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Citation:

Pedro B. F. Duarte, Zubair Md. Fadlullah, Athanasios V. Vasilakos, and Nei Kato, "Channel Assignment on Wireless Mesh Network Backbone with Potential Game Approach," 2nd International ICST Conference on Game Theory for Networks (GameNets 2011), Shanghai, China, pp. 43-56, Apr. 2011.

URL:

http://www.springerlink.com/content/q824628vh11h2251/

Channel Assignment on Wireless Mesh Network Backbone with Potential Game approach

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Abstract

The Wireless Mesh Network (WMN) has already been recognized as a promising technology as broadband access network from both academic and industry points of view. In order to improve its performance, research has been carried on how to increase the number of simultaneous transmissions in the network while avoiding signal interference among radios. Considering WMNs based upon IEEE 802.11 b/g standards, lately most of researchers have been relying on the usage of orthogonal channels for solving the Channel Assignment (CA) problem. However, in this paper, we introduce a novel CA algorithm exploiting partially overlapped channels (POC) that overcome the common orthogonal channel approach. This algorithm is derived based on Game Theory framework using Potential Games and yields near optimum CA.

Index Terms

Wireless Mesh Networks, channel assignment problem, partially overlapped channels, game theory, potential games

I. Introduction

Wireless Mesh Networks (WMNs) have attracted interest from researchers, industry, and users [1]. Its multi-hop characteristics can greatly improve the network coverage area with lower transmission power and provide reliable broadband access services for campus and community networks. WMNs are considered to be a key technology in Next Generation Networks (NGNs) and aims to deploy ubiquitous Internet access. With such a promising future, several standards have been developed for different access ranges, namely IEEE 802.15.4, IEEE 802.11s and IEEE 802.16j, which target Wireless Personal Area Networks (WPANs), Wireless Local Area Networks (WLANs) and Wireless Metropolitan Area Networks (WMANs), respectively. This paper will focus on WMNs based on WLAN technology.

WMNs consist of a multi-hop environment nevertheless its concepts and targets differ from conventional Mobile Adhoc Networks (MANET). A WMN comprises two different types of nodes, namely Mesh Routers (MRs) and Mesh Clients (MCs). The former is responsible for network routing and bridging while the latter, being a light-weight node, would perform just the routing function, if necessary. Moreover, MRs compose a backbone network and concerning mobility and battery life-time, they are usually static and have no constrains on energy consumption. Such differences between WMNs and MANETs led to novel protocols development to address specific challenges on WMNs.

As the users' requests for better services, e.g., higher transmission rates and lower delay networks, are an ever increasing demand, solutions to improve the network capacity are constantly addressed by researchers. On WMN, several solutions have been already proposed to improve its capacity, such as modified Medium Access Control (MAC) protocols, directional and Multiple Input Multiple Output (MIMO) antennas and Multi-Radio Multi-Channel (MRMC) topology.

Inside the MRMC field, one of the most promising techniques is Partially Overlapped Channel Assignment by using IEEE 802.11 b/g devices, which can increase the network throughput by exploiting more simultaneous transmissions. According to the afore-mentioned standard, there are 11 channels available to communication on the 2.4 GHz ISM band. Each of them has a bandwidth of 22 MHz and a center frequency distance of only 5 MHz. Hence, there are just three orthogonal[1] channels available, namely, channels 1, 6 and 11. Using these three channels configuration does not provide an efficient frequency-spatial reuse. However, by exploiting all eleven channels in a systematic approach to avoid the interference among adjacent channels, we are able to achieve a greater number of simultaneous transmissions rather than just three orthogonal channels. Nevertheless, this systematic approach is not trivial and if not well planned, it can actually severely degrade the network performance (throughput and delay) due to adjacent channel interference, that is considerably more harmful than co-channel interference.

