# Resource Allocation for Multi-Channel Multi-Radio Wireless Backhaul Networks: A Game-Theoretic Approach

Li-Hsing Yen*, Yuan-Kao Dai*, and Kuang-Hui Chi†
*Dept. of Computer Science & Information Engineering, National University of Kaohsiung, Kaohsiung, Taiwan 811, R.O.C.
†Institute of Electrical Engineering, National Yunlin University of Science and Technology, Yunlin, Taiwan 640, R.O.C.

***Abstract*—Radio interfaces and channels are two sorts of resources in a multi-channel, multi-radio wireless mesh network. An efficient allocation of radio resources to mesh devices should reduce co-channel interference for higher throughput while maintaining network connectivity. Unlike much research effort on such optimization dealing with link- or higher-level interference, this study is concerned with physical-layer interference. We propose a two-stage radio allocation scheme. The first stage assigns channels to radios using a game-theoretic approach while the second stage assigns the resulting radio-channel pairs to links using a greedy method. In the proposed game, wireless interfaces are modeled as players participating in a radio resource game with a utility function defined to minimize co-channel interference from other players. We prove that the game eventually reaches a pure-strategy Nash equilibrium regardless of the game's initial configuration. Simulation results indicate that the proposed scheme leads to more operative links than previous methods.**

## I. Introduction

A wireless mesh network is a network of radio nodes organized in a mesh topology. Its coverage extends by deploying mesh access points (MAPs) and mesh points (MPs) which are interconnected over the wireless medium to form a backhaul network. MAPs provide wireless access services to end users in a large geographical area. The backhaul network, which may adopt transmission technology different from that used for wireless access, allows for multiple gateways to the wired backbone and more than one frame forwarding path between each pair of MAPs.

Mesh points are basic entities in the backhaul network for forwarding frames. An MP may establish several wireless links, namely *designated links*, each to a neighboring MP. Two wireless devices should tune to a same channel before communication starts. When any other devices in proximity transmit on the same channel, the receiving end of current communication may experience co-channel interference. From the physical layer perspective, co-channel interference degrades the quality of received signal, causing high data error rate. If viewed from the link layer or above, co-channel interference brings about transmission collision and bandwidth contention, thus degrading goodputs. IEEE 802.11a and other technology provide several non-overlapping channels for use. If these channels can be efficiently utilized, performance degradation by co-channel interference can be prevented or alleviated.

There has been active research on efficient utilization of multiple channels. So and Vaidya [1] proposed dynamic channel switching to allow the use of multiple channels by a single radio. This scheme demands tight synchronizations among all the involved nodes, at the expense of complexity. When channels taken by all the nodes in a multi-hop routing path diverge, the resulting delay may significantly increase end-to-end message delay.

A device with multiple radios, each operating on a dedicated channel, can conduct simultaneous communications with other devices without channel switching delay. However, such arrangements should be done in a proper way to make all the designated links operative. More specifically, a link is *operative* if both ends of the link have a radio operating on the same channel (*common channel constraint*) and experiencing sufficiently low interference (*interference constraint*) [2]. These two constraints are often conflicting, especially in a dense network where a number of radios and channels are to be allocated to a larger number of designated links in close proximity. How to maximize the number of operative links subject to the two constraints is an optimization problem.

Previous research toward this optimization problem mostly concerned interference on the link layer or above. As a commonly adopted interference model, the protocol model [3] asserts binary interference relations on transceivers based on the notion of *interference range*. That is, transceiver $u$ interferes with transceiver $v$ ($v$ becomes inoperative) and *vice versa*, if $v$ is within the interference range of $u$. A more general model is the physical model [3] that considers the intensity of interference experienced by transceivers, taking on a form of exponentially decreasing function of distance to the interferer. Accordingly, transceiver $u$ becomes inoperative if the aggregate interference intensity from all other transceivers exceeds some threshold. This study adopts the physical model under the common channel constraint and uses signal-to-interference ratio (SIR) to resolve link operability. Besides, we shall target co-channel interference as a performance metric rather than a requirement to meet.

