Channel Assignment Based on the End-to-End Throughput in Multi-hop Wireless 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. The proposed approach can support different target objectives, which are expressed as utility functions of the end-to-end throughput from the gateways to the mesh nodes. The latter accounts for the 802.11 MAC sharing model and rate diversity. The model can be extended to the case of multipath routing, where there are multiple paths from the same or different gateways to the mesh nodes, and for performing joint channel assignment, topology control, and routing.

Keywords: end-to-end throughput, 802.11 MAC, multi-rate

1 Introduction

Channel assignment in wireless mesh networks (WMNs) influences the contention among wireless links and the network topology or connectivity between mesh nodes. There is a trade-off between minimizing the level of contention and maximizing connectivity [1–3]. Moreover, channel assignment affects 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 occurs 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.

Prior work on channel assignment considered minimizing the interference [6–8]. On the other hand, the channel assignment procedure proposed in this paper considers an optimization objective that is a function of the end-to-end (e2e) throughput, which accounts for the 802.11 MAC sharing of the wireless channel. The works of [2, 9–14] consider the throughput for channel assignment.

* This work was supported in part by the European Commission in the 7th Framework Programme through project EU-MESH (Enhanced, Ubiquitous, and Dependable Broadband Access using MESH Networks), ICT-215320, http://www.eu-mesh.eu

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[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, 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 which is based on the e2e throughput. The application of a utility-based framework to congestion control is fundamentally different than the application to channel and topology control, since the latter is a discrete problem.

The work of [10] considers the problem of joint channel assignment and routing, while satisfying fairness constraints. Our work differs in that we investigate joint channel assignment and topology control, and our model supports rate diversity and different target objectives. [16] investigates 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 e2e 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 can lead to low transmission rates, which significantly reduce the network's performance. On the other hand, assigning a common channel to all nodes reduces the available interfaces and the chance for more intelligent channel assignment, which is significant since practical mesh networks contain nodes with a few (typically 3-4) interfaces. The work in this paper also differs from our previous work [17] where channel assignment considered the per link throughput, rather than the e2e throughput of flows.

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 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.

In summary, the proposed channel assignment and topology control approach has the following key features:

– Channel assignment can be performed with different target objectives, which reflect different operator-dependant requirements.
– Target objectives are expressed as utility functions of the end-to-end throughput of flows from gateways to nodes, which captures the MAC layer sharing and rate diversity.
– The node connectivity is not known a priori. Rather, the node connectivity (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.

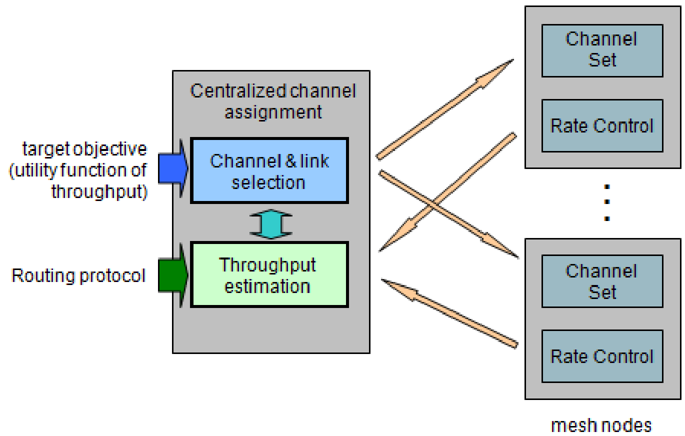


Fig. 1. The channel assignment and topology control procedure consists of two modules: the end-to-end throughput estimation and the channel and link selection module.

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 and the distribution of throughput across flows. Such flexibility in operating a network is significant for the cost-effectiveness of future wireless access networks, enabling them to adapt to different operator and application requirements.

The remainder of the paper is structured as follows: In Section 2 we present an overview of the proposed channel assignment and topology control procedure, and in Section 3 we present the mathematical formulation of the problem, and its extension for multiple paths and for joint channel, topology, and routing control. In Section 4 we present more details for the channel and link selection algorithm, and the end-to-end throughput estimation algorithm. In Section 5 we present and discuss simulation results, and finally, in Section 6 we conclude the paper.

2 Channel assignment and topology control model

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 throughput estimation module estimates the throughput of all end-to-end flows, for a specific channel assignment and node connectivity; this estimation considers the paths for all flows, which are determined by the routing protocol, and the transmission rate, which depends on the rate control algorithm at the transmitters. 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.