In this work, we derive and investigate a novel near-optimal CA. In order to derive this near-optimal CA, we use a Game Theory approach. This mathematical tool is specially useful in the network engineering field to model high complex scenarios that may include complex traffic models, mobility, unpredictable link quality, in which pure mathematical analysis has met limited success [2]. Game Theory, a field of applied mathematics, suits this purpose because of its ability to model individual, independent decision makers, or players, that interacts and impact other decision makers, which closely resembles WMNs and MANETs dynamics[2].

The remainder of this paper is organized as follows. Section II surveys related works on solving MRMC

[1] *Orthogonal* and *non-overlapping* channels are interchangeably used

[2] *Players*, *nodes*, and *routers* are interchangeably used

CA problem, followed by Section III which reviews the interference model used for this article. The near-optimal CA is derived on Section IV. The performance of the proposed algorithm is evaluated in Section V, and finally Section VI concludes the paper.

II. Related Works

A multi-channel MAC (MMAC) protocol for handling multi-channel assignment using a single radio was proposed in [3]. The protocol uses non-overlapping channels and it reserves one channel for control packets and two others for data packets.

Draves et al. [4] start employing multi-radio topology. In their contribution, a new routing metric Weighted Cumulative Expected Transmission Time (WCETT) is developed. In addition, they assume non-interfering channels and they employ fixed CA. In 2007, a survey on channel assignment was performed by Skalli et al. [5]. It reviews several CA strategies and also proposes a new one. Including the surveyed and proposed algorithms, all of them employ non-overlapping channels. According to this paper, "this leads to efficient spectrum utilization and increases the actual bandwidth available to the network".

More recently, Bukkapatanam et al. [6] using numerical analysis showed that the usage of overlapping channels achieves better performance than three non-overlapping channels in the backbone network, expanding the previous work of Mishra [7]. However, none of the three above cited works actually describes a novel CA algorithm exploiting POC.

Using the Game Theoretical perspective to address complex engineering related issues has attracted the attention of several researchers in the last decade and its applicability abound: power control in cellular radio systems [8], optimal routing control [9] and reputation mechanisms for ad hoc networks [10] are few examples.

Although works on Game Theory concerning CA are also numerous, usually POC are not considered by the proposed models. For example, in [11] the authors derive a perfectly fair CA using concepts as Nash equilibrium (NE) and fairness under a non-cooperative game, however their model is simply based on orthogonal channels and their simulations just evaluate a single collision domain. In [12], Gao and Wang, model the game as for the CA as a coalition rather than a non-cooperative game and than prove the existence of a Nash equilibrium under such conditions. That work also assumes non-overlapping channels and just single collision domain. In Zhang and Fang's research [13], a joint solution for channel and power allocation is studied from the Game Theoretical perspective. Differently from our work, they mainly focus on the access network issue rather than the backbone.

In short terms, in this paper, we address the CA problem on the WMN backbone and we develop a novel CA algorithm exploiting POC. We also employ Game Theory concepts to model MRs as decision makers of a cooperative game. The interaction among all MRs can be classified as an *identical interest* *game* as in [13]. Further, we introduce a negotiation-based CA algorithm for the frequency assignment that converges to a steady state (NE), and as a property of identical interest games, this condition implies achieving an optimum CA. Therefore, the contributions of this work are two fold: 1) develop a game theory mathematical model that comprises the interference models necessary to POC assignment. 2) Game theoretic CA algorithm that yields near-optimal throughput performance.

III. Interference Model

We may define the CA problem as an optimization one in terms of mapping available communication channels to network interfaces in order to maximize the communication capacity while minimizing signal interference. Interference range is defined as the distance within which interference occurs. Two different transmissions are considered to interfere to each other if they lie within interference range.

In a multi-channel environment, four different types of interference and their influence on the network capacity should be addressed. Here, we describe them in more details. For this description, we consider two pairs of nodes, each of them having a sender and a receiver. Let the sender and receiver of the first pair be denoted by S_1 and R_1, and those of the second pair be denoted by S_2 and R_2. All these nodes are positioned within the interference range.