While most schemes are based on heuristics, this study proposes a game theoretic approach. Game theory provides a mathematical framework for exercising strategies in a competition where players have conflicting interests or goals. For the last decade, game theory has been used in resource/duty sharing in wireless network environments. In particular, this study formulates a non-cooperative game for allocating channels to radios, in which radios act as players and channels available to a radio represent the player's strategy set. The utility of a player assumes the resulting SIR value when the player takes some strategy. We shall prove the stability of our game, showing that the game always ends up with a Nash equilibrium regardless of its initial configuration. Apart from the classical best response function, an alternative *better response* function is also presented. Following the game, an independent means is used to assign radio-channel pairs to links. Simulation results indicate that the proposed approach outperforms other game-theoretic counterparts [4], [5] in the number of operative links. The performance of our approach appears comparable to that of a recent heuristic approach [2] as well.

The remainder of this paper is organized as follows: A brief background is described in Section II. Section III elaborates on our approach. In Section IV, simulation results are discussed and compared among subject schemes. Lastly Section V concludes this paper.

## II. Preliminaries

### A. Background

A wireless mesh network consists of a number of wireless access domains and a wireless backhaul network. We assume that wireless access domains use a technology or spectrum different from that used in the wireless backhaul network such that wireless access communication does not interfere with that in the backhaul network. This study investigates radio resource (radios and channels) allocations for designated links in the backhaul network. All channels under consideration are non-overlapping (i.e., no interference from adjacent channels is expected), so only co-channel interference is of concern.

Radio resource allocation schemes can be classified into three categories: fixed assignment, dynamic assignment, and hybrid assignment [6]. In fixed assignment, each radio is statically tuned to a certain channel. If different nodes are assigned distinct sets of channels, radio resource utilization generally increases. However, fixed assignment may not meet the common channel constraint, making some links inoperative or even the whole network disconnected. As a remedy, the common channel approach (CCA) assigns Channel 1 to Radio 1, Channel 2 to Radio 2, and so forth at each node [7]. CCA ensures network connectivity but under-utilizes radio resources, leading to interference as in a single-radio environment. A more generic solution leverages the use of a *default channel*. That is, every node reserves a radio operating on a default channel, so as to guarantee the common channel constraint. Remaining radios are assigned to other channels than the default channel to maximize radio resource utilization.

In dynamic assignment, a radio operates on multiple channels in a time-multiplexing manner. Both the sending and the receiving radios should tune to a same channel at the same time. This can be done through a prearranged schedule or an on-line coordination. However, a weakness is that repeated channel switching costs delay, especially when channels taken by all the nodes in a multi-hop routing path diverge.

In hybrid assignment, radios are partitioned into two sets: one for fixed assignment and the other for dynamic assignment. Kyasanur and Vaidya [6] proposed to let each node use a dedicated radio listening in on a particular channel to receive data. Other radios are tasked to send data and enabled to change channels whenever necessary. During communication, the sender must use one of these radios and tune its channel to the receiver's receiving channel.

Traffic-aware channel allocation methods [8], [9] take link traffic as the weight to determine which link is to assign some channel subsequently. An important issue is that accurate, representative information of time-varying traffic conditions can hardly be acquired. These approaches also incur extra overhead if performing allocation every time traffic condition changes. In view of such potential weaknesses, this study does not consider link traffic information.

We remark that previous research differs significantly in the goal of channel allocations. Possible goals lie in minimizing local interference of individual nodes [10], minimizing overall network interference [11], minimizing the maximal link interference [12], maximizing the number of operative links [13], [2], or maximizing network throughput [8], [9]. Among others, this study aims to maximize the number of operative links.

### B. Related Work

Radio resource allocation is essentially to arrange radios and assign a channel for each designated link at both ends of the link. This can be done in various ways. *Link-centric* schemes allocate radio/channel to links in some order [2], [9], [13]. *Node-centric* schemes perform allocation in a node-by-node fashion [9], [10], [12], allocating channels to all radios of the node or to all links incident on the node. *Radio-centric* schemes assign channels and serving links to radios [14]. In what follows, we highlight several well-known schemes.

Skalli *et al*. [9] proposed a node-centric approach to determining preference for channel allocation based on three metrics with regard to each node. Metrics include the distance (hop count) to the gateway, the number of equipped radios, and traffic load. For a concerned node, this approach processes all the incident links in non-increasing order of their traffic loads. Concerning a link, this approach assigns a channel to both ends of the link. If links incident on a node outnumbers its radios, a link can reuse the least loaded radio.