3 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. Also, 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 $k \in C$; C is the set of available channels. X_i denotes the end-to-end throughput of the flow from a gateway to node i. Note that there can exist multiple links between two mesh nodes, operating on different channels and different nodes can communicate with the same node on the same channel.

The channel assignment and topology control problem can be written as

$$\begin{aligned} \text{Maximize} \quad & \sum_{i \in N} U(\{X_i, i \in N\}) \qquad (1) \\ \text{over} \quad & L = \{(i, j; k) : i, j \in N, k \in C\} \\ \text{such that} \quad & \exists \text{ path from a gateway to node } i, \forall i \in N \text{ and} \\ & K_i \leq I_i, \forall i \in N \end{aligned}$$

The path of a flow is determined by the routing protocol.

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

Aggregate throughput objective: This objective corresponds to the following aggregate utility:

$$U(\{X_i, i \in N\}) = \sum_{i \in N} X_i \,, \qquad (2)$$

i.e., the aggregate utility is equal to the sum of the end-to-end throughput of all flows from the gateways to the nodes.

Fairness objective: This objective corresponds to the following utility:

$$U(\{X_i, i \in N\}) = \sum_{i \in N} \log(X_i) \,. \qquad (3)$$

This objective tries to achieve fairness among the various end-to-end flows.

Load balancing objective: This objective tries to balance the load across gateways. Let G be the set of gateway nodes, F_m be the set of flows that traverse gateway m. The load balancing objective corresponds to the following utility:

$$U(\{X_i, i \in N\}) = \sum_{m \in G} \log \left(\sum_{i \in F_m} X_i \right) . \tag{4}$$

3.1 Extensions

Multi-path: The formulation in Section 3 assumes that there is a single flow from a gateway to every node $i \in N$. The formulation can be extended to more than one flows to every node, possibly from different gateways. Multiple paths increase the network's redundancy, enabling it to overcome link failures.

Joint channel assignment, topology control, and routing: The formulation in Section 3 assumes that a flow's path is determined by the routing protocol. The following modification corresponds to a joint channel assignment, topology control, and routing problem.

$$\begin{aligned} \text{Maximize} \quad & \sum_{i \in N} U(\{X_i, i \in N\}) \\ \text{over} \quad & L = \{(i,j;k) : i,j \in N, k \in C\}, P \\ \text{such that} \quad & \exists \text{ path from a gateway to node } i, \forall i \in N \text{ and} \\ & K_i \leq I_i, \forall i \in N \end{aligned}$$

where P is the set of paths for all flows to nodes $i \in N$. In the above formulation, a flow's path is not determined externally by the routing protocol, but is determined by the optimization problem.

4 Utility-based channel assignment using the end-to-end throughput estimation

Next we discuss the functionality of the channel and link selection module, and the end-to-end throughput estimation module.

4.1 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, given by (1). The order in which flows are created 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 based on e2e throughput

1: **Variables:**
2: $N_{unassigned}$: set of nodes that have not been assigned an end-to-end flow from a gateway
3: 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
4: $U(L)$: aggregate utility for set of links L
5: p_i: ordered set of nodes in the path from a gateway to node i as determined by the routing algorithm
6: $M(i)$: set of links, which contains elements of the form $(i, j, ; k)$, for forming the path from a gateway to link i
7: $U'(i)$: aggregate utility if channels are assigned to the links along the path from a gateway to link i
8: **Algorithm:**
9: **repeat**
10:   **for all** $i \in N_{unassigned}$ **do**
11:     p_i = ordered set of nodes from gateway to node i, as determined from routing algorithm
12:     **for all** $(i, j) \in p_i$ in order from closest to farthest from gateway **do**
13:       **select** channel k that yields largest utility **then**
14:         $M_i = M_i + \{(i, j; k)\}$
15:       **end select**
16:     **end for**
17:     $U'(i) = U(L + M_i)$
18:   **end for**
19:   **select** $i \in N_{unassigned}$ with highest $U'(i)$ and smallest number of hops from gateway **then**
20:     $L = L + M_i$ {Assign channels to form a flow from gateway to i}
21:     Remove i from $N_{unassigned}$
22:   **end select**
23: **until** $N_{unassigned}$ not empty

The algorithm considers paths from a gateway to all nodes, as determined by the routing algorithm. The paths, and subsequently the links forming the paths, are created in order of increasing aggregate utility: For all possible paths, channels are assigned in a greedy manner, starting with links in the path that are closest to the gateway (line 12). The path whose assignment would yield the highest utility is then selected (line 19), and the corresponding channel assignments are made (line 20). The procedure ends when all paths are created.

