Interference-aware Game-based Channel Assignment Algorithm for MR-MC WMNs

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***Abstract*—One of the main challenges of multi-radio multi-channel wireless mesh networks (MR-MC WMNs) is how to efficiently avail from the radio resources available in the network. The level of interference experienced by the mesh nodes rises when the network becomes more connected and the number of radios per node increases. To mitigate interference experienced by the wireless mesh nodes while taking advantage from the multi-channel network aspect, we propose a novel Interference-aware Game based Channel Assignment algorithm, named IGCA. We prove through simulations that our proposed algorithm contributes in alleviating the node interference degree, fairly allocates interfaces to network non-overlapping channels and increases simultaneous transmissions in the network. An improvement up to 50% of both interference degree and simultaneous connections is particularly observed in comparison with a prominent existing approach - the Near-optimal Partially Overlapping Channel Assignment algorithm.**

Keywords: WMNs, Multi-Radio Multi-Channel, Channel Assignment, Interference Aware, Game Theory, Potential Game.

I. Introduction

Wireless mesh networks (WMNs) are considered as a potentially attractive key-solution to provide broadband wireless access services. Due to their promising features including self-organization, self-configuration, easy network maintenance and reliable service coverage, such networks provide a flexible high-bandwidth wireless backhaul over large geographical areas, especially when multiple channels and multiple radio interfaces are deployed. While single radio mesh nodes operating on a single channel suffer from capacity constraints, deploying multiple radios and multiple channels on mesh routers can improve significantly the capacity of the network and increase the aggregate bandwidth [1]. However, considering an efficient channel assignment which pursues an appropriate mapping between the available channels and nodes' radios is required. In fact, despite the availability of multiple frequencies offered by the IEEE 802.11 standards, the total number of radio interfaces in a WMN is much higher than the number of available channels. So, many neighboring nodes radio interfaces could be assigned the same channel or channels that are partially overlapping to each other resulting in a network performance degradation due to interference problem. To design an efficient channel assignment in multi-radio multi-channel WMNs, many important issues should be handled carefully such as minimizing interference effect, maintaining the network connectivity and improving the aggregate network capacity. To reach this goal, channel assignment for multi-channel wireless mesh networks has been widely proposed in the literature, but still very knotty when it comes to meet all the challenges. In this paper, we investigate how to design an efficient channel assignment algorithm that reaches these requirements. Specifically, we propose a new interference-aware game-theoretic approach for channel assignment in a mesh backbone. We first formulate the problem as a potential game, i.e, an identical interest game. Indeed, mesh routers (or MRs) are modeled as players trying to maximize a specific utility in order to alleviate the "a priori" interference between them. We then describe our proposed Interference-aware Game-based Channel Assignment Algorithm (IGCA) with perfect information. To gauge the effectiveness of our proposal, we compare the IGCA algorithm with a prominent existing approach: the Near-optimal Partially Overlapping Channel Assignment algorithm [2]. Results show that IGCA reduces significantly nodes interference degree, ensures a fair distribution of radios between channels and most importantly permits a considerable number of simultaneous connections in the mesh backbone, when compared to NPOCA.

The reminder of the paper is organized as follows. Section II discusses literature that is relevant to this work. Section III presents the system model used in our approach and the problem formulation as a potential game. The game-based proposed algorithm is then introduced in section IV. Simulation results are provided in section V. Finally, section VI concludes this paper.

