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Interface assignment and bandwidth allocation for multi-channel wireless mesh networks

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ABSTRACT

With the ability of simultaneous transmissions, multi-channel multi-interface wireless mesh networks (WMNs) have emerged with great potential in the improvement of network throughput and fairness. However, most proposed channel assignment algorithms for WMNs made an assumption that the network interface cards (NICs) are evenly assigned to the mesh routers. In this paper, we investigate the problems of NIC assignment and bandwidth allocation to minimize the infrastructure cost, and meanwhile guarantee the application requirements. We argue evenly assigning NICs to all routers is neither a necessary condition nor an effective solution, since not only the interference but also the traffic flows are important factors that will affect the parallel use of the bandwidth. One of the principal challenges addressing these problems is their interactive impact on the optimization of network throughput. By analyzing all kinds of constraints for traffic, NIC and performance, we formally define a problem space that addresses the relationships between different assignment and allocation problems. Furthermore, we demonstrate that a hard NIC assignment and bandwidth allocation problem can be decomposed and formulated into a well-defined single or multiple-phase problem. In addition to the linear programming (LP) solutions, we propose novel efficient heuristics for on-line decisions for the situation whenever the network architecture changes and needs recompute the system performance in real-time. We show through extensive simulations that the heuristic algorithms can achieve close to optimal solution and outperform the equal NIC assignment method with even a smaller number of NICs.

1. Introduction

Recent years, wireless mesh networks (WMNs) [6] have emerged as a promising technology that provides wireless broadband accessibility to extend the Internet connectivity at the edge end and improve the network coverage. A typical deployment of a multi-hop infrastructure-based WMN (IWMN) consists of three major components: a base station (or so called gateway), a set of mesh routers and mesh clients. A base station is present that is wired to a larger network, e.g., the Internet; a set of mesh routers integrate traffic flows for local clients (one hop) and relay communications for other mesh routers to transfer data to or from the Internet through the gateway; a large number of mesh clients can be any of the mobile devices such as laptops, PDAs and cell phones. Mesh routers are normally stationary and therefore, have less topology change, node failure and energy constraints.

Using WMN as a backbone for large wireless access imposes high bandwidth requirements. At the same time, the interference among simultaneous transmissions may dramatically cause capacity reduction [13]. An obvious solution towards addressing the interference problem is to use multiple non-overlapping channels on the interfering links to maximize the parallel transmission and throughput [18,27]. For example, IEEE 802.11b/g and 802.11a standards specify 3 and 12 non-interfering channels, respectively.

In order to achieve successful communication, a pair of network interface cards (NICs) on neighboring routers have to be tuned to one of the channels. Although the one-NIC architecture is able to support simultaneous transmissions as long as the interfering links operate in different channels, its limit on the parallel use of multiple channels cannot be ignored [8,18,27]. On the other hand, recent advances in the development of multi-NICs for mesh network have made it possible for one node to access multiple channels at the same time, since different NICs can operate on different channels

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without interference as long as there is no neighboring transmission using the same channel. With regards to the channel assignment problem, researchers [7,11,19,21–25,27,30,31,33,34] have done great work with the purpose of maximizing the network throughput in WMNs. However, all of them pre-assumed that each WMN router was equipped with one or equal number of NICs (also called k-NIC architecture). In this paper, we argue that evenly assigning the NICs to every router is neither a necessary condition nor an effective solution to satisfy the whole network traffic on demand. This is because not only the peer-to-peer wireless interference but also the NICs assignment on each node will influence the WMN capacity [8,18]. Given the number of channels and the application bandwidth requirements, the fundamental problem are: how many NICs are needed to satisfy the best performance in both throughput and fairness as required? And what's the interactive relationship between the problems of bandwidth allocation and NIC assignment?

In this paper, we study the problems and relationships between the bandwidth allocation and NIC assignment with the objective of optimizing the throughput and fairness in WMNs. Here, NIC assignment means specifying a certain number of NICs for each router. The major contributions of this paper are as follows.

