A Game Theoretic Approach to Multi-Radio Multi-Channel Assignment in Wireless Networks

Devu Manikantan Shila, Yu Cheng and Tricha Anjali

Illinois Institute of Technology
{dmanikan,cheng,anjali}@iit.edu

Abstract. It has been long recognized that the interference among concurrent wireless transmissions plays a crucial role in limiting the performance of wireless networks. Recently, studies indicate that equipping nodes with multiple radios and operating these radios on multiple frequency channels can greatly enhance the capacity of wireless networks. On the other hand, to fully realize the benefits of multi-radio multi-channel communication, one may need to design an efficient channel assignment algorithm. In this paper, we study the channel assignment problem by proposing an algorithm that achieves load balancing Nash Equilibrium solution even in a selfish as well as topology-blind environment. Our simulation results also depict the effectiveness of the proposed channel assignment solution.

1 Introduction

One of crucial challenges that affect the performance of wireless networks is the presence of interference among multiple concurrent transmissions. With the motivation of enhancing the performance of wireless networks, recently great attention has been devoted to networks where each node is equipped with multiple radios and can operate on multiple channels [1],[9],[12]. This new degree of freedom has been shown to potentially allow for increased capacity with respect to single-channel single radio networks. On the other hand, to fully realize the benefits of multi-radio multi-channel network, one may need to design efficient channel assignment algorithms. In this paper, we study the so-called channel assignment problem from the perspective of game theory [2],[3],[4],[5] in a competitive wireless network. Though there exists a large body of literatures ([7],[9],[12] and the referenced therein) focusing on the problem of channel assignment in wireless networks, most of these works assume that nodes are collaborative and hence can achieve a high system performance. Nevertheless, this assumption is not true as the users of these nodes are usually selfish and need to maximize their own utilities/performance without necessarily respecting the system goals. Therefore, we focus our attention on a non-cooperative or selfish channel assignment game (game is referred to as selfish since each node is required to agree on sharing a common wireless medium in a distributed manner) and analyze the scenario of a single collision clique where each node's transmission can interfere with the transmission of every other node. In [6], authors study a similar channel assignment game and prove the existence of load balancing Nash Equilibrium of this game. They also present a distributed algorithm based on perfect as well as imperfect information to achieve this load-balancing Nash Equilibrium.

Nonetheless the algorithm using imperfect information can sometimes lead to an unbalanced channel allocation state i.e., state where some channels are completely under-utilized, which in turn reduces the throughput that each node can sustain. In this paper, we consider this issue of unbalanced channel allocation and design a novel multi-radio multi-channel allocation algorithm based on imperfect information for single collision clique wireless networks. Our proposed solution operates in three stages, each stage focusing on improving the total achievable data rate of each node.

The rest of the paper is organized as follows: In section 2, we discuss our system model along with a game-theoretic description of non-cooperative channel assignment. Section 3 presents the proposed distributed algorithm and some simulation results to highlight the performance of the proposed solution. Finally, we summarize our work in section 4.

2 System Model and Problem Formulation

We assume that the available frequency band is split into orthogonal channels of the same bandwidth using the Frequency Division Multiple Access (FDMA) method [1],[12] and the set of available channels obtained in this manner are denoted by $C = \{c_1, c_2, \cdots, c_{|C|}\}$, where $|.|$ represents the number of elements in the corresponding set. In this paper, as in [6], we also assume that each node participates in only one communication scenario and communicates with each other over a single hop termed as *single collision clique*. Further, each node is equipped with $k \leq |C|$ radio transmitters, all having the same data rate. We consider a finite set of players [1] denoted by $P = \{p_1, p_2, \cdots, p_{|P|}\}$. The key objective of each player is to maximize his total throughput or channel utilization and such players are referred to as *selfish players*. This work also assumes that there is a mechanism that enables each player to communicate simultaneously by using multiple orthogonal frequency channels [8], [12]. We denote the set of radios of player p_i using channel c by $k_{p_i,c}$ for every $c \in C$. For the purpose of suppressing the co-channel interference in a node, we also assume that different radios of the same player cannot employ the same channel i.e., $k_{p_i,c} \leq 1$, where $p_i \in P$ and $c \in C$. Next, we formulate the channel assignment problem as a non-cooperative game, which corresponds to a fixed channel allocation among the players. Each player's strategy consists of defining the number of radios on each of the channels. Hence, we define the strategy of player p_i as its channel assignment vector: $s_{p_i} = (k_{p_i,1}, k_{p_i,2}, \cdots k_{p_i,|C|})$ The strategy vectors of all players define the strategy matrix S, where the row i of the matrix represents the strategy vector of player p_i.