II. Related Work

Owing to the importance of efficiently assigning radios to channels in order to improve the performance of MR–MC WMNs, extensive studies have been carried out to tackle this issue. Several multi-channel allocation solutions have been proposed in the literature. Each one of them focuses on a specific aspect and addresses a particular need. Comprehensive literature surveys providing interested classifications of channel assignment approaches designed for MR-MC WMNs can be found in [1] [3] [4]. Here, we mention only studies that are directly relevant to our work, i.e. those that have applied game theory to solve the channel assignment (CA) problem. Gao et al. presented in [5] a static cooperative game with perfect information in which players within a coalition collaborate to achieve high data rates. The focus was on the performance improvement of the multihop links, induced by cooperation gains, without sacrificing the performance of single-hop ones. Authors introduced the min-max coalition-proof Nash equilibrium (MMCPNE) channel allocation scheme in the game. However, this work has mostly a theoretical interest. Some assumptions made by the authors like the fact that "each node participates in only one communication session" and that "the whole network is a single collision domain" do not reflect usually a real network behavior. In [6] and [7], the CA problem has been formulated as a non-cooperative game where each node aims at maximizing its own profit selfishly. Yang et al. proposed in [6] a CA scheme designed for MR-MC wireless networks with multiple collision domains. The proposed strategic game named ChAlloc has been formulated as a strategic game. To avoid possible oscillation in ChAlloc game, a charging scheme was designed to induce players to converge to a Nash Equilibrium. Manikantan Shila et al. [7] proposed an algorithm achieving a load balancing Nash Equilibrium solution in a selfish and a topology-blind environment. The algorithm is based on imperfect information for single collision clique wireless networks. The solution operates in three stages, each stage focuses on improving the total achievable data rate of each node.

The two above proposed schemes are very interesting. However, they do not match well with our specific context of application. They are designed for non cooperative MC-MR wireless networks, where the network consists of heterogeneous wireless nodes each owned by an independent individual. Nevertheless, we consider in our study wireless mesh backbones where mesh routers tend to be cooperative since they are managed by the same administrator. Assuming that mesh backbone nodes may have a selfish behavior neglecting the system performance may not hold in practice.

Nezhad et al. proposed SICA [8], a game formulation of CA taking into account the co-channel interference. The proposed interference-aware CA scheme is semi-dynamic and distributed. Besides, it applies an on-line learner algorithm which assumes that nodes do not have perfect information. Thus, players (mesh routers) play a mixed strategy based on their weights to solve it. However, besides having selfish nodes that try to occupy the best channels, SICA uses three radios for each node (the first to receive, the second to transmit and the third tuned to a common channel for all nodes) which cannot be managed in all WMNs. In the same context and aiming to especially reduce physical-layer interference, Yen et al. proposed in [9] a two-stage radio allocation scheme where wireless interfaces are modeled as players participating in a radio resource game. On one hand, the first stage assigns channels to radios using a game-theoretic approach. On the other hand, the second stage assigns the resulting radio-channel pairs to links using a greedy method. Availing from partially overlapped Channels, Duarte et al. presented respectively in [2] and [10] the Near-optimal Partially Overlapping Channel Assignment (NPOCA) and Heuristic Partially Overlapped Channel Assignment (HPOCA) schemes using a cooperative and potential game. These algorithms have the overall objective of maximizing the network throughput while reducing co-channel interference. Unfortunately, the proposed channel selection mechanisms are not optimal. They broadcast a lot of coordination messages in the network. Moreover, they do not take into account the connectivity issue. Later, we compare our proposal to the NPOCA scheme, arising the interest in developing strategic approaches with perfect information to solve the CA problem.

III. Context and problem formulation

We consider a wireless MR-MC backbone mesh consisting of several mesh routers. In our study, we focus on providing a suitable CA algorithm that aims to reduce channel interference while keeping a connected network and avoiding channel congestion. In the following, we first present the necessary notions used in our model. Then, we expose the corresponding problem formulation based on a game theoretic approach.

A. Notations

- $A = \{a_1, a_2, ..., a_n\}$ is the set of nodes, where $|A|$ is the total number of nodes deployed in the mesh backbone.
- I denotes the number of radios per node.
- C denotes the number of non-overlapping channels in the network.
- k_{ij} is the number of radios of player i assigned to channel j.
- n_{ij} is the number of interfering neighbors of player i which are using channel j on one of their radios.
- N_i denotes the number of potentially interfering neighbors of i (i.e. nodes in the interference range of node i)
- S_i represents the strategy of player i and is denoted by $S_i = \{k_{i1}, k_{i2}, .., k_{iC}\}$
- $S = \times_{i \in A} S_i = S_1 \times S_2 \times ... \times S_n$ is the game profile defined as the Cartesian product of the players' strategy vector.

For our model, we assume the following:

- $\sum_{j \in C} K_{ij} = 1$: All radios must be affected to channels.
- $k_{ij} \leq 1$: Radios of a same player must be affected to different channels.
- $|C| > I$: The number of interfaces per node is smaller than the number of channels available in the network.
- I is fixed and is the same for all players.