- We define all kinds of different constraints for traffic flows, NIC assignment and performance objectives under the restriction of wireless transmission and interference model. According to different requirements and constraints, we further present a taxonomy of problem space to illustrate the relationships between the problems of bandwidth allocation and NIC assignment.
- We demonstrate that a hard problem with different bandwidth or NIC requirements can be decomposed and formulated into a well-defined single problem or multiple-phase problems, depending on the variety of the objectives in the problem space.
- We analyze a specific Qos-aware bandwidth allocation and NIC assignment problem. We formulate the problem into four phases with detailed constraints and objectives. In addition to the optimal solutions (by formulating the LP problem), we propose novel traffic and interference aware efficient algorithms to address those problems. We show through extensive experiments that the proposed algorithms can achieve close to optimal performance. And they outperform the equal NIC assignment method very much with even a smaller number of NICs.
- To the best of our knowledge, this paper for the first time investigates the NIC assignment problem together with the bandwidth allocation problem for multi-channel multi-interface WMNs.

The rest of the paper is organized as follows. We state the system model in Section 2. We present detailed constraints and problem definitions in Section 3. We study a specific NIC assignment and bandwidth allocation problem in Section 4 and in Section 5 we propose heuristic solutions. Further discussion is presented in Section 6. Section 7 shows related work. Finally, we draw our conclusions and discuss future work in Section 8.

2. System model

2.1. System architecture

The system is considered as a multi-hop infrastructure wireless mesh network (IWMN) that consists of several static wireless mesh routers. The routers provide network connectivity to end-users within their coverage area. One router together with all its one-hop clients is considered as one node in this paper. One of the routers is designated as the gateway that provides functionality to enable direct connection to a large network, e.g., the Internet. Here, we assume there is only one gateway (*gw*) for the whole WMN. The one-gateway architecture is reasonable since we can easily extend the work to a network with multiple gateways by assuming all gateways connecting to a virtual super gateway or partition the network to multiple sub-networks with only one gateway in each. We model the backbone of this IWMN as a directed graph $G = (V, E)$; where V represents the set of nodes in the network and E represents the set of directed links (denote transmissions). The set of non-gateway nodes is represented as V' where $V' = V - \{gw\}$.

Each node u ($u \in V$) may be equipped with a number of NICs, where the number is denoted as $I(u)$ ($I(u) \geqslant 1$); and each NIC can only operate on a particular channel at one moment. Here, we assume there are totally k non-overlapping channels, and the channel set is denoted as C ($|C| = k$). Each NIC can be fixed on one channel during the entire transmission lifetime (identified as Fix-NIC) or can switch channels after several packets have been sent out (identified as Switch-NIC). Two nodes can communicate with each other via wireless links when one pair of their NICs are tuned to be on the same channel.

The traffic within the mesh is either from the user devices to the gateway or vice-versa. Because the traffic is relayed to or from the gateway, the paths taken by the traffic flows are likely to form a tree structure in which the gateway is the "root" and the user devices are the "leaves". Here, we can simply use a breadth-first search to construct a minimum spanning routing tree T for the graph G, in which the root is the gateway. For each node except the gateway, traffic can be separated as uplink and downlink flows. For ease of exposition, in this paper, we will address the problems for all uplink flows, and this can be extended to bidirectional link easily if we consider the uplink and downlink separately. For example, the time frame can be divided into a downlink subframe and an uplink subframe. And each of these subframes is composed of several time slots. Then the bandwidth (time slots) can be allocated to uplink and downlink flows proportionally and the proportion coefficient may change dynamically according to the bandwidth requirement. In the rest of the paper, if a transmission is from node u to node v, v is called the parent node of u, denoted as $PAR(u)$; and the children set of node u is represented as $CHI(u)$. Also, we denote $T(u)$ as the sub-tree of T, where node u is the root of $T(u)$.

2.2. Transmission and interference model

To accomplish a transmission, the receiver has to be within the transmission range of the sender, using a common channel assigned to one pair of their NICs. Two sets of nodes using the same channel may interfere with each other if they stand within the interference range. However, they can transmit packets simultaneously without any interference if they are using different channels. In this paper, we assume all transmission ranges (denoted as R^T) are the same and all interference ranges (denoted as R^I) are the same. But the interference range is larger than the transmission range. We say node v is node u's "neighbor" if and only if node v is in the interference range of node u. The neighbor set for node u is denoted as $NEI(u)$.

In this paper, we have the following transmission constraints. First, a node cannot send and receive on the same channel at the same time. Second, a receiver can successfully receive the transmission packets if and only if (i) it stands within the transmission range of the sender and (ii) there are no other simultaneously transmissions that will cause interference at the receiver.

We can use Fig. 1 to illustrate the interference model more clearly. In this figure, R^T represents the transmission range and R^I represents the interference range. We assume node *N1* is sending