4.2 End-to-end throughput estimation

In this section we describe a simple model for estimating the end-to-end throughput of flows in a multi-radio, multi-channel and multi-rate wireless mesh network (WMN) with non-saturated traffic conditions. The WMN is represented as a graph $G = (V, E)$, where V is the set of wireless interfaces and E is the set of directional links between them.

Traffic is generated by UDP senders, which limit their rate to the end-to-end throughput with which the WMN is able to forward their traffic. Each UDP flow has a single, known path that originates at a source interface and is destined to a sink interface of the WMN. Let F be the set of flows in the network. The end-to-end throughput of a flow $f \in F$ will be $x_f = \frac{b_f}{T}$, where b_f is the number of bits served by flow f over a period of time T. Let $N(v)$ be the set of wireless interfaces whose transmissions can conflict with interface v's transmissions, due to the CSMA-based access protocol, and includes v. Hence, $N(v)$ contains all interfaces that are inside v's carrier sense range, and use the same channel as v. Transmissions from the interfaces in $N(v)$ determine the aggregate channel occupation time T_v seen by v, including the channel occupation time due to its own packet transmissions. T_v can be estimated from

$$T_v = \sum_{u \in N(v)} \sum_{f \in F_u} b_f T_{u,f} \ , \tag{5}$$

where F_u is the set of flows whose packets are forwarded by interface u, and $T_{u,f}$ is the time needed for interface u to forward a single bit from flow f. Each pair (u, f) uniquely determines the link e over which interface u transmits flow f's packets; $T_{u,f}$ depends on the link e's transmission rate [20].

We use an iterative, water-filling procedure for calculating the values of b_f. Initially each flow f has zero b_f and is in a non-bottlenecked state. In every round of the procedure [21]:

- We increment the number of bits sent by all source interfaces that have at least one non-bottlenecked flow originating from them, by the same amount S. This reflects the fair channel access among contending interfaces in 802.11. Interfaces may belong to the same or different multi-radio nodes. If more than one non-bottlenecked flows have the same source interface, then the amount S is equally shared among these flows, which increase b_f by the same amount.
- We calculate the aggregate channel occupation time seen by each interface $v \in V$ using (5). If for some interface $v \in V$ holds that $T_v \geq T$, then all non-bottlenecked flows that either originate, terminate, or traverse the interface are marked as bottlenecked and in case $T_v > T$ their b_f values are decreased equitably so that either $T_v = T$ of $b_f = 0$. This reflects the fact that for any directional link of the WMN we may not increase the total number of bits transmitted over the link if either the transmitter or the receiver of the link perceives a fully occupied channel. Furthermore, the reduction of b_f values so that either $T_v = T$ of $b_f = 0$ models successfully throughput reduction or even flow starvation in well-known problematic scenarios of CSMA-based protocols like 802.11 DCF, such as information asymmetry, flow-in-the-middle, and near/far hidden terminal scenarios [22].

The above iterative procedure terminates when all flows are marked as bottlenecked; the derived values of b_f are used to calculate each flow's throughput.

5 Performance evaluation

In this section we present simulation results for the proposed channel assignment algorithm, using the network simulator OMNET++. The simulations used the IEEE 802.11b network model. Traffic was generated by UDP senders, which limited their rate to the end-to-end throughput supported by the network. We present results that compare the proposed channel assignment algorithm for the aggregate throughput objective defined by (2), and the fairness objectives defined by (3), with an ad hoc channel assignment and node connectivity. The results also include the fairness index given by Fairness Index $= \frac{\left(\sum_{i=1}^{N} X_i\right)^2}{N \sum_{i=1}^{N} X_i^2}$, where X_i is the e2e throughput for the flow to node i and N is the total number of nodes.

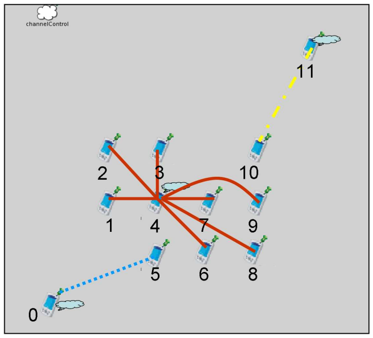
Figure 2 depicts the channel assignment for a grid topology with 11 nodes and 3 gateways, for the proposed algorithm using the aggregate throughput and fairness objective, and for two ad hoc channel assignments. Gateway nodes in this and the other topologies investigated have three interfaces, whereas the other mesh nodes have two interfaces. Table 1 shows the corresponding results. The table shows that the throughput objective achieves the highest aggregate throughput, and the highest maximum flow throughput; this is achieved at the cost of fairness, since the aggregate throughput objective achieves the lowest fairness index and the lowest minimum flow throughput. On the other hand, the fairness objective achieves the highest fairness, at the cost of lower aggregate throughput. The two ad hoc channel assignments achieve worst aggregate throughput and fairness compared to the proposed channel assignment algorithm, for both the aggregate throughput and the fairness objective.

