing.

1. Introduction

Wireless mesh networks (WMN) are emerging as a promising solution for broadband connectivity, due to its flexibility and cost-effectiveness in bringing a large number of users online, in comparison to competing solutions that depend on a wireline infrastructure [2,5]. In a WMN, Internet gateways, mesh routers and client nodes are organized into a mesh topology. Data flows are routed between the clients and the gateways through wireless links, in a multi-hop fashion. A notable challenge in WMN is to provide support for multicast applications that surged on the Internet during the past decade, such as file dissemination, video conferencing and live media streaming. Such applications usually serve a large number of users, and consume high network bandwidth.

We consider two techniques for addressing the high-throughput requirement of multicast applications in WMNs. The first is to use multi-gateways. A gateway is directly connected to the Internet, and hence serves as the data source for users in a WMN. A single gateway design makes the gateway node a bottleneck, and is prone to congestion during high network activities. Having multiple gateways can dramatically improve the network performance at a reasonable cost. These gateways can collaboratively serve their clients using minimal signalling among the gateways. The second is to exploit the diversity in wireless channels, and provide a multi-channel multicast solution. Wireless interference is a critical limitation on throughput of WMN applications [18]. Utilizing distinct channels at neighbouring nodes for transmission can help

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reduce interference to minimum. For example, the IEEE 802.11b/g protocol defines 13 channels within a 2.4 GHz frequency band [9]. The further apart two channels are, the lower interference exists between them; in particular, channels 1, 6 and 13 are totally orthogonal. However, only considering the orthogonal channels will result in collision and reduced throughput, especially in more dense networks like urban areas. We consider using non-orthogonal channels and show that judiciously assigned, this selection will result in lower interference and enhanced performance.

We first formulate the multi-gateway multi-channel multicast problem in WMNs as a mathematical programming problem, which jointly considers channel assignment and transmission power tuning at the MAC/PHY layer, as well as multicast routing at the network layer. Two important regions that the formulation is based on, the channel capacity region and the routing region, are both convex. Furthermore, the objective function that models the utility of multicast throughput is strictly concave. Therefore, the entire optimization model we obtain is a convex program, if we can freely select the frequency band for a channels. However, with pre-defined channels such as in IEEE 802.11, the optimization model contains discrete variables, which complicates the solution design.

In order to provide an efficient and practical solution to the optimization model, we apply the classic Lagrange relaxation technique [7,31], and derive an iterative primal–dual optimization algorithm that leads to a cross-layer multicast solution. Towards this direction, we first relax the link capacity constraints that couple the channel region and the routing region, and decompose the overall optimization into two smaller sub-problems, one for channel assignment at the MAC/PHY layer, and one for multicast routing at the network layer. Our primal–dual solution framework then iteratively refines the primal solution, with help of the Lagrange dual that signalizes capacity demand at each wireless link. The dual is updated during each iteration based on the latest primal solutions.

To complete the solution defined by the primal–dual framework, we need to precisely define the channel region and the routing region, and design a solution algorithm for each of the channel assignment and routing sub-problems. We formulate the channel assignment problem as a mathematical program, in which channel capacities are computed from their signal-to-noise-and-interference ratio (SINR), and the computation of SINR in turn appropriately takes into account the separation between different wireless channels used at neighbouring mesh nodes. The main challenge in solving this mathematical program lies in the presence of discrete channel assignment variables. We design an efficient heuristic, *progressive channel assignment*, for overcoming this difficulty. Finally, we discuss both multicast tree based and network coding based solutions for the multicast routing sub-problem. Extensive simulations, with various network sizes, were conducted for evaluating the effectiveness of both the overall primal–dual optimization framework and the sub-problem solutions. Throughput improvement of up to 100% were observed, when the proposed solution is compared to straightforward channel assignment schemes such as orthogonal channel assignment and consecutive channel assignment.

The rest of the paper is organized as follows. We review related research in Section 3. Section 4 presents the optimization problem formulation for multicast in WMN. Section 5 introduces the problem decomposition and the overall primal–dual solution framework. Section 6 presents solutions for the sub-problems. Section 7 is simulation results and Section 8 concludes the paper.

2. Motivating example

In this section, we present an example to illustrate the importance of multicast channel assignment in multi-channel wireless networks. Fig. 1 illustrates a mesh network consisting of 25 nodes within a 150 m × 150 m area. The network contains four gateways providing the connectivity to the same multicast source. Multicast receivers, D1–D7, each wishes to connect to one of the available gateways to access multicast data. We assume using 802.11 g in an indoor environment. The effective communication

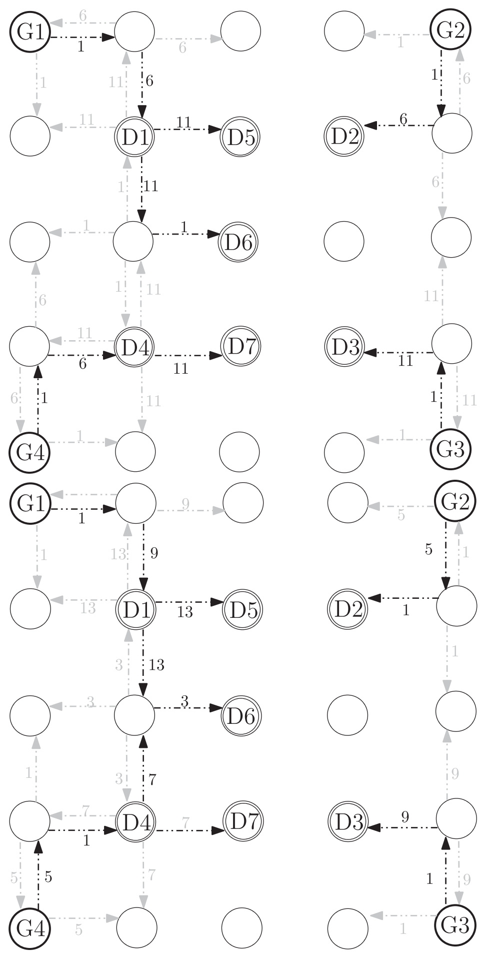

Fig. 1. Motivating example: Multi-gateway multicast in a WMN in a crowded area, using orthogonal channels: (a) Hop count-based multicast. (b) Multicast flow and corresponding channel assignment based on our optimization framework.