$$S = \begin{pmatrix} s_{p_1} \\ \cdots \\ s_{p_{|P|}} \end{pmatrix}$$

Furthermore, we denote the strategy matrix except for the strategy of player i by S_{-i} (see [3],[5] for more details on game theory). Let the total number of radios used by player p_i be $k_{p_i} = \sum_c k_{p_i,c}$. Likewise, k_c defines the number of

[1] In this paper, we use the terms nodes, users, devices and players interchangeably.

radios using a particular channel $k_c = \sum_{p_i} k_{p_i,c}$. Since the players are assumed to be rational, their main objective is to maximize the payoff i.e., achievable total rate, in the network. We denote the payoff obtained by each player p_i as part of the channel allocation process as $U_{p_i},\ i = 1$ to $|P|$. Similar to [6], we also assume that the total rate achievable on channel c, denoted as $R(k_c)$, is a decreasing function of the number of radios k_c deployed on this channel. When player p_i assigns its radio to channel c, its achievable rate on this channel can be written as $R_{p_i,c} = k_{p_i,c} \cdot R(k_c)$. Since the total rate on a given channel is equally shared by all the radios assigned to it, we can say that the higher the number of radios in a given channel, the lower the rate per radio. We can obtain the rate R_{p_i} for each player p_i by $R_{p_i} = \sum_c R_{p_i,c}$. In brief, we can write the payoff function of each player p_i as follows:$U_{p_i} = R_{p_i} = \sum_c R_{p_i,c} = \sum_c k_{p_i,c} \cdot R(k_c)$.

We next summarize two important theorems from [2],[6] regarding a Nash Equilibrium [3],[4],[5] channel allocation for wireless networks which guide our development of the channel allocation algorithm in Section 3.

Theorem 1. S^* is a NE iff the following two conditions hold: (1) $\eta_{x,y} \leq 1$ *for any* $x,\ y \in C$ *and* (2) $k_{p_i,c} \leq 1$ *for any* $c \in C$*, where* $\eta_{x,y} = |k_x - k_y|$.

Theorem 2. A NE channel allocation S^* is max-min fair iff $\sum_{c \in C_{min}} k_{p_i,c} = \sum_{c \in C_{min}} k_{p_j,c}$ for all $p_i, p_j \in P$, where C_{min} is the minimum number of allocated channels. This implies that $U_{p_i} = U_{p_j},\ \forall\ p_i, p_j \in P$.

3 Convergence to a Nash Equilibrium Solution

Based on the theorems given in Section 2, we next present a distributed channel assignment algorithm (Algorithm 1) that enables the selfish players to converge to the NE from an arbitrary initial configuration. The proposed distributed solution operates in three stages. In the first stage, each player, in a distributed manner, allocate its k radios to channels in a sequential manner. The implication is that the first k channels i.e., $c_i \in |C|,\ i = 1$ to k, will be occupied by all the k radios of each player. In [6], authors actually consider a random channel assignment, however we note that such random assignments can sometime lead to increased convergence time. After the sequential channel assignment process, in the second stage as well as in third stage, each player improves its total rate by reallocating those radios to the remaining channels. Similar to [6], to avoid that all players change its radios simultaneously, we employ the technique of backoff mechanism seen in the IEEE 802.11 medium access technology [1],[10],[11]. When the backoff counter reaches zero, bw $= 0$, players compare the number of radios on its channel d, where $d = c_1, \cdots, c_k$, with the average number of radios, $k_{avg} = \frac{|P| \cdot k}{|C|}$. If the number of radios exceeds k_{avg}, players reallocate those radios to unused channels i.e., to $|C| \setminus d = c_1, \cdots, c_k$. Finally each player, after the second channel allocation stage, compares its observed total rate R_{p_i} with the average estimated total rate. If the observed rate falls below the estimated rate, we need the players to reorganize its radios till an improved rate (i.e., greater than average estimated rate) is achieved. Note that, the second as well as third stage design focuses on the theorems 1 and 2 to ensure NE as well as fairness of the solution. Though our algorithm ensures NE channel allocation, sometimes the process is not fair. This is because some players will always get an advantage of channel

Algorithm 1 NE Channel Assignment Algorithm with Local Information

Stage 1: Each node, in a distributed manner, assign its radios to channels sequentially.
for a given player $p_i \in |P|$ **do**
  for $j = 1$ to k radios **do**
    move each radio j to c_j.
  end for
end for
Stage 2: After initial channel assignment, each player improves the total rate by switching its radios to $|C| \setminus d = c_1, \cdots, c_k$ channels. Each player has knowledge of only the number of radios on its own channel. Let $k_{avg} = \frac{|P| \cdot k}{|C|}$
for a given player $p_i \in |P|$ **do**
  if (backoff counter==0) **then**
    for $j = 1$ to k radios **do**
      radio j uses channel $\in d = c_1, \cdots, c_k$
      if $k_d - k_{avg} \geq 1$ and $k_{p_i,|C| \setminus d} = 0$ **then**
        move the radio j from channel d to $|C| \setminus d = c_1, \cdots, c_k$ with uniform probability $\frac{1}{|C| \setminus d}$.
      end if
    end for
  end if
end for
Stage 3: Convergence to NE.
Let the average rate be $R_{avg} = k \cdot R(k_{avg})$, where $R(k_{avg})$ denotes the rate of channel with k_{avg} radios.
Let $C_{p_i} \in C$ be the channels used by player p_i.
while (true) **do**
  for a given player $p_i \in |P|$ **do**
    if (backoff counter==0) **then**
      if $\sum_{C_{p_i}} R_{p_i} < R_{avg}$ **then**
        for $j = 1$ to k radios **do**
          if $k_{C_{p_i}} - k_{avg} \geq 1$ **then**
            move radio j to channel $|C| \setminus C_{p_i}$ with uniform probability $\frac{1}{|C| \setminus C_{p_i}}$.
          end if
        end for
      end if
    end if
  end for
end while

assignment over others and correspondingly, higher payoff. In Figure 1, we also present the performance of our algorithm for two different scenarios ($|P| = 10, |C| = 8, k = 3$ and $|P| = 10, |C| = 8, k = 4$). The maximum number of rounds for the algorithm termination is set as 15.

4 Conclusion

In this paper, we have devoted our attention on the problem of non-cooperative channel allocation among devices that use multiple radios. We developed a game theoretical solution with imperfect information that balance and maximize all

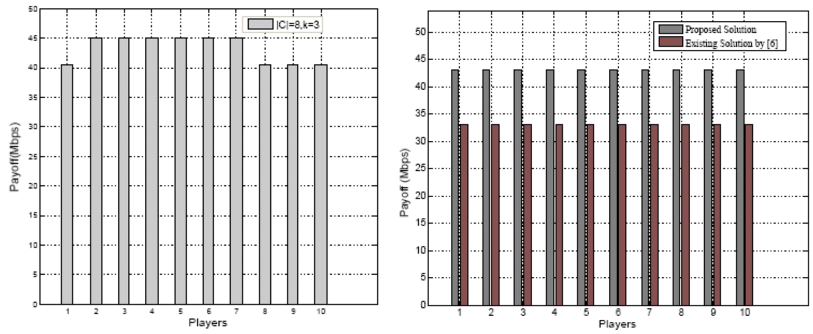

Fig. 1. Payoff of players, $|P|$, for $k = 3$ and $|C| = 8$ and $|P|$, for $k = 4$ and $|C| = 8$, $\epsilon = 10^{-4}$ for the proposed solution as well as the existing solution in [6] respectively.

of the players total payoff under the constraints of the number of channels and radios in a selfish as well as a topology-blind environment.

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