Raniwala *et al*. allowed for both routing and channel assignment [8]. In this scheme, links with higher traffic load are assigned channels prior to those with lighter load. The resulting assignment is then checked to see if every link obtains bandwidth adequate to its traffic load. If not, reassignment is carried out. Xiao *et al*. [15] also considered joint routing and channel assignment problems. They proposed a greedy link-centric method that assigns the channel with least interference to links.

Subramanian *et al*. [11] developed a distributed algorithm in the protocol model context whereby each node assigns channels to all the incident links in light of interference and the number of available radios. Each node notifies all its neighbors of its assignment results, which helps neighbors re-assign their channels to avoid co-channel interference. Such re-assignment repeats until every node is unable to further reduce the interference with any of its incident links.

Tam *et al*. [16] assumed that each node has a single radio interface when multiple channels are available. These channels are utilized by dividing link-layer transmission time into series of time slots during which transmission and reception slots are scheduled to reduce possible co-channel interference. This approach requires network-wide tight time synchronization. Meanwhile, repeated channel switching incurs nontrivial delay.

Marina *et al*. [12] considered a limited number of radios and channels to minimize the maximum interference in the network. The authors showed that this problem is NP-hard and devised a heuristic approach that assigns channels to radios in a node-by-node manner. Each node is associated with a priority indicative of its order for assignment. The priority may be altered during the assignment procedure as per the common channel constraint.

Yen *et al.* [2] assumed the physical model and proposed a heuristic scheme that selects channels according to the estimated best and worst signal-to-interference-plus-noise ratios (SINRs). This scheme restricts the number of channels assignable to a node. The common channel constraint is well maintained thanks to the Pigeonhole Principle.

There is some literature on applying game theory to radio resource allocation. Chen and Zhong [4] treated the entire network as a single collision domain. Under an assumption that all radios operating on the same channel evenly share the bandwidth of a single channel, channel assignment was modeled as a non-cooperative game. In this game, nodes behave as players with the objective of maximizing the amount of obtainable bandwidth. The authors derived and proved a special solution that is Nash equilibrium yet perfectly fair. Duarte *et al.* [5] assumed overlapping channels under the protocol model, and approached the channel allocation problem by a cooperative game where players have common interest. The authors proved the existence of a Nash equilibrium in this game, and presented two ways to reach the equilibrium.

## III. The Proposed Approach

Our scheme consists of two stages. The first assigns channels to radios using a game-theoretic approach. The second stage assigns the resulting radio-channel pairs to links using a greedy method, as can be seen shortly.

### *A. Allocations of Channels to Radios: The Game*

Consider henceforth a network of $n$ nodes numbered from 1 to $n$. Let $r_i$ be the number of radio interfaces available to node $i$. We model radios as players, so there are $m = \sum_i r_i$ players in the game. The player set takes on $P = \{p_1, p_2, \dots, p_m\}$. Suppose that all the non-overlapping channels are numbered from 1 to $k$. To guarantee the common channel constraint, the proposed game follows the rule presented in [2] to delimit the set of channels for each node. More specifically, given that $N_i$ denotes the set of $i$'s neighboring nodes, the set of channels that can be allocated to radios of node $i$ is $\{1, 2, \dots, u\}$, where

$$u = \min(k, \min_{j \in N_i}\{r_i + r_j - 1\}). \tag{1}$$

The common channel constraint is ensured for every link by the Pigeonhole Principle. If all nodes have equally $r$ radios, (1) reduces to $u = \min(k, 2r - 1)$.

Let $S_i$ represent player $p_i$'s *strategy set*, the set of channels available to $p_i$ subject to (1). A *strategy profile* is an $m$-tuple $C = (c_1, c_2, \dots, c_m)$, where $c_i \in S_i$ denotes player $p_i$'s choice. We may express $C$ as $(c_i, C_{-i})$. Given a strategy profile $C$, our game defines the utility of $p_i$ associated with $C$ as

$$u_i(C) = u_i(c_i, C_{-i}) = -\sum_{j \neq i} f(c_i, c_j), \tag{2}$$

where $f(c_i, c_j)$ is a function that returns the cost of choosing strategy $c_i$ (by player $p_i$) with respect to strategy $c_j$ (of another player $p_j \neq p_i$). The definition of $f(c_i, c_j)$ is as follows.

$$f(c_i, c_j) = \begin{cases} 1/d_{i,j}^{\alpha} & \text{if } c_i = c_j \text{ and } d_{i,j} > d \\ c & \text{if } c_i = c_j \text{ and } d_{i,j} \leq d \\ 0 & \text{if } c_i \neq c_j, \end{cases} \tag{3}$$

where $d_{i,j}$ is the physical distance between $p_i$ and $p_j$; $\alpha$, $d$, and $c$ are constants. Intuitively, $f(c_i, c_j)$ reflects the degree of interference experienced by $p_i$ or $p_j$ when $p_i$ chooses channel $c_i$ while $p_j$ chooses channel $c_j$. If $c_i = c_j$ and the distance between $p_i$ and $p_j$ is sufficiently long (larger than $d$), the degree of interference is proportional to $1/d_{i,j}^{\alpha}$, where $\alpha$ ranging from 2 to 4 stands for the path loss exponent. In case that $c_i = c_j$ and $p_i$ is close to $p_j$, $f(c_i, c_j)$ returns a large cost $c \gg 1/d^{\alpha}$. If $c_i \neq c_j$, no costs arise.

Our channel allocation game can be represented as $\Gamma = [P; \{S_i\}_{i=1}^m; \{u_i\}_{i=1}^m]$. This is a non-cooperative game, meaning that players do not cooperate with each other to seek system's benefit. In fact, all players are selfish. This is also a dynamic game, in that players take turns to make decisions, knowing what decisions have already been made. Players are also myopic, i.e., a player will change its strategy whenever that change increases its utility. Formally, we define two types of response function for players. The *better response* function for player $p_i$ is

$$r_i(c_i, C_{-i}) = \{c_j \in S_i | u_i(c_j, C_{-i}) > u_i(c_i, C_{-i})\}, \tag{4}$$

which characterizes a subset of $S_i$ that can yield a higher utility value than $p_i$'s current strategy $c_i$ provided that all other player's strategies remain unchanged. The *best response function* is defined as

$$\begin{aligned} b_i(c_i, C_{-i}) = &\{c_j \in r_i(c_i, C_{-i}) | \forall c'_j \in r_i(c_i, C_{-i}) : \\ & u_i(c_j, C_{-i}) > u_i(c'_j, C_{-i})\}. \end{aligned} \tag{5}$$

Fig. 1 depicts a simple mesh network of three nodes, where more than four channels are available. According to (1), the greatest channel numbers allocatable to radios of nodes A, B, C are 4, 3, and 3, respectively. Table I shows a possible game

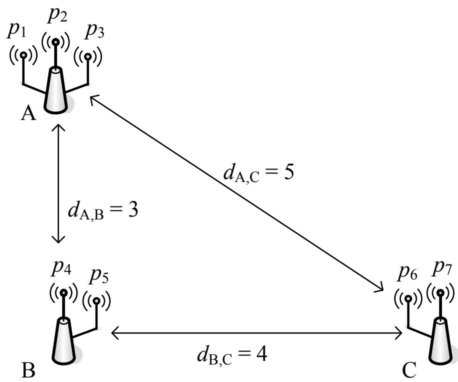



Fig. 1. A network with three nodes.

TABLE I
A POSSIBLE GAME EVOLVING SEQUENCE

| Step | Before | After |
|---|---|---|
| 1 | (1,2,3,1,2,1,2) | (1,2,3,1,2,1,3) |
| 2 | (1,2,3,1,2,1,3) | (4,2,3,1,2,1,3) |

evolving sequence (i.e., transitions of strategy profiles) if CCA is initially used to allocate channels to radios. When the game ends up with strategy profile $(4, 2, 3, 1, 2, 1, 3)$, no player has the incentive to further change its strategy. That is, the game enters a Nash equilibrium.

We now proceed to prove the stability of our game. First of all, the utility of player $p_i$ after it changes strategy to $c_i'$ is

$$u_i(c_i', C_{-i}) = -\sum_{j \neq i} f(c_i', c_j). \tag{6}$$

For other players $p_j \neq p_i$, its utility after $p_i$ changes strategy to $c_i'$ is as follows.