B. Utility

The main objective of our game is to minimize the network interference. Thus, we define an interference-aware metric G_i as the gain of player i:

$$G_i = 1 - \sum_{j \ \in C} \frac{k_{ij} \times n_{ij}}{N_i \times I} \tag{1}$$

Each player is a decision maker which chooses a strategy S_i. It maximizes its gain by minimizing the cost of interference expressed by the second term of the metric G_i. This cost can be seen as a penalty fee imposed on player i due to its choice. The player's utility is defined as:

$$U_i(S) = U(S) = \frac{\sum_{i \ \in A} G_i}{|A|} \tag{2}$$

Theorem: The proposed channel allocation game is an identical interest game.

Proof: We first prove that our game is a potential game. Then, we prove that it belongs to the specific subclass of identical interest game. A potential game is a normal form game such that any change in the utility function of any player due to a unilateral deviation by that player is correspondingly reflected in a global function referred to as the potential function [11].

Definition: A game is an exact potential game if there is a function $\phi : S \to \mathbb{R}$ such that $\forall S_{-i} \in S$, $\forall S'_i, S''_i \in S$:
$\phi(S'_i, S_{-i}) - \phi(S''_i, S_{-i}) = U(S'_i, S_{-i}) - U(S''_i, S_{-i})$

Or, it is obvious that the utility function defined in Eq. (2) is a potential function for IGCA. Thus, we deal here with an exact potential game. Besides, we have: $\phi(S) = U_i(S) = (S)$, $\forall i \in A$. As a result, our game is an identical interest game (called also common interest game or team game). In such game, the players' utilities are chosen to be the same and players aim to maximize their common utility. Identical interest games are a particular case of exact potential games [12]. Thus, they inherit all of their properties. In fact, for a potential game, the following holds:

- Every finite potential game possesses at least one pure strategy Nash Equilibrium.
- All NE are either local or global maximizers of the utility function.

C. Algorithm

Given the utility function previously described in section III.B, we propose a game-based algorithm with perfect information in which each player knows the strategies of the others. We use in our model an "extensive form" game where players play one after the other. Players' choices are based on the "better response", a known scheme used to reach utility function's maximizers. Note that usually a wireless mesh backbone is managed by an administrator. In order to reduce transmission overhead, our algorithm uses a partially centralized approach which can be suitable to a large scale mesh backbone. Besides, it avoids congestion by flooding the network with redundant information. Hence, we made the following assumptions:

- A common channel for communication between players in the negotiation phase is assumed to be available.
- The real allocation of channels is done after the execution of the following algorithm.
- T is the stop condition in terms of time or maximum number of negotiations.

Algorithm 1: IGCA Algorithm

Input: A, I, C
Output: S set of strategies $S_1, S_2, \ldots, S_|A|$

$Initiator \leftarrow SelectAnInitiator(A)$
$Order \leftarrow SelectRandomOrder(Initiator, |A|)$
$Broadcast(Order, A)$
for i ***from*** 1 ***to*** $|A|$ **do**
  $S_i(0) \leftarrow RandomValidStrategy(I, C)$
  $Strat[i] \leftarrow SendInitialStrategy(Initiator, S_i(0))$
$j \leftarrow 1$
$i \leftarrow Order[j]$
$sender \leftarrow Initiator$
while $T = false$ **do**
  $SendUpdatedStrategies(sender, i, Strat)$
  $S_irand \leftarrow RandomValidStrategy(I, C)$
  if $S_irand > S_i(t)$ **then**
    $S_i(t+1) \leftarrow S_irand$
  else
    $S_i(t+1) \leftarrow S_i(t)$
  $Strat[i] \leftarrow S_i(t+1)$
  $sender \leftarrow i$
  $Updatej$
  $i \leftarrow Order[j]$
  $UpdateT$
$SendStrategies(sender, Initiator, Strat)$
return S

