Utility-based Channel Assignment and Topology Control in Wireless Mesh Networks

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***Abstract*—We define a utility-based framework for joint channel assignment and topology control in multi-rate multi-radio wireless mesh networks, and present a greedy algorithm for solving the corresponding optimization problem. Key features of the proposed approach are the support for different target objectives, which are expressed as utility functions of the MAC layer throughput, and the efficient utilization of wired network gateways, while guaranteeing that for every mesh node there exists a path to a gateway. Investigations show the influence of different target objectives on the channel assignment and network topology, demonstrate the proposed approach's load balancing properties in mesh networks containing multiple gateways, show the effect of 802.11a adjacent channel interference on the channel assignment, and compare the performance of the proposed procedure with a rate-based channel assignment scheme.**

I. Introduction

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 [1], [2], [3]. 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 [4], [5], which is the case 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. Indeed, a wireless mesh network can be considered a radio access network that provides wireless stations with connectivity to a wired backbone network, through access to the aggregate capacity of all wired connections in gateways.

Prior work on channel assignment considered minimizing the physical layer interference [6], [7], [8]. On the other hand, the channel assignment procedure proposed in this paper considers an optimization objective that is a function of the MAC throughput. The works of [2], [9], [10], [11], [12], [13], [14] consider the throughput for channel assignment. [15], [13], [14] also consider a utility-based framework: [15] for joint congestion control and channel assignment, assuming a known network topology, [13] for joint congestion control and channel assignment, assuming orthogonal channels, and [14] for joint congestion control, channel allocation, and scheduling, for which a greedy heuristic assuming orthogonal channels is proposed. Our work differs in that we present a utility-based optimization framework for joint channel assignment and topology control; additionally, we investigate the effects that the utility function has on both, and our model captures rate diversity. The application of a utility-based framework to congestion control is fundamentally different than the application to channel assignment and topology control, since the latter is a discrete problem. Also, unlike [13], [14] we consider non-orthogonal channels. The works of [15] and [16] also deal with non-orthogonal channels, but they consider only 802.11b and do not account for MAC layer sharing and rate diversity. [10] considers the problem of joint channel assignment and routing while satisfying fairness constraints related to throughput demands. Our work differs in that we investigate joint channel assignment and topology control, our model accounts for rate diversity and adjacent channel interference, and include target objectives related to redundancy. [17] considers the problem of topology control, and proposes a channel assignment procedure to minimize the aggregate interference, while satisfying a minimum node connectivity. Our approach differs in that we consider utility-based objectives for topology control, which are functions of the throughput. Other works assume full connectivity between nodes that are within range [1], [2], [8], or assign a common channel to one interface of all mesh nodes [6]. The former approach has disadvantages for multi-rate networks, since the distance between two interfaces affects the transmission rate; assuming that all nodes within range communicate can result in low rates, which significantly reduces the network's performance. On the other hand, assigning a common channel to all nodes reduces the interfaces available for more intelligent channel assignment, which is significant since practical mesh networks contain nodes with a few (typically 3-4) interfaces.

The channel assignment problem in mesh networks with multi-radio nodes is known to be NP-hard [18]. For this reason, channel assignment is typically based on heuristics which assign channels to interfaces or links based on some order or rank; the rank can depend on traffic load, distance to

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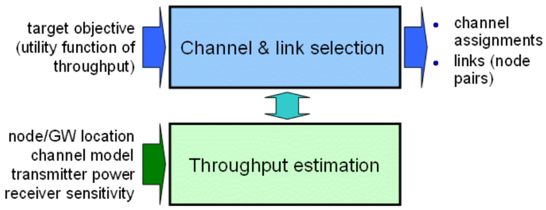


Fig. 1. The channel assignment procedure consists of two modules: the throughput estimation module, and the channel and link selection module.

gateway, interference level, etc. In order of decreasing rank, interfaces are assigned the "best" channel according to some criteria [18], [19], [2], [6], [3]. The procedure proposed in this paper also considers assigning channels in some order; however, the order is not fixed or a priori known, but rather is determined during the execution of the channel assignment procedure, and is based on the target objective.

The contribution of this paper 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. Second, we propose a greedy channel assignment procedure for solving the corresponding optimization problem. The proposed approach has the following key features:

- Channel assignment can be performed with different target objectives, which can reflect different operator-dependant requirements.
- Target objectives are expressed as utility functions of the MAC throughput, which captures rate diversity.
- No a priori assumption is made about the node connectivity. Rather, the node connectivity (or network topology) is determined together with channel assignment.
- The approach efficiently utilizes multiple wired network gateways, and ensures that for every mesh node there exists at least one path to a gateway.
- The approach captures the influence of 802.11a adjacent channel interference on channel assignment in *multi-radio* mesh networks.