*Lemma 1:* Let $C = (c_i, C_{-i})$. For each player $p_j \neq p_i$, its utility if $p_i$ changes strategy from $c_i$ to $c_i'$ is

$$u_j(c_i', C_{-i}) = u_j(C) + f(c_j, c_i) - f(c_j, c_i'). \tag{7}$$

*Proof:* Before $p_i$ changes its strategy, the utility of $p_j \neq p_i$ is

$$u_j(c_i, C_{-i}) = -\sum_{k \neq i,j} f(c_j, c_k) - f(c_j, c_i). \tag{8}$$

After $p_i$ changes its strategy, the utility of $p_j \neq p_i$ becomes

$$u_j(c_i', C_{-i}) = -\sum_{k \neq i,j} f(c_j, c_k) - f(c_j, c_i'). \tag{9}$$

Subtracting (8) from (9) yields the change of $p_j$'s utility due to $p_i$'s change of strategy:

$$u_j(c_i', C_{-i}) - u_j(c_i, C_{-i}) = -f(c_j, c_i') + f(c_j, c_i). \tag{10}$$

Therefore,

$$u_j(c_i', C_{-i}) = u_j(c_i, C_{-i}) + f(c_j, c_i) - f(c_j, c_i'). \tag{11}$$

■

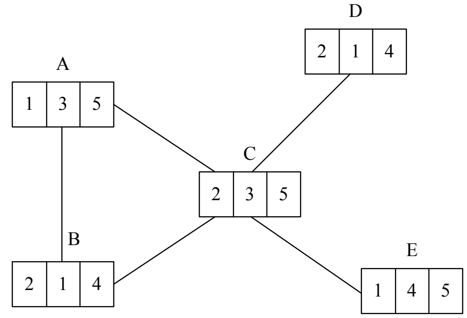



Fig. 2. A scenario illustrating a channel allocation result.

Let $U = \sum_j u_j(c_i, C_{-i})$ and $U' = \sum_j u_j(c_i', C_{-i})$ sum up all the player's utilities before and after $p_i$ changes strategy from $c_i$ to $c_i'$, respectively. We can prove the stability of this game by showing that $U' > U$. That is, every time a player changes its strategy, the sum of all the player's utilities increases. Since we cannot increase the sum unlimitedly, the game eventually ends up with a solution in which no player can further increase its utility unilaterally. By then, allocation reaches a Nash equilibrium.

*Theorem 1:* The proposed channel allocation game will end up in a Nash equilibrium regardless of its initial configuration.

*Proof:* As for the new aggregate $U'$ of utilities, we can express $U' = u_i(c_i', C_{-i}) + \sum_{j \neq i} u_j(c_i', C_{-i})$. By Lemma 1, we have

$$\begin{aligned} U' &= u_i(c_i', C_{-i}) + \sum_{j \neq i} [u_j(C) + f(c_j, c_i) - f(c_j, c_i')] \\ &= u_i(c_i', C_{-i}) + \sum_{j \neq i} u_j(C) + \sum_{j \neq i} f(c_j, c_i) - \sum_{j \neq i} f(c_j, c_i') \\ &= u_i(c_i', C_{-i}) + U - u_i(c_i, C_{-i}) - u_i(c_i, C_{-i}) + u_i(c_i', C_{-i}) \\ &= U + 2(u_i(c_i', C_{-i}) - u_i(c_i, C_{-i})) \end{aligned} \tag{12}$$

Since $p_i$ changes strategy from $c_i$ to $c_i'$ only if $u_i(c_i', C_{-i}) > u_i(c_i, C_{-i})$, (12) implies that $U' > U$. Because the total utility cannot be increased unlimitedly, the game eventually leads to a Nash equilibrium. ■

### B. Assignments of Radio-Channel Pairs to Links

The foregoing stage produces allocation of one channel to every radio. The next stage is to assign these radio-channel pairs to links. This is not trivial because there may be several candidate radio-channel pairs for a link or several links may need to share a radio-channel pair. However, now that radios are all identical, it is only necessary to determine channels for links in this assignment task.

Consider the scenario shown in Fig. 2, where channels have been allocated to radios. Since nodes A and C are allocated two common channels (Channels 3 and 5), link $(\mathrm{A}, \mathrm{C})$ can be assigned either channel. However, Channel 3 appears to have lower interference than Channel 5 as fewer radios are allocated Channel 3. On the other hand, there are four incident links on node C, whereas C has only three radio-channel pairs. Hence, at least one channel must be shared between two links.