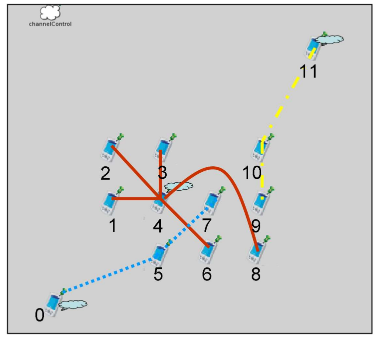
Figure 3 shows the channel assignment and node connectivity for the grid B topology, which contains 11 nodes and 2 gateways. Table 2 shows the corresponding simulation results. As in the previous grid topology, the aggregate throughput objective achieves the highest aggregate throughput, at the cost of lower fairness. Also, the aggregate throughput is more than two times the aggregate throughput achieved with the first ad hoc channel assignment, and more than four times the aggregate throughput achieved with the second ad hoc channel assignment. Moreover, in this scenario the lowest minimum flow throughput is achieved with the second ad hoc channel assignment. The fairness objective achieves the highest fairness utility, given by (3) and a high fairness index which is close to the fairness index achieved by the first ad hoc channel assignment. Observe, however, that the fairness objective achieves a significantly higher aggregate throughput compared to the first ad hoc channel assignment.

Figure 4 depicts the channel assignment for a grid with 20 nodes and 3 gateways. Table 3 shows that, as in the previous two topologies, the aggregate throughput objective achieves the highest aggregate throughput, and the highest maximum end-to-end flow throughput. Also, the fairness objective achieves

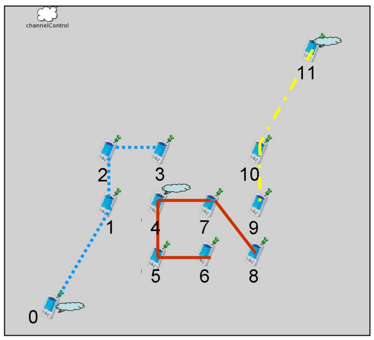
Table 1. Results for grid A

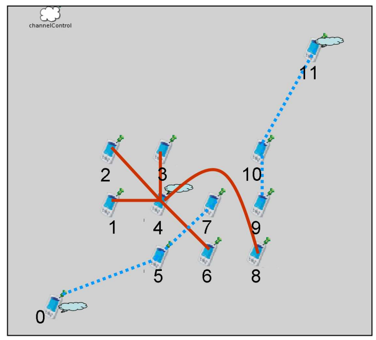
	Aggregate throughput objective	Fairness objective	Ad hoc assign.#1	Ad hoc assign.#2
Aggregate throughput	19,11	14,88	11,95	10,77
Fairness index	0,491	0,989	0,899	0,983
Fairness utility	1,478	1,814	0,930	0,665
Min flow throughput	0,836	1,150	1,051	0,939
Max flow throughput	6,169	2,174	2,238	1,449





(a) Throughput objective (b) Fairness objective





(c) Ad hoc assignment #1 (d) Ad hoc assignment #2

Fig. 2. Channel assignment and node connectivity for grid A: 11 nodes with 3 gateways (nodes 0,4,11). Available channels: 1, 6, 11.

the highest fairness. Comparing the results for this topology, with the results for the previous two grid topologies, we note that the fairness achieved in this grid topology is significantly smaller than the fairness achieved in the previous two topologies; this occurs because this topology has a larger number of nodes, hence has higher contention for channel access, which results in flows having significantly different end-to-end throughput values; this is also the reason that some flows achieve a very small throughput, as indicated by the minimum flow throughput in Table 3. For the aggregate throughput objective, a few flows achieve very high throughput, while the other flows achieve very low throughput, and some of these achieve throughput that is almost zero.