Support for different objectives 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 redundancy. Such flexibility is significant for the cost-effectiveness of future wireless access networks, enabling them to adapt to different operator and application requirements.

The proposed channel assignment and topology control procedure 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; 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 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. Note that the channel selection and throughput estimation modules are independent, hence the proposed channel and link selection procedure can work with some other throughput estimation module. Of course, the performance of the channel assignment depends on the joint operation of the two modules.

The remainder of the paper is structured as follows. In Section II we present the utility-based optimization problem formulation, and in Section III we present a greedy utility-based procedure for solving this problem. In Section IV we discuss three extensions that include consideration of end-to-end throughput, an adaptive lookahead procedure, and the distributed implementation of the proposed procedure. In Section V we present investigations that show the effect of the utility function and adjacent channel interference on the resulting channel assignment and node connectivity, show the load balancing properties of the proposed procedure, and compare its performance with a rate-based channel assignment scheme. Finally, in Section VI we conclude the paper identifying ongoing research.

II. Problem formulation

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 assignment and topology control objective is to maximize the aggregate utility:

$$\begin{aligned} \max_{L} \quad & \sum_{i,j \in N} U(X_{ij}) \qquad (1) \\ \text{s.t.} \quad & \exists \text{ path from } i \text{ to a gateway}, \forall i \in N \text{ and} \\ & K_i \leq I_i, \forall i \in N \end{aligned}$$

The utility $U(X_{ij})$ is a function of the throughput of links between nodes i and j. This formulation considers the hop-by-hop throughput between nodes connected by one or more links. The formulation with the end-to-end throughput from gateways to nodes is discussed in Section IV-A.

The utility $U(\cdot)$ in (1) encodes different operator-dependent requirements. Next we discuss different target objectives that correspond to different expressions for $U(\cdot)$.

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

$$U(X_{ij}) = \sum_{l \in L_{ij}} x_l \,, \tag{2}$$

i.e., the utility depends only on the aggregate throughput achieved by all links between nodes i and j. Similarly, the aggregate utility (1) for the whole network depends on the total throughput achieved by all the links in the network.

Fairness objective: This objective corresponds to the following utility for the node pair i, j:

$$U(X_{ij}) = \log \left(\sum_{l \in L_{ij}} x_l \right) \,. \tag{3}$$

As above, the utility for the node pair i, j depends only on the total throughput of 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, compared to node pairs with a high 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 gateway or expected to carry a higher traffic load, can have a larger weight.

Redundancy objective: This objective corresponds to the following utility for the node pair i, j:

$$U(X_{ij}) = \sum_{l \in L_{ij}} \log (x_l) \,. \tag{4}$$

The above utility gives higher value to multiple links between nodes with a small throughput, thus improving redundancy, rather than a few links with a higher throughput.

III. Utility-based channel assignment and topology control

Next we discuss the functionality of the channel and link selection, and the throughput estimation modules.

A. Channel and link selection algorithm

The proposed channel assignment procedure implements a greedy heuristic that tries to maximize the aggregate utility of the mesh network (1). The order in which interfaces are assigned channels is based on the utility the corresponding channel assignment yields, which is estimated during the execution of the algorithm and not known a priori. The pseudo-code for the channel selection procedure, which is executed in some central location, is shown in Algorithm 1. L is the set of links, which contains elements $(i, j, ; k)$ that denote a link between nodes i and j, operating on channel k. $U(L)$ is the aggregate utility for the link set L.

Algorithm 1 Greedy utility-based channel and link selection

1: **Variables:**
2: $N_{unassigned}$: set of nodes that have been assigned fewer channels than their number of interfaces; initially contains all nodes
3: $N_{path-to-gw}$: set of nodes with path to a gateway; initially contains only the gateway nodes
4: L: set of links, which contains elements of the form $(i, j, ; k)$, denoting there is a link between nodes i and j operating on channel k; initially empty
5: $Chs(i)$: set of channels currently assigned to interfaces of node i
6: $Ifs(i)$: number of interfaces in node i
7: $U(L)$: aggregate utility for set of links L
8: $U'(i, j, ; k)$: aggregate utility if link between i and j, operating on channel k, is added to current set of links
9: K: set of all available channels
10: **Algorithm:**
11: **do**
12:   **for all** $i \in N_{unassigned}$ **do**
13:     **for all** $j \in N_{path-to-gw}$ **do**
14:       **if** $|Chs(j)| == Ifs(j)$ **then** $K' = Chs(j)$ **else** $K' = K$
15:       **for** $k \in K'$ **do**
16:         $U'(i, j, k) = U(L + \{(i, j, ; k)\})$
17:       **end for**
18:     **end for**
19:   **end for**
20:   $L' = \{(i', j'; k') : U'(i', j', k') \geq U'(i, j, k) \quad \forall i, j, k\}$
21:   **if** L' has one element $(i, j, ; k)$ **then**
22:     **if** $U'(i, j, k) > U_{last}$ or node i does not have path to a gateway **then**
23:       $L = L + \{(i, j, ; k)\}$ /* Add link between i, j on channel k */
24:       Add node i to $N_{path-to-gw}$
25:       $U_{last} = U'(i, j, k)$
26:     **end if**
27:   **else** /* L' has multiple elements */
28:     **select** $(i, j, ; k) \in L'$ with smallest number of hops to a gateway and ($U'(i, j, k) > U_{last}$ or node i does not have path to a gateway) **then**
29:       $L = L + \{(i, j, ; k)\}$ /* Add link between i, j on channel k */
30:       Add node i to $N_{path-to-gw}$
31:       $U_{last} = U'(i, j, k)$
32:     **end select**
33:   **end if**
34:   **if** $|Chs(i)| == Ifs(i)$ **then** remove i from $N_{unassigned}$
35:   **if** $|Chs(j)| == Ifs(j)$ **then** remove j from $N_{unassigned}$
36: **while** Last execution of loop resulted in new channel assignment