Let $\Omega$ be the set of channels common to radios of $u$ and $v$. We apply the following rules to assign one channel to each link $(u, v)$ in a link-by-link manner:

- If there is only one channel in $\Omega$, assign this channel and the associated radio to $(u, v)$. For example, link $(\mathrm{A}, \mathrm{B})$ in Fig. 2 is assigned Channel 1.
- If there are multiple channels in $\Omega$, select the one that has been least frequently assigned to neighboring links of $(u, v)$ at the time of assignment. For each node $u$, let $\rho_u(c)$ count how many times channel $c$ has been allocated to incident links on $u$. Define $\sigma_{u,v}(c)$ as

$$\sigma_{u,v}(c) = \sum_{x \in N_u} \rho_x(c) + \sum_{x \in N_v} \rho_x(c), \tag{13}$$

where $N_u$ and $N_v$ are the sets of neighboring nodes of $u$ and $v$, respectively. This rule assigns $(u, v)$ channel $c'$ that is determined by

$$c' = \arg\min_{c \in \Omega} \sigma_{u,v}(c). \tag{14}$$

For instance, $\Omega = \{3,5\}$ for link (A,C) in Fig. 2. When all other links have been assigned channels, $\sigma_{\mathrm{A,C}}(3) = 0$ and $\sigma_{\mathrm{A,C}}(5) = 1$. Therefore, link (A,C) will be assigned Channel 3.

## IV. Simulation Results

Simulations in this study compare the performance of the proposed algorithm with a recent heuristic method termed *link-preserving* [2], the cooperative channel assignment game (CoCAG) [5], and the perfectly-fair game [4]. To investigate how many operative links were yielded by different schemes, we measured *operational link ratio* (OLR), which is defined as the number of operative links over the total number of designated links. A link was viewed operative only if its SIR was higher than 1 dB. Only path loss was considered in the measurements of signal strength. Shadowing and fading effects were not taken into account because these factors are environment-dependent, time-varying, and difficult to be incorporated into the game model. Our simulations involved 100 scenarios. These scenarios served as test cases, and the average of these cases was taken as the result. In each scenario, a number of nodes were randomly placed in a $1000 \times 1000$ m$^2$ area. We varied the total number $n$ of nodes, the number $r$ of radios per node, and the transmission range $r_t$.

First, each node was assumed to have a fixed number of radios to see how OLR changed with the number of deployed nodes. Fig. 3 shows results from $r = 2$, $r = 4$, and $r = 6$ collectively. In all cases, more nodes increase interference and thereby decrease the resulting OLR values. The proposed approach with the better response function generally outperforms its counterparts, especially when many nodes are involved. The performance of the link-preserving method is comparable to that of the better response approach only when sufficiently many radios are available (Fig. 3c).

Next simulations fixed $r_t$ to find the relationship between $r$ and OLR. When $r_t = 125$ m (Fig. 4a), link density is low and OLR can grow higher than 0.9 as long as adequate radios are provided. When $r_t$ increases to 250 m, more designated links are created and thus no method achieves an OLR higher than 0.9. Our better-response approach and the link-preserving method exhibit comparable performance in this condition and comprise the leading group (Fig. 4b). When a higher transmission range is set for signifying a higher link density, the link-preserving method performs worse than the proposed better-response approach when $r \leq 3$ and better than the better-response approach when $r > 3$ (Fig. 4c).

The best and better response functions differ not only in the resulting OLR values, but also in the time to a Nash equilibrium. Fig. 5 shows the average number of strategy changes per node before reaching a Nash equilibrium for these two functions in various settings. The best-response approach yields fewer strategy transition times than the better-response approach in all settings. This finding is justifiable since, as (12) indicates, the difference between $U'$ and $U$ is proportional to the difference between $u_i(c_i', C_{-i})$ and $u_i(c_i, C_{-i})$. The best-response approach attempts to maximize the difference and thus leads to shorter convergence time.

Simulation results suggest that the better-response approach generally outperforms its counterparts in terms of the number of operative links. It maintains its advantage over the link-preserving method unless many radios are available in a high link density environment. The best-response approach has a lower operative link ratio than the better-response approach, but converges faster.