- Co-channel Interference: consider that all four nodes are operating in the same channel. Because of CSMA/CA, this type of interference is less harmful for the network capacity than Adjacent Channel Interference. Consider the following scenario: node S_1 is starting to transmit a packet to R_1. It checks if the medium is busy or idle. If it is busy, the node will withdraw its transmission and postpone it. However, if the medium is idle, it will proceed with the transmission. Meanwhile S_1 is sending data to R_1, S_2 also attempts to send a packet to R_2. In this case, the medium will be busy. Hence, S_2 will withdraw the transmission attempt and wait over backoff period. Later on, it will attempt again and the transmission between S_1-R_1 will be already ceased. Then, S_2 will succeed with the signal transmission. In this scenario, we have a contention based access, in which a concurrent access to the medium occurs.
- Orthogonal Channels: In this scenario interference will not occur. Consider S_1-R_1 and S_2-R_2 using two orthogonal channels. Again, S_1 detects an idle medium and starts the packet transmission. Meanwhile, S_2 will also detect an idle medium since it is operating on a distinct channel. Both pairs are able to successfully transmit their packets simultaneously, because there is no overlapping frequency band between those channels.
- Adjacent Channel Interference (ACI): This kind of interference seriously degrade the network capacity. Here, we consider S_1-R_1 and S_2-R_2 assigned to channel 1 and 3, respectively. Following

the same scheme in which S_1 begins transmitting first, S_2 will detect an idle medium in channel 3 and also starts to send its packet. However, since channels 1 and 3 share a common frequency band, the receivers will not be able to successfully decode the packets, causing a transmission error that severely degrades the network throughput. Although, it is important to note that the interference range for adjacent channels is inversely proportional to the actual channel separation.

- Self Interference: Self Interference is defined as a node itself causing interference to one of its own transmissions. This case will occur in multiple radio nodes using omni-directional antennas. To explain this case, consider S_1 with two network interfaces, assigned to channel 1 and 3. Whenever S_1 tries to simultaneously send packets on both interfaces, the SIR (Signal to Interference Ratio) will be degraded no matter where the receiver node is. This type of interference can be avoided if no node has its interfaces assigned to overlapping channels. This means that in IEEE 802.11b/g, we can assemble at most 3 interfaces using orthogonal channels at any given node.

Considering the afore-mentioned types of interference, the authors in [14] developed a schematic procedure for CA. This model is named as I-Matrix and it determines whether it is possible or not to assign channels to a given link exploiting POC. We adopt the Interference Factor concept from their work, in order to devise our interference model.

A. Interference Factor

The *interference factor* $f_{i,j}$ takes as input parameters geographical distance and channel separation, and provides the effective spectral overlapping level between channels i and j. In order to calculate $f_{i,j}$, the experimental measurements showed in [15] are used and scaled by a factor of 10. We use the *interference range* (IR) table where δ is the channel separation $\delta = |i - j|$ and $IR(\delta)$ is the maximum geographical distance in which there will be interference between channels i and j.

TABLE I

INTERFERENCE RANGE (IR)

δ	0	1	2	3	4	5
$IR(\delta)$	132.6	90.8	75.9	46.9	32.1	0

Given the IR table, let d be the Euclidean distance between transceivers using channels i and j. Also by definition, considering the case that the transceivers are assembled in the same node, we define d being zero. To calculate $f_{i,j}$ we should consider the three following cases:

1) $f_{i,j} = 0$: when $\delta \geq 5$ or $d > IR(\delta)$

In this case there will be no interference between the radios since either they are assigned orthogonal channels, or they are distant enough not to cause interference given IR for channel i and j.

2) $1 < f_{i,j} < \infty$: when $0 \leq \delta < 5$ and $d \leq IR(\delta)$
Here we have two radios assigned to overlapping channels i and j, and also the distance between them is within the interference range. Thus, interference factor should be calculated as the following equation in which $f_{i,j}$ is inversely proportional to the distance between radios.

$$f_{i,j} = IR(\delta)/d : \tag{1}$$

3) $f_{i,j} = \infty$: when $0 \leq \delta < 5$ and $d = 0$
As mentioned before, here we strictly exclude the self interference to happen. Two overlapping channels ($\delta < 5$) will not be assigned at a given node.