The algorithm includes an initial loop (lines 11-36) which is continuously executed while there exist channel assignments that increase the aggregate utility, or if there are nodes without a path to a gateway. The body of the loop contains two parts. The first (lines 12-19) computes, for each node with available interfaces, and for all possible links of this node to a node with a path to a gateway and all possible channel assignments, the aggregate utility if this link is added to the set of links (line 16). If a node j has already been assigned channels equal to the number of its interfaces ($|Chs(j)| == Ifs(j)$, line 14), then only the channels assigned to node j are considered ($K' = Chs(j)$, line 14); on the other hand, if node j has been assigned fewer channels than the number of its interfaces, then all channels are considered ($K' = K$, line 14).

The second part of the algorithm (lines 20-35), selects the link and channel that gives the highest aggregate utility. The corresponding channel assignment is performed if it increases the aggregate utility or if the link involves a node without a path to a gateway (line 22). If more than one links give the same aggregate utility, then the one with the smallest number of hops from a gateway is selected (line 28). The addition of the selected link to the set L in lines 23 and 29 involves assigning channel k to one of the interfaces of node i, and to one of the interfaces of node j, if the latter does not already have an interface operating on channel k.

The algorithm ends when all interfaces are assigned a channel, or the remaining unassigned interfaces belong to nodes that already have a path to a gateway and assigning a channel to them does not increase the aggregate utility. The complexity of the algorithm is $O(|I| \cdot |N|^2 \cdot |K|)$, where $|I|, |N|, |K|$ is the total number of interfaces, the number of nodes, and the number of channels, respectively.

B. Throughput estimation

The throughput module provides MAC layer throughput estimates for each wireless link, and consists of two models: the physical layer model and the MAC layer model.

The physical layer model is used to estimate the transmission rate for each wireless link, based on the signal-to-interference-and-noise ratio (SINR) at the receiving end of the link. We use an additive interference model, which considers the sum of the interference from different neighboring channels; this is motivated by inaccuracies of simpler models such as the protocol model or the non-additive model, which considers the interference only from a single node [20]. To estimate the interference power level at an interface i we consider, for all channels other than the channel that i is on, the interface that is closest to i; these interfaces cause the largest interference to i. Summing the received power at i from these interfaces gives the total interference. In the interference power we do not consider interfaces that use the same channel as i, since they are either too far to cause significant interference, or are close enough for the MAC layer carrier sensing mechanism to prohibit them from transmitting concurrently; the latter is taken into account by the MAC layer sharing model described below. Finally, to model the adjacent channel interference, we consider the power leakage for 802.11a channels shown in Table I, which are derived using an analytical model verified with measurements in an actual test-bed [5].

From the SINR at the receiving end of a communication link, the transmission rate is estimated based on the minimum SINR threshold for each transmission rate, which depend on the receiver sensitivity. The investigations in Section V consider the threshold values shown in Table II.

The MAC model considers a connectivity graph, $G = (V, E)$, where V represents the set of interfaces and E the set of directed links, and the conflict graph $G^c = (V^c, E^c)$, where each vertex in V^c represents a link and each edge in E^c indicates that the two vertices it connects cannot be simultaneously active. The throughput estimation is based on identifying all maximal cliques of the conflict graph G^c; there are efficient approximate methods for doing this in wireless networks [21].

We assume saturated conditions, i.e. transmitters always have a packet for transmission, and all links have fair access to the wireless channel. We disregard collisions, and for simplicity in the equations presented next we do not account for protocol overheads and assume all packets have equal length (the actual implementation accounts for the overheads and different packet sizes). In the case of a single maximal clique c, the time for the transmission of one packet over a link l using transmission rate r_l is proportional to $1/r_l$, and the time share of link l belonging to clique c is

$$\tilde{s}_{c,l} = \frac{\frac{1}{r_l}}{\sum_{m \in L_c} \frac{1}{r_m}} , \tag{5}$$

where L_c is the set of links in maximal clique c. The last equation captures rate diversity, since links with a lower transmission rate occupy the channel for a longer time.

The throughput for all links belonging to a maximal clique c, when these links are limited by this clique, is:

$$\tilde{x}_c = \frac{1}{\sum_{m \in L_c} \frac{1}{r_m}} . \tag{6}$$

Now we consider the case of multiple cliques. If a link belongs to more than one maximal cliques, then its throughput is determined by the most congested clique. A key observation is that *all* links of the most congested maximal clique c get a smaller *time share* in c than in any other maximal clique they belong to. Based on this, we can compute the throughput for all links using a max-min sharing procedure that begins by finding the most congested maximal clique.

According to the max-min sharing procedure, the links of the less congested maximal cliques will share the unused time shares of links that belong to a more congested maximal clique. Let $L_c^x \subset L_c$ be the set of links that belong to both the maximal clique c and a more congested maximal clique. The total excess time T_c^e to be shared among links $l \in L_c - L_c^x$ is

$$T_c^e = \sum_{\forall m \in L_c^x} (\tilde{s}_{c,m} - s_{f(m),m}) , \tag{7}$$

where $\tilde{s}_{c,m}$, given by (5), is the time share of link m in clique c if this clique was alone, $s_{c,m}$ is the time share of link m in clique c, and $f(m)$ is the most congested maximal clique that link m belongs to. From T_c^e, we can calculate the excess time share and the excess throughput for each link $l \in L_c - L_c^x$:

$$s_{c,l}^e = \frac{(\frac{1}{r_l}) \cdot T_c^e}{\sum_{m \in (L_c - L_c^x)} \frac{1}{r_m}} , \qquad x_c^e = \frac{T_c^e}{\sum_{m \in (L_c - L_c^x)} \frac{1}{r_m}} , \tag{8}$$

and the total time share and throughput:

$$s_{c,l} = \tilde{s}_{c,l} + s_{c,l}^e , \qquad x_c = \tilde{x}_c + x_c^e . \tag{9}$$

TABLE I
ADJACENT CHANNEL POWER LEAKAGE

Interferer power (dBm)	Receiver bandwidth	Adjacent channel power leakage	Next adjacent channel power leakage
0	20 MHz	-22.04	-39.67
	∞	-19.5	-36.67

TABLE II
MINIMUM SINR VALUES

Transmission rate	6	9	12	18	24	36	48	54
Min SINR (dBm)	4.8	5.8	7.8	8.8	12.8	15.8	21.8	24.8

The procedure for computing $s_{c,l}$ and x_c proceeds iteratively: in each iteration, the most congested maximal clique - which is the clique with the smallest $s_{c,l}$ - is identified; this clique determines the throughput x_c of links l for which $f(l) = c$, and the values of $s_{c,l}$ used in subsequent iterations.

IV. Extensions

Next we discuss three extensions of the model described above: the modification to consider the end-to-end throughput from the gateways to nodes, an adaptive lookahead that enhances the greedy search scheme and the distributed implementation of the channel assignment procedure. Due to space limitations, the presentation remains at a high level.

A. End-to-end throughput

The model in Section II can be modified to consider the end-to-end throughput by replacing X_{ij} in (1), with the end-to-end throughput from a gateway to a node i. The procedure for estimating the throughput in Section III-B needs to be modified, since the end-to-end throughput of a flow is limited by its most congested link, which operates in the channel with the highest contention; the procedure for estimating the throughput can proceed using a max-min sharing procedure.

The above formulation adds the dependence on routing to the optimization model. One alternative is to consider an external routing module which determines the paths; the selected paths are an additional input to the throughput estimation module in Figure 1, which now computes the end-to-end throughput from a gateway to a node, rather than the hop-by-hop throughput as in the formulation of Section II. Another alternative is to include path selection in the optimization model, and hence perform jointly optimal channel assignment, topology control, and routing; in this case path selection is performed in the channel and link selection module, Figure 1. Consideration of the end-to-end throughput enables the introduction of new target objectives, which consider load balancing across gateways and redundancy by exploiting multiple paths to different gateways.

B. Adaptive lookahead search

The channel selection algorithm in Section III-A greedily assigns channels based on the resulting utility. The links considered involve nodes with a path to a gateway. Hence, the procedure initially assigns channels to nodes that are close to gateways. If the gateways along with their neighboring nodes are far from each other, then for interfaces that do not interfere and have paths to different gateways, the greedy selection approach can be lured to selecting channels that are costly later on, when channels are assigned to interfaces that are within interference range, and have paths to different gateways; the sub-optimal selection can occur because the initial channel assignment does not consider the latter interference.

One approach for improving greedy algorithms is to use lookahead search [22]. The basic idea of lookahead search is to repeatedly apply the greedy selection, and take decisions based on more information, hence make them "less greedy". In particular, the k-depth lookahead search applies the greedy search selection k steps ahead (rather than one step as in the simple greedy search), and takes the next search decision based on the information from all k forward steps. The straightforward application to the channel assignment problem would require that the next assignment is based on the utility after the next k assignments, each selected using a greedy utility-based search.

The depth k determines the amount of information considered in the search decision, and affects the tradeoff between search time and data storage, and the avoidance of local maxima; in general, the best value of k is problem-dependant. However, the nature of the channel assignment problem allows us to adaptively select k. As noted above, the proposed greedy selection procedure initially assigns channels to nodes close to gateways; this can lead to local maxima, if later channels are assigned to nodes that have a path to a different gateway, but are within range of each other, hence their assignment of channels cannot be independent. This motivates to adaptively set k equal to the minimum lookahead depth at which channels are assigned to nodes that are within interference range, and have paths to different gateways. In this way, the greedy channel selection early-on accounts for information that helps it avoid making selections that lead to local optima.

The implementation of the above adaptive lookahead scheme involves replacing line 16 in Algorithm 1, with a recursive function that performs a greedy utility-based channel selection until the condition identified above is met.

C. Distributed implementation

Next we discuss the requirements for the distributed implementation of the proposed channel assignment procedure. A key requirement is to allow local implementation of the channel and link selection. To achieve this, a node requires, for all available channels, knowledge of the rate for all transmitters within the node's transmission range. Additionally, the node needs routing information (to identify nodes with a path to a gateway), and knowledge of the transmission rate to its neighbors. The above information can be disseminated using a flooding procedure, as in link state routing algorithms such as OLSR (Optimized Link State Routing). Indeed, in [23] we proposed and implemented in OLSR a contention-aware routing metric that uses information identical to that identified above. Due to situations such as hidden terminal scenarios, the above dissemination approach does not necessarily result in all nodes having complete and up-to-date information; such a cost is often incurred with distributed algorithms.

A second issue for a distributed implementation is the ordering of channel assignments. Recall that in the centralized implementation, channel assignments occur in order of decreasing utility. One approach to achieve the same ordering in a distributed manner is to follow a delay-based approach, where nodes delay performing their channel assignment by an interval that is an increasing function of the utility achieved by the assignment. Of course, the specific form of the function that maps utility values to delay intervals will effect the convergence of such a distributed procedure.

V. Performance evaluation

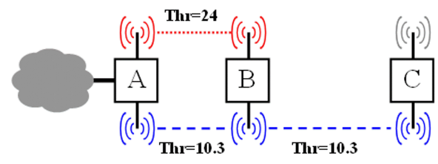
The novel contribution of this paper is a new framework and procedure for joint channel assignment and topology control that supports different objectives. Hence, in this section we present performance results that show the influence of the target objective on the channel assignment and network topology. Additionally, the results show that the proposed approach can effectively utilize multiple wired network gateways, connecting nodes to gateways while taking into accounts the number of interfaces in each gateway and balancing the throughput of different links. We also present results showing the effects of 802.11a adjacent channel interference on channel assignment. Finally, we compare the performance of the proposed approach with a rate-based channel assignment scheme. The investigations in this section are based on the throughput estimation model presented in Section III-B.

The path loss model used in the investigations is $PathLoss\ (\mathrm{dB}) = P_1 + 10 \cdot \log_{10}(d^n)$, where d is the distance between the transmitting and receiving interfaces in meters, P_1 is the path loss for one meter, and n is the loss exponent. We consider $P_1 = 41$ dB and $n = 2.9$. Moreover, we assume that all interfaces are connected to omnidirectional antennas and have the same transmission power plus antenna gain: 30 dBm. For the above path loss model, transmission power, and the minimum SINR values indicated in Section III-B, the transmission range is approximately 360 meters.

A. *Influence of target objective on channel assignment and network topology*

We initially consider a simple linear network with three mesh nodes, Figure 2. The channel assignment and node connectivity is shown in Figure 2(a) if the target objective is to maximize the aggregate throughput, which corresponds to utility (2), and in Figure 2(b) if the target objective is fairness, which corresponds to utility (3). Figure 2(a) shows that the aggregate throughput objective results in a large unbalance of the total throughput for connections A-B (34.3 Mbps) and B-C (10.3 Mbps). On the other hand, the fairness objective achieves a more balanced throughput for connections A-B (24 Mbps) and B-C (18 Mbps), at the expense of lower total throughput: 42 Mbps compared to 44.6 Mbps in the case of the aggregate throughput objective.

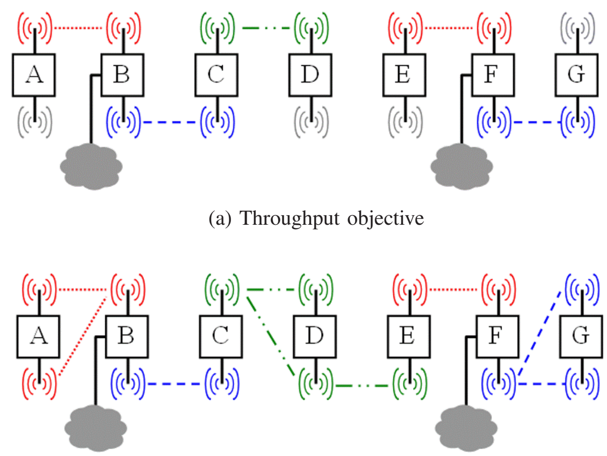
The influence of the aggregate throughput and redundancy objectives on the channel assignment for a 7-node linear network with two gateways is shown in Figure 3. Observe that with the aggregate throughput objective some interfaces are not assigned a channel, Figure 3(a), since no channel assignment for any of these interfaces can improve the aggregate throughput. The assignment for the redundancy objective, which corresponds to utility (4), is shown in Figure 3(b). Observe that with the redundancy objective, there exist multiple links between some mesh nodes, which improves the availability and reliability of the mesh network.



(a) Throughput objective

(b) Fairness objective

Fig. 2. Channel assignment for a linear network with three mesh nodes and one gateway. The distance between A-B is 150 m and B-C is 230 m. The transmission range is $\approx$ 360 m. Channels considered: 1-7



(a) Throughput objective

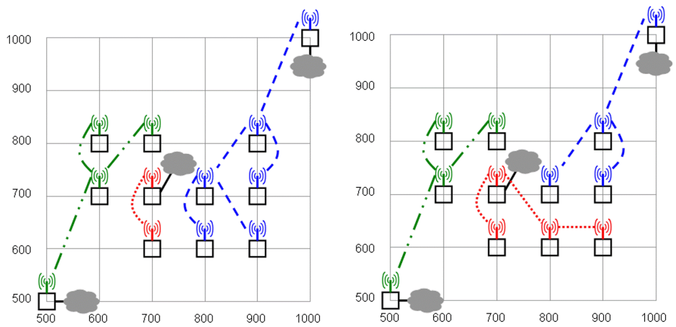
(b) Redundancy objective

Fig. 3. Channel assignment for a linear network with 7 nodes and 2 gateways. Distance between neighboring nodes is 150 m. Channels considered: 1-7.

The results in Figures 2 and 3 considered 7 consecutive channels in 802.11a. However, the resulting channel assignment uses only channels[1] 1, 4, and 7; the reason is that channels with a smaller separation have a high inter-channel interference when assigned to interfaces located in the same mesh node; this is discussed further in Section V-C.

Next we investigate the influence of the target objective on the node connectivity, using the 12-node grid network shown in Figure 4. The channel assignment and node connectivity for the aggregate throughput objective is shown in Figure 4(a). Observe that the resulting distribution of mesh nodes to gateways is unbalanced. In addition, there is a large unfairness in the throughput achieved on the various links, which ranges from 6 Mbps (for links in the path to the top-right gateway) to 36 Mbps (for the link with the middle gateway). Figure 4(b) shows the channel assignment and node

[1]For simplicity, we use the integers 1, 2, 3, etc, to denote the 802.11a channels 36 (5.18 GHz), 40 (5.20 GHz), 44 (5.22 GHz), etc.



(a) Throughput objective (b) Fairness objective

Fig. 4. Influence of target objective on channel assignment and topology for 12-node grid network. Channels considered: 1, 4, 7.

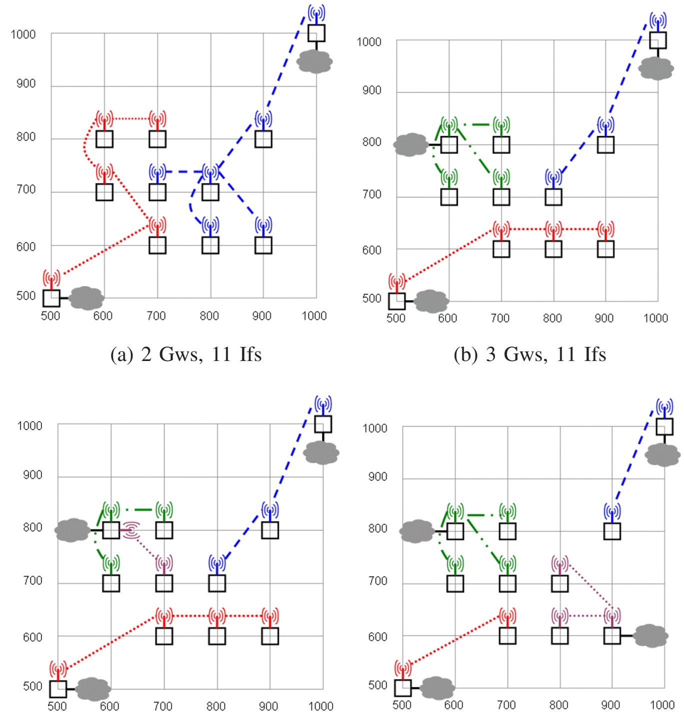
connectivity for the fairness objective. Observe that now there is a balanced distribution of the mesh nodes to the three gateways. Moreover, the throughput achieved on the various links is fairer, with minimum value 9 Mbps and maximum value 12 Mbps. The above results show that maximizing the aggregate throughput does not necessarily achieve load balancing and fairness, justifying the support for multiple objectives, which is a key feature of the proposed channel assignment procedure.

B. Load balancing with multiple gateways

We further investigate the load balancing properties of the proposed channel assignment and topology control procedure, showing that it effectively utilizes additional gateways and interfaces in the gateways. Moreover, the investigation in this subsection suggests how the modelling framework presented in this paper, which finds the optimal channel assignment and network topology, can be used for network planning. Our goal is to achieve a balanced throughput for all links, hence in the investigations that follow we consider the fairness objective.

Figure 5 shows the channel assignment and node connectivity for an 11-node grid network that includes 2-4 gateways. Comparison of Figures 5(a) and 5(b) shows that the proposed procedure can effectively utilize the additional gateway, achieving a balanced distribution of mesh nodes to gateways. Table III shows that the addition of a third interface to one of the gateways in the three gateway scenario, Figure 5(c), improves the aggregate throughput compared to the case of three gateways each with one wireless interface, Figure 5(b). However, the scenario with four gateways each with one wireless interface, Figure 5(d), achieves a more balanced link throughput, indicated by the min and max link throughput values in the bottom two lines of Table III, exploiting the more uniform distribution of the four interfaces located in gateways.

The proposed scheme achieves load balancing not solely by balancing the number of mesh nodes connected to different gateways. Rather, the scheme achieves a fair distribution of the



(a) 2 Gws, 11 Ifs (b) 3 Gws, 11 Ifs

(c) 3 Gws, 12 Ifs (d) 4 Gws, 11 Ifs

Fig. 5. Channel assignment and node connectivity for 11-node grid network. Channels: 1, 4, 7, 10. Fairness objective. (Gws: Gateways, Ifs: Interfaces)

throughput for various links[2], by performing channel selection based on an estimation of throughput that captures the effects of rate diversity in wireless mesh networks. For example, consider Figure 5(d). Because the distance of nodes closest to the gateways located at (500, 500) and (1000, 1000) is larger than the distance of the nodes closest to the other two gateways located at (600, 800) and (900, 600), the transmission rate of links involving the first two gateways is lower (18 Mbps) than the transmission rate of links involving the other two gateways (36 Mbps). Hence, to achieve a balanced distribution of throughput values, more mesh nodes are connected to the latter two gateways located at (600, 800) and (900, 600), whereas only one node is connected to the other two gateways at (500, 500) and (1000, 1000).

The above results pertain to the model in Section II, which considers the hop-by-hop throughput. The extension presented in Section IV-A that considers the end-to-end throughput can support balancing of the aggregate throughput flowing through the gateways. Due to space limitations, results with this model will be included in an extended version of this paper.

C. Effect of 802.11a adjacent channel interference

As discussed in Section III-B, the physical layer model considered in the throughput estimation accounts for the interference between adjacent IEEE 802.11a channels; this allows

[2]For simplicity, in the investigations we consider the fairness utility (3), which gives the same importance to all links. Adding weights, as discussed in Section II, can give more importance to links closer to gateways.

TABLE III
AGGREGATE AND MIN/MAX LINK THROUGHPUT, ESTIMATED USING THE MODEL IN SECTION III-B, FOR THE CHANNEL ASSIGNMENTS AND NODE CONNECTIVITY IN FIGURE 5. (GWS: GATEWAYS, IFS: INTERFACES)

	Aggregate throughput (Mbps)	Min link throughput (Mbps)	Max link throughput (Mbps)
2 Gws, 11 Ifs	58.8	6	7.2
3 Gws, 11 Ifs	87	9	12
3 Gws, 12 Ifs	123	9	36
4 Gws, 11 Ifs	108	12	18

us to capture the effects that such interference has on the channel assignment procedure. The channel assignment shown in Figure 3 considers seven consecutive 802.11a channels, which have a spacing of 20 MHz between neighboring channels. The proposed scheme eventually utilizes only three (1, 4, 7) of the available seven channels. Using channels with a smaller separation than 3 would result in significant adjacent channel interference, because these channels would be assigned to interfaces in the same mesh node, whose antennas are close. This is also the reason that the bottom interfaces of nodes D and E in Figure 3(a) are not assigned a channel: if the links between nodes C-D and E-F operate on channels 1 and 4 then, due to adjacent channel interference, assigning channels 2, 3, 5 or 6 to the two free interfaces of D and E would reduce performance. Moreover, assigning channels 1, 4, or 7 would not improve performance, since they would interfere with other links in the transmission range of nodes D and E.

From the above discussion, we see that interference between adjacent 802.11a channels can have a significant effect on channel assignment in wireless mesh networks with multi-radio nodes. Surprisingly, most of the works on channel assignment in multi-radio wireless mesh networks incorrectly assume that all 802.11a channels are orthogonal.[3]

D. Comparison with rate-based channel assignment

Next we compare the proposed utility-based channel assignment procedure with a rate-based assignment procedure. The rate-based channel assignment procedure considered in this subsection utilizes the knowledge of non-interfering channels, and selects links with the highest transmission rate. The rate-based channel assignment procedure randomly considers nodes with unassigned interfaces and, similar to the greedy utility-based algorithm, selects nodes with a path to a gateway to form a link with. Hence, the rate-based procedure also guarantees that upon termination all nodes will have a path to a gateway. However, unlike the greedy utility-based procedure, where links are selected based on the improvement of the aggregate utility, the rate-based procedure selects links with the highest transmission rate; if there are more than one such links, then one is randomly selected. If the selected node to form a link contains interfaces that have already been assigned a channel and interfaces without an assigned channel, then the procedure randomly selects either; in the case it selects to

[3]802.11a channels, when assigned to single radio access points, could be considered orthogonal. However, they can interfere when assigned to interfaces whose antennas are very close.

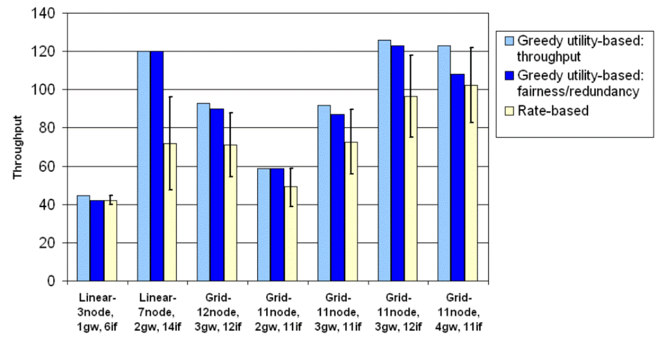


Fig. 6. Aggregate throughput achieved by the greedy utility-based and rate-based channel assignment procedures; for the latter, the average of 100 runs and the 95% confidence interval is shown. The channel assignment and node connectivity for the greedy utility-based selection procedure are shown in Figures 2, 3, 4, 5(a), 5(b), 5(c), 5(d).

connect to an interface that has not already been assigned a channel, then the procedure tries to make use of all available channels. If all channels have been used, then a channel is selected randomly. Based on the above description, the rate-based procedure does not consider trivial assignments where all interfaces are assigned the same channel.

Figure 6 shows that the utility-based channel assignment procedure, for both the aggregate throughput and the fairness or redundancy objectives, achieves an average aggregate throughput that can be up to 67% higher than the average achieved with the rate-based channel assignment procedure; the improvement tends to be higher for a higher number of total interfaces in the multi-radio nodes. The results of Figure 6 should not be seen in isolation to the results of the previous subsections: the greedy utility-based channel assignment procedure with the fairness and redundancy objectives achieves a higher aggregate throughput, while also trying to optimize the specific objective. Hence, even in the scenarios where the aggregate throughput is close, e.g. in the case of a 3-node network with 1 gateway Figure 2, the difference in the fairness can be large.

Additional investigations not reported in this paper, show that the greedy utility-based procedure achieves the true global optimum, found using a brute force search, for scenarios with up to 8 nodes, such as the 3-node network in Figure 2.

VI. CONCLUSIONS AND FUTURE WORK

We formulated a new utility-based framework for joint channel assignment and topology control that supports different target objectives, expressed as utility functions of the MAC layer throughput, and presented a greedy procedure for solving the corresponding optimization problem. Investigations showed the influence of the target objective on the channel assignment and node connectivity, the load-balancing properties of the proposed approach, the influence of 802.11a adjacent channel interference on channel assignment, and the higher performance compared to a rate-based channel assignment scheme.

Ongoing work is investigating the use of actual measurements in the path loss model, and the implementation of the channel assignment procedure in a test-bed. Additionally, we are investigating the optimization framework that involves utility functions of the end-to-end throughput between gateways and mesh nodes, which was presented briefly in Section IV-A.

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