## V. Conclusion

This paper presented a two-stage radio resource allocation scheme for multi-channel, multi-radio wireless backhaul networks. The first stage assigned channels to radio interfaces with a game-theoretic design. In our design, we considered the best response function and the better response function and prove the stability of the game. The second stage assigned radio-channel pairs to links using a greedy method. Experimental results revealed that the better-response approach generally outperformed its counterparts in the number of operative links. The best-response approach produced fewer operative links but converged faster than the better-response approach.

## References

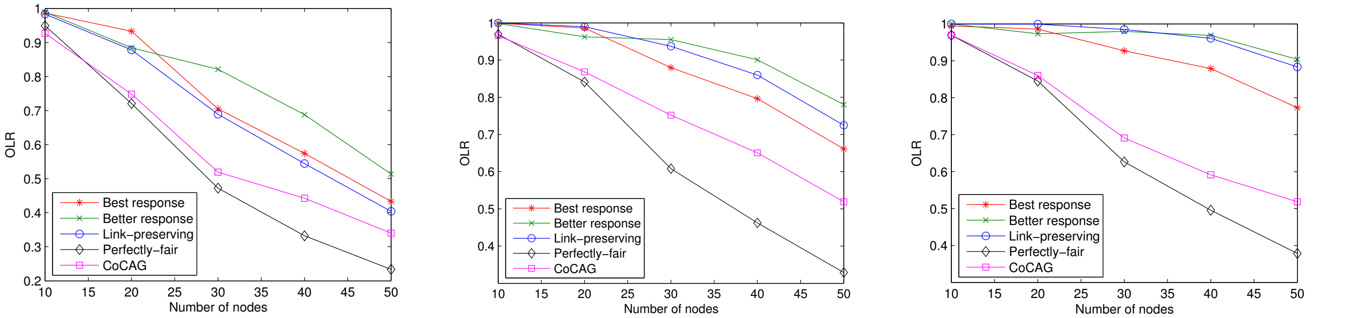

[1] J. So and N. H. Vaidya, “Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver,” in *Proc. 5th ACM Int’l Symposium on Mobile Ad Hoc Networking and Computing*, 2004, pp. 222–233.

[2] L.-H. Yen, K.-W. Huang, and V. C. Leung, “Link-preserving interference-minimization channel assignment in multi-radio wireless mesh networks,” in *Proc. IEEE ICC*, Ottawa, Canada, Jun. 2012.

[3] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *IEEE Trans. on Information Theory*, vol. 46, no. 2, pp. 384–404, Mar. 2000.

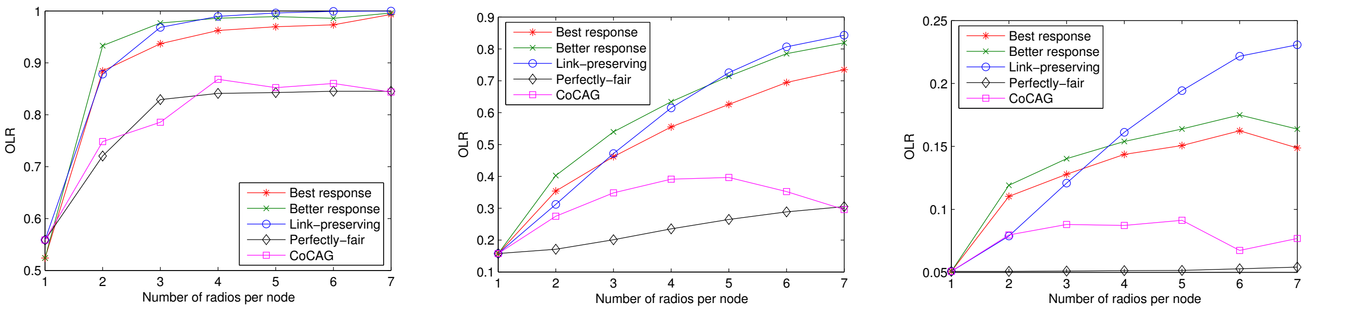
[4] T. Chen and S. Zhong, “Perfectly fair channel assignment in non-cooperative multi-radio multi-channel wireless networks,” *Comput. Commun.*, vol. 32, no. 6, pp. 1058–1061, 2009.

[5] P. B. F. Duarte, Z. M. Fadlullah, A. V. Vasilakos, and N. Kato, “On the partially overlapped channel assignment on wireless mesh network backbone: A game theoretic approach,” *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 1, pp. 119–127, Jan. 2012.