IV. Modeling Channel Assignment Game

In this section, we model our MRs as players as in Game Theory. The main objective here is to derive an near optimal CA using the mathematical analyses provided by the Game Theory framework. Each MR is considered *player*, i.e. *decision maker* of the game, and we model the interactions among them as a cooperative channel assignment game (CoCAG). The game is composed of a finite set of players, $\mathbf{A} = \{a_1, a_2, \ldots, a_N\}$ and all the players have a common strategy space $\mathbf{S} = \mathbf{S_i}, \forall i$. In this context, we map the channel(s) assigned to any given MRs' radios as its chosen strategy. Formally, the strategy of i^{th} player is $\mathbf{s_i} = \{k_{i,1}, \ldots, k_{i,c}, \ldots, k_{i,|C|}\}$, where $k_{i,c}$ is a binary value set to 1 if channel c is assigned to one of the player's radio, 0 otherwise, and $|C|$ is the number of channels for the channel set $\mathbf{C}$. The game profile is defined as the cartesian product of the players' strategy vector, $\mathbf{\Psi} = \times_{i \in \mathbf{A}} \mathbf{s_i} = \mathbf{s_1} \times \mathbf{s_2} \times \cdots \times \mathbf{s_N}$. Note that a game profile includes, one and only one strategy for each player. $\mathbf{s_{-i}}$ is specially defined as the strategy set chosen by all other players except player i.

The objective of the game is to maximize the network throughput. We define a joint metric M_i, for each player i, that correlates the links configuration and topology to a numerical value. This metric is directly proportional to the number of assigned links in each node. Each link capacity (transmission rate) is evaluated according to number of interfering links. Also two topology control factors, k and h, are included, since the network should not be evaluated only by its number of links but also how efficiently these links connects the MRs towards the GW, *i.e.* hop count.

$$M_i = k \frac{\sum_{j \in \mathbf{C}} \frac{R}{n_j}}{h} \tag{2}$$

where

– k is a connectivity factor set to 1 if the node is can indirectly reach the GW, 0 otherwise.
– R is the link data rate (Mbps).
– n is the number of interfering links.
– h is hop count from the node to the GW.

Finally, each player has its utility function dependent on its strategy and the other players' strategy $U_i(\mathbf{\Psi})$, and since we defined a cooperative game, the following holds and U_{NET} stands for utility of the network:

$$U_{NET}(\mathbf{\Psi}) = U_i(\mathbf{\Psi}) = \sum_{i \in \mathbf{A}} M_i, \forall i \tag{3}$$

Players will negotiate and change their interdependent strategies in $\mathbf{S}$ in order to achieve an optimal value for U_{NET}. Then two important issues arise: 1) whether they ever reach a consensus, or steady state 2) how efficient would be this steady state performance, if ever existent. The answers for these questions are the following:

In game theory, *Nash Equilibrium* is an important concept. The players will meet an agreement if NE exists. NE formal definition as in [16] is described bellow.

Definition 1. *strategy* $\mathrm{s}^* \in \mathbf{S}$ *is a Nash Equilibrium if*

$$U_i(\mathrm{s}^*) \geq U_i(\mathrm{s}_\mathbf{i}^{'}, \mathrm{s}_{-\mathbf{i}}) \ \forall \ \mathrm{s}_\mathbf{i}^{'} \in \mathbf{S}_\mathbf{i}, \forall i \in \mathbf{A} \tag{4}$$

According to this definition no player can benefit by deviating from its strategy if other player do not change hers[3]. In other words, this result guarantees an agreement for negotiations among players, although no optimal outcome or fairness is intrinsically guaranteed. Nevertheless, a specific type of game, denominated *potential games*, has very useful properties that address the outