A Utility-based Framework for Joint Channel, Topology, and Routing Control in Wireless Mesh Networks

Theodoros Dionysiou, Vasilios A. Siris, and George Stamatakis

Institute of Computer Science (ICS)
Foundation for Research and Technology - Hellas (FORTH)
P.O. Box 1385, GR 711 10 Heraklion, Crete, Greece
{theodion,vsiris}@ics.forth.gr

Abstract. We define a utility-based framework for joint channel assignment, topology control and routing in multi-rate multi-radio wireless mesh networks, and present a greedy algorithm for solving the corresponding optimization problem. A key and novel feature of the proposed approach is the support for different target objectives, which are defined as utility functions of the MAC layer throughput, that allow operators to express different requirements in terms of throughput and availability. Such flexibility is important in future access networks.

1 Motivation and Contribution

Channel assignment in wireless mesh networks influences the contention among wireless links and the network topology or connectivity between mesh nodes. Indeed, there is a trade-off between minimizing the level of contention and maximizing connectivity, e.g. see [3, 2]. Moreover, channel assignment determines the interference between adjacent channels; such interference exists not only for 802.11b/g, but - contrary to common belief - also for 802.11a when the distance of antennas is small [1], e.g. when they are located in the same mesh node. Finally, channel assignment influences the connectivity of mesh nodes with wired network gateways, which is a key application of wireless mesh networks.

The contribution of this work is twofold: First, we formulate a new utility-based framework for joint channel assignment and topology control in multi-rate multi-radio wireless mesh networks, which can be extended to incorporate routing. Second, we propose a greedy channel assignment procedure for solving the corresponding optimization problem. The proposed approach has the following key features: 1) channel assignment can be performed with different target objectives, which can reflect different operator-dependant requirements, 2) target objectives are expressed as utility functions of the MAC layer throughput, which captures transmission rate diversity, and 3) the approach efficiently utilizes multiple wired network gateways, and ensures that for every mesh node there exists at least one path to a gateway. Key differences with related work are that we consider throughput estimations in the channel and topology control.
problem, and the framework allows different objectives, which is motivated by the fact that network operators can have different operation and performance requirements, hence value differently the aggregate throughput achieved by the network, the distribution of throughput across mesh links, and the link availability/redundancy; such flexibility is important in future access networks.

2 Problem Formulation for Joint Channel Assignment and Topology Control

We consider a wireless mesh network with a set of nodes $N$. Each mesh node has multiple radio interfaces. Some nodes, which are referred to as gateway nodes, have wired network connections. The problem we address is to assign channels to mesh nodes and define node pairs that have a communication link, while ensuring that all nodes have a path to at least one gateway. Channel assignment alone does not fully define the node connectivity, since an interface’s transmission rate depends on the destination interface it communicates with; the transmission rate in turn influences the throughput that is achieved by that link, as well as all other links in the same transmission range that operate on the same channel. Let $L$ be the set of links between nodes, which contains elements of the form $(i, j; k)$, denoting a link between nodes $i$ and $j$ operating on channel $k$. Note that there can exist multiple links between two mesh nodes, operating on different channels. Also, different nodes can communicate with the same node on the same channel. $L_{ij}$ denotes the set of links, and $X_{ij} = \{x_l, l \in L_{ij}\}$ the throughput of the links between nodes $i$ and $j$. Finally, $K_i$ and $I_i$ is the number of assigned channels and the number of interfaces in node $i$, respectively. The channel and topology control objective is to maximize the aggregate utility:

$$\max_{L} \sum_{i,j \in N} U(X_{ij})$$

s.t. $\exists$ path from $i$ to a gateway, $\forall i \in N$ and $K_i \leq I_i, \forall i \in N$

The utility $U(X_{ij})$ is a function of the throughput of links between nodes $i$ and $j$. The formulation when the utility is a function of a node’s end-to-end throughput to a wired network gateway is discussed in the next section.

Different expressions of $U(\cdot)$ in (1) encodes different operator-dependent requirements and objectives, as discussed next.

**Aggregate throughput objective**: This objective corresponds to the following utility for the links between nodes $i$ and $j$:

$$U(X_{ij}) = \sum_{l \in L_{ij}} x_l,$$

i.e., the utility depends only on the aggregate throughput achieved by all links between nodes $i$ and $j$. 
**Fairness objective:** The corresponding utility for the node pair $i, j$ is:

$$U(X_{ij}) = \log \left( \sum_{l \in L_{ij}} x_l \right).$$

As above, the utility for the node pair $i, j$ depends only on the total throughput achieved by the links between the two nodes. However, now the network’s aggregate utility is the sum of logarithms, hence more value is placed on node pairs with a small throughput; this imposes some fairness across different node pairs. The above definition can be extended with the addition of weights, which reflect the relative importance of links. For example, links closer to a wired network gateway or expected to carry a higher traffic load, can have a larger weight.

**Redundancy objective:** The corresponding utility for the node pair $i, j$ is:

$$U(X_{ij}) = \sum_{l \in L_{ij}} \log (x_l).$$

This utility gives higher value to having, between two nodes, multiple links with a small throughput, rather than a few links with a higher throughput.

---

**Fig. 1.** The channel assignment procedure consists of two modules: the throughput estimation module, and the channel and link selection module.

The proposed channel assignment and topology control procedure for solving the joint channel assignment and topology control problem in (1) consists of two modules: the throughput estimation module, and the channel and link selection module, Figure 1. The former estimates the throughput for a specific channel assignment and node connectivity, taking into account rate diversity; this estimation considers the location of the mesh nodes and gateways, the channel model, the transmission power, and the receiver sensitivity. The channel model captures both the path loss and the adjacent channel interference.

The throughput estimation is based on the link conflict graph, and maximal cliques. All links belonging to the same maximal clique have an equal throughput share, while links belonging to more than one cliques are assigned the throughput of the most congested one. The throughput estimation for each clique depends on the time for each link belonging to the clique to transmit one packet, which is inversely proportional to its transmission rate (if we disregard overheads). Finally, the estimation procedure proceeds by assigning throughputs with increasing throughput values, i.e. follows a max-min sharing of wireless resources.
The channel and link selection module takes as input the target objective, expressed as a utility function, and selects the channel assignment and node connectivity that optimizes the specific objective. The channel assignment procedure consists of the following steps:

**Step 1:** For each interface, and for all possible connections of this interface to an interface with a path to a gateway, select the channel that gives the highest aggregate utility, given by (1).

**Step 2:** Select the interface that gives the highest aggregate utility, and assign the channel determined by the previous step to it, provided that the interface belongs to a node without a path to a gateway or the aggregate utility is higher than the aggregate utility without this interface.

**Step 3:** If all interfaces are assigned a channel, or if Step 2 did not result in a channel assignment, then End, else goto Step 1.

In Step 2, if two or more interfaces give the same aggregate utility, a channel is assigned to an interface that belongs to node without a path to a gateway or to the interface that yields the shortest path to a gateway. The greedy utility-based channel assignment procedure ensures that all nodes obtain a path to at least one gateway. This is ensured through Step 2, which always assigns a channel to an interface of a node without a prior path to a gateway, independently of whether the specific channel assignment yields a lower aggregate utility, compared to the aggregate utility prior to assigning the channel.

### 3 Joint Channel, Topology, and Routing Control

The objective in the case of joint channel assignment, topology control, and routing is given by (1), where $X_{ij}$ is replaced by $X_i$, which denotes the end-to-end throughput from node $i$ to one or more wired network gateways. We can identify two cases related to path selection: If path selection is performed by an external routing module, then the selected paths are an additional input to the throughput estimation module shown in Figure 1, which now computes the end-to-end throughput from a node to a gateway, rather than the hop-by-hop throughput as in the problem formulation of Section 2. On the other hand, if we include path selection in the optimization problem, and perform jointly optimal channel assignment, topology control, and path selection, then the path selection is performed within the channel and link selection module in Figure 1, based on a greedy selection algorithm similar to the one discussed in the previous section.

### References