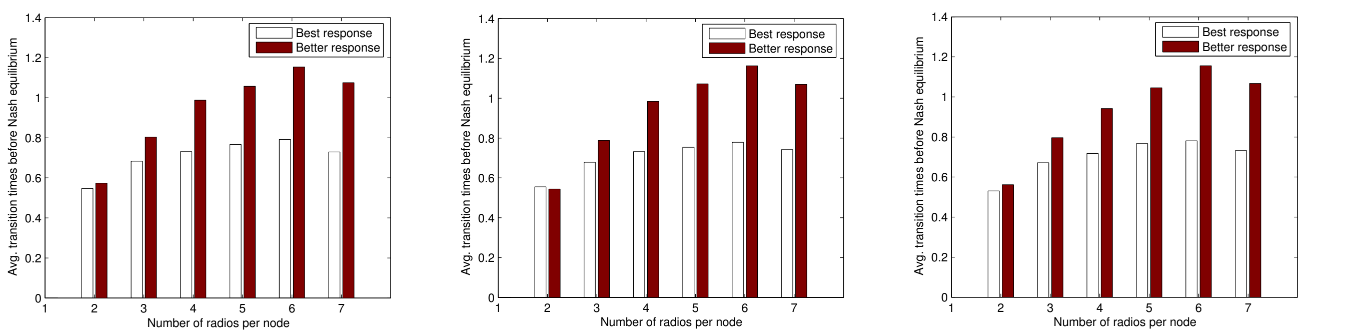

(a) (b) (c)

Fig. 3. OLR versus the number of nodes in case of (a) $r=2$ (b) $r=4$ and (c) $r=6$.




(a) (b) (c)

Fig. 4. OLR versus the number of radios with transmission range set to (a) 125 m (b) 250 m and (c) 500 m




(a) (b) (c)

Fig. 5. Average number of strategy transition times per node before Nash equilibrium with transmission range set to (a) 125 m (b) 250 m and (c) 500 m.


[6] P. Kyasanur and N. H. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," in *Proc. IEEE WCNC*, Mar. 2005, pp. 2051–2056.

[7] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," *Wireless Networks*, no. 4, pp. 471–487, 2005.

[8] A. Raniwala, K. Gopalan, and T. cker Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *ACM Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50–65, Apr. 2004.

[9] H. Skalli, S. Ghosh, S. K. Das, L. Lenzini, and M. Conti, "Channel assignment strategies for multiradio wireless mesh networks: Issues and solutions," *IEEE Communications Magazine*, no. 11, pp. 86–93, Nov. 2007.

[10] B.-J. Ko, V. Misra, J. Padhye, and D. Rubenstein, "Distributed channel assignment in multi-radio 802.11 mesh networks," in *Proc. IEEE WCNC*, 2007, pp. 3978–3983.

[11] A. P. Subramanian, H. Gupta, S. R. Das, and J. Cao, "Minimum interference channel assignment in multiradio wireless mesh networks," *IEEE Trans. on Mobile Computing*, no. 12, pp. 1459–1473, Dec. 2008.

[12] M. K. Marina, S. R. Das, and A. P. Subramanian, "A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks," *Computer Networks*, vol. 54, no. 2, pp. 241–256, Feb. 2010.

[13] V. Rajakumar, M. N. Smadi, S. C. Ghosh, T. D. Todd, and S. Hranilovic, "Interference management in WLAN mesh networks using free-space optical links," *Journal of Lightwave Technology*, vol. 26, no. 13, pp. 1735–1743, 2008.

[14] K. Ramachandran, E. Belding-Royer, K. Almeroth, and M. Buddhikot, "Interference-aware channel assignment in multi-radio wireless mesh networks," in *Proc. IEEE INFOCOM*, Apr. 2006.

[15] J. Xiao, N. Xiong, L. T. Yang, and Y. He, "A joint selfish routing and channel assignment game in wireless mesh networks," *Comput. Commun.*, vol. 31, no. 7, pp. 1447–1459, 2008.

[16] W.-H. Tam and Y.-C. Tseng, "Joint multi-channel link layer and multi-path routing design for wireless mesh networks," in *Proc. IEEE INFOCOM*, Anchorage, AK, May 2007, pp. 2081–2089.