At the beginning, a game initiator is chosen between all the mesh routers. The choice can be done randomly or the most connected node can be elected to avoid multi-hop transmissions in the network. The initiator picks out the order by which players will perform the game. Then, it broadcasts a signal containing the order of the game to all players informing them to start the game. Each player picks a random valid strategy and sends it back to the initiator. After collecting all strategies, the latter sends them to the first player. This player selects a random valid strategy in the set of all valid strategies that it can perform according to the assumptions mentioned earlier and which maintains the connectivity of the network (i.e. The backbone is a connected graph). It compares it with its current strategy and keeps the one that keeps the network connected and yields a higher value of the utility function (i.e. it compares the following utilities : $U_i(S_i rand, S_{-i})$ and $U_i(S_i(t), S_{-i})$). Then, it sends its new decision (i.e. the chosen strategy), following the order of the game, to the next player which will do the same. The step of selecting an improving strategy or maintaining the previous one is repeated until the stop condition T is met. Finally, the last player will send the set of final strategies S to the initiator of the game. This step is needed in case we want to further improve the CA of the network. In fact, the CA procedure can be dynamic. Thus, our algorithm can be repeated when needed. It can restart at the 7th line of the algorithm with the actual set of strategies S instead of restarting the strategies to random ones. In general, this step can be seen as a negotiation phase on a common channel before actually affecting channels to the interfaces. It is worth noting that the IGCA algorithm may sometimes not reach the global-optimum if one player is trapped in a local-optimal NE value since more than one NE can exist.

IV. Performance Evaluation

In this section, we evaluate the performance of our game theoretic algorithm. We first present the simulation environment and describe the used scenarios. Then, we describe the results of our experiments. We used the interference-aware NPOCA [2] algorithm as baseline to which IGCA improvements are compared.

A. Simulation Environment

We consider in our experiments a random wireless mesh backbone network consisting of 10 mesh routers placed in a $100m \times 100m$ field. The network uses the IEEE.802.11a standard as wireless technology and possesses 8 non-overlapping channels. We shift the number of nodes' radios from 2 to 5. The break parameter T is fixed to 1000 iterations. All nodes have the same communication range $CR = 30m$. The interference range (IR) is estimated as follows: $IR = 1.5 \times CR$. Simulations were performed using 50 different seeds regarding a specific random node distribution.

B. Performance Metrics

In order to evaluate the performance of IGCA, we have considered the following metrics:

- *Connectivity degree*: the connectivity degree of a node i with reference to the channel allocation is equal to the number of neighbors that can communicate directly with node i using a common channel.
- *Interference Degree*: the interference degree of a MR is defined as the number of interfering neighbors regarding the chosen CA scheme.
- *Channel distribution*: the channel distribution of a channel $c \in C$ is equal to the number of all interfaces assigned to channel c. In other words, it is the number of nodes that can use channel c to send data.
- *Number of possible simultaneous connections*: It is equal to the number of possible connections that can be handled simultaneously on non-interfering links using a specific channel $c \in C$.

C. Simulation Results

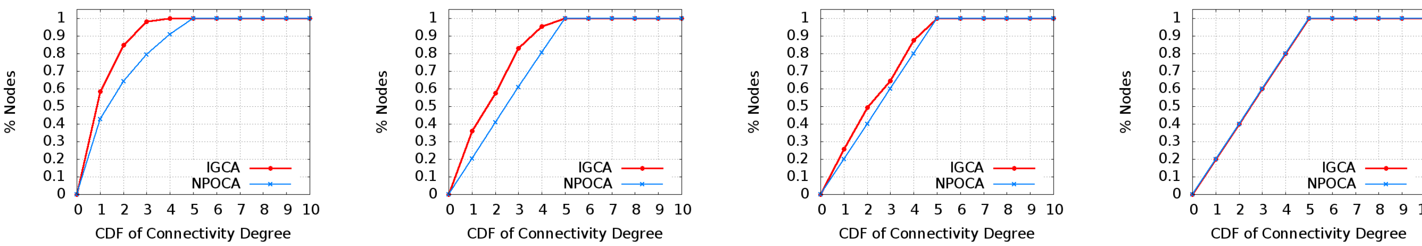
In what follows, we present our simulation results in terms of connectivity degree, interference degree, channel distribution, and number of possible simultaneous connections.

1) Connectivity Degree:

This evaluation metric is fundamental for the good deployment of any wireless network. It is important to note that connectivity is well addressed by our algorithm since IGCA returns always a connected graph. Nevertheless, NPOCA algorithm can provide a non-connected network graph. Hence, in order to conduct a fair comparison between the utility functions of both approaches, we added the connectivity condition to NPOCA. In the first set of experiments, we studied the performance of our proposed IGCA algorithm in terms of Cumulative Distributed Function (CDF) of node connectivity degree. 1(a) and 1(b) show the impact of the number of interfaces per node on the connectivity degree. From that figure, we can observe that with 2 and 3 radios per node, NPOCA gives slightly better results than IGCA. In fact, unlike our gain metric G_i, the metric used in the utility function of the NPOCA algorithm is based on two topology control factors (i.e. the hop count from the node to the gateway and a connectivity factor set to 1 if the node can reach the gateway) which warrant the efficiency of network links toward the gateway. But still, our approach gives a good node connectivity degree and the improvement of NPOCA is merely of 1 node more. In addition, we notice that starting from 4 interfaces, IGCA converges to the best connectivity scheme with regards to the same random 10 nodes distribution in the network.

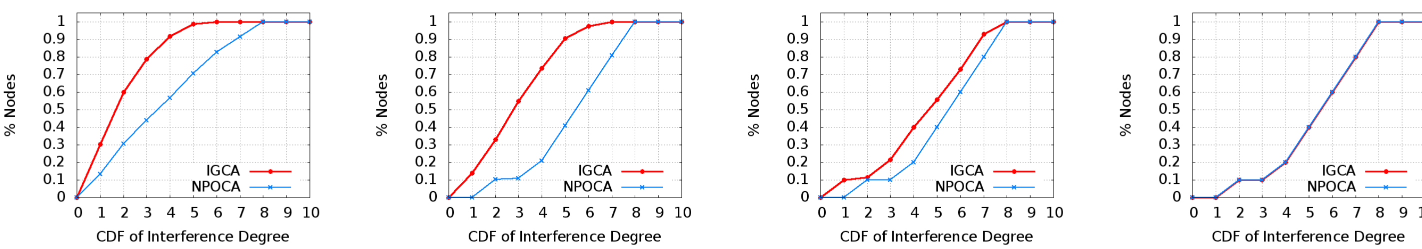
2) Interference Degree:

Fig. 2 shows the CDF of interference degree for both IGRA and NPOCA algorithms. Note that this performance metric is closely related to the previous one and a good interpretation must be done with reference to



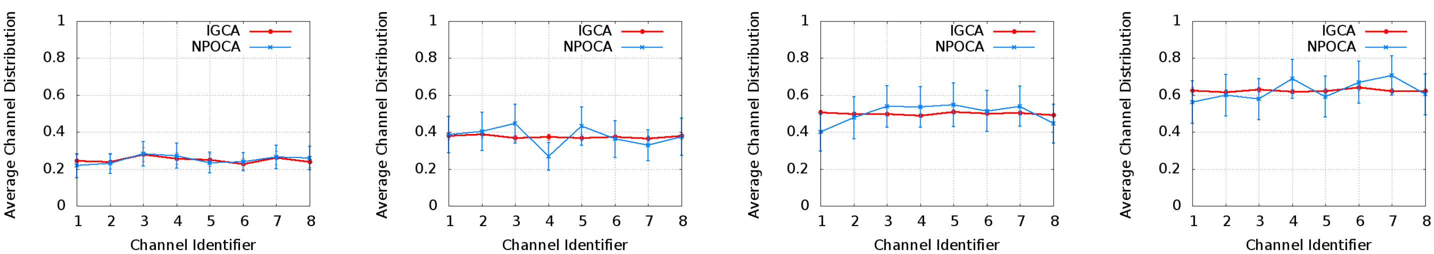
(a) $I = 2$ (b) $I = 3$ (c) $I = 4$ (d) $I = 5$

Figure 1. CDF of connectivity degree in a 10 nodes backbone with CR=30m



(a) $I = 2$ (b) $I = 3$ (c) $I = 4$ (d) $I = 5$

Figure 2. CDF of interference degree in a 10 nodes backbone with CR=30m



(a) $I = 2$ (b) $I = 3$ (c) $I = 4$ (d) $I = 5$

Figure 3. Channel distribution in a 10 nodes backbone with CR=30m

	IGCA				**NPOCA**			
Channel Identifier	$I = 2$	$I = 3$	$I = 4$	$I = 5$	$I = 2$	$I = 3$	$I = 4$	$I = 5$
1	0.62	1	1.16	1.32	0.34	0.7	0.76	1.08
2	0.44	0.98	1.14	1.5	0.44	0.72	0.92	1.18
3	0.62	0.98	1.12	1.46	0.52	0.84	1.02	1.1
4	0.62	1.02	1.2	1.32	0.44	0.46	1.02	1.4
5	0.46	1.04	1.22	1.62	0.4	0.82	1.02	1.16
6	0.54	1	1.18	1.54	0.48	0.62	0.98	1.3
7	0.54	1.1	1.18	1.44	0.42	0.58	1.1	1.4
8	0.64	1	1.12	1.44	0.48	0.62	0.88	1.22
Average per number of interfaces	0.56	1.015	1.165	1.45	0.44	0.67	0.9625	1.23
Average possible communications in the network	**4.64**	**8.12**	**9.32**	**11.6**	**3.52**	**5.36**	**7.7**	**9.84**

Table I
AVERAGE NUMBER OF POSSIBLE SIMULTANEOUS CONNECTIONS PER CHANNEL ON A 10 NODES MESH BACKBONE

the both. From Fig. 2(a), we can notice that, using the IGCA algorithm, 80% of MRs interfere with 3 nodes or less while they interfere with the double using NPOCA. Recall that in this same scenario, 80% of nodes are connected to 2 nodes or less with IGCA and to 3 nodes or less with NPOCA (see Fig. 1(a)). With a same reasoning, we observe that 80% and 60% of the backbone nodes, having respectively 2 and 3 interfaces per node, have at most $\frac{1}{2}$ of interfering nodes that can carry transmission data using NPOCA. While, using IGCA, at most $\frac{2}{3}$ of them can. In addition, we observe that the improvement achieved by IGCA in node interference degree can exceed 50% compared to NPOCA when $I \leqslant 3$. This can be explained by the good design of our interference-aware utility function that strengthens the interference awareness of the nodes. However, we notice that the performance of IGCA degrades and becomes closer to NPOCA for high values of I. This is simply because, with considering high number of interfaces per node, the interference becomes unavoidable whatever the CA scheme used.

3) Channel Distribution:

Fig. 3 further investigates how the assigned channels are distributed within the network. Note that in our simulations, 8 channels per radio interface are available. From this figure, we can clearly observe the unrelenting fairness of IGCA approach in distributing interfaces between channels. This is very important to avoid having underused and overused channels in the network. Whereas, channel distribution graphs related to NPOCA become more serrated when the number of radios per node increases.

4) Number of possible simultaneous connections:

To further show the benefit of our approach, we plot in Table I the average number of possible simultaneous connections, i.e., the average number of non-interfering links per channel using the aforementioned scenarios. We can clearly observe that the average number of possible communications in the network is improved using IGCA in comparison with NPOCA and this result is independent from the number of interfaces per node. The gain is up to 51%. In addition, the values given by IGCA for every specific value of I are smoother than those given by NPOCA. Hence, besides being fair in distributing radios on channels, IGCA enables equitable number of possible transmissions over channels.

V. Conclusion

In this paper, we have envisioned a new channel assignment algorithm for Multi-Radio Multi-Channel Wireless Mesh Networks. We proposed an interference-aware channel assignment algorithm based on a potential game, called IGCA, which intends to alleviate the interference experienced by the Mesh routers (MRs) and maintains the connectivity of the network. To gauge the effectiveness of our proposal, numerous simulations were performed. We evaluated the potential performance gains of IGCA and proved that it achieves significant gains. We appreciate how much our proposed CA game theoretic algorithm contributes in minimizing interference between neighbors, generates a fair distribution of nodes' radios between the available network channels and, above all, allows a better number of simultaneous connections in the network in comparison with a prominent game-based approach: the NPOCA algorithm.

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