6 Conclusion

We have presented a utility-based framework for joint channel assignment and topology control in multi-rate multi-hop wireless networks. The framework supports different target objectives, expressed as utility functions of the end-to-end throughput of flows from gateways to nodes. Simulation results show the perfor-

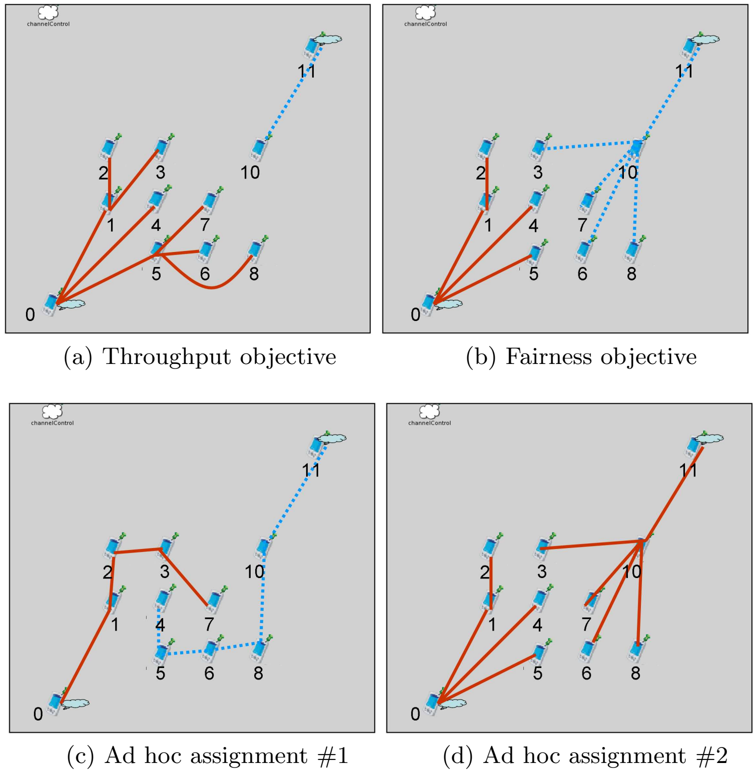


Fig. 3. Channel assignment and node connectivity for grid B: 11 nodes with 2 gateways (nodes 0,11). Available channels: 1, 6, 11.

mance in terms of aggregate throughput and fairness achieved by the proposed approach, and illustrate the influence of the target objective.

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Table 2. Results for grid B

	Aggregate throughput objective	Fairness objective	Ad hoc assign.#1	Ad hoc assign.#2
Aggregate throughput	10,16	8,93	4,17	2,98
Fairness index	0,287	0,932	0,954	0,915
Fairness utility	-1,627	-0,172	-3,096	-4,464
Min flow throughput	0,479	0,706	0,358	0,239
Max flow throughput	6,165	1,333	0,582	0,602

Table 3. Results for grid C

	Aggregate throughput objective	Fairness objective	Ad hoc assignment
Aggregate throughput	27,99	23,68	21,73
Fairness index	0,326	0,529	0,498
Fairness utility	-9,478	-0,514	-2,734
Min flow throughput	0,009	0,217	0,002
Max flow throughput	6,161	4,519	5,818

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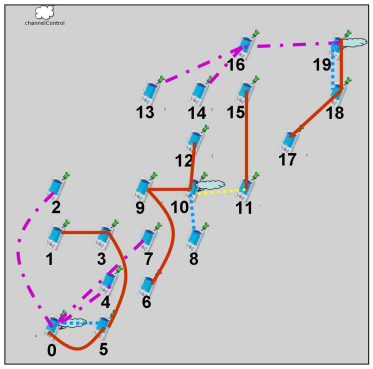
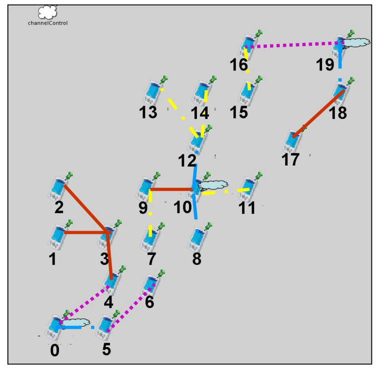
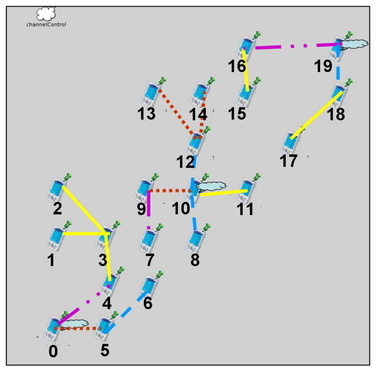


(a) Throughput objective



(b) Fairness objective



(c) Ad hoc assignment

Fig. 4. Channel assignment and node connectivity for grid C: 20 nodes with 3 gateways (nodes 0,10,19). Available channels: 1, 4, 7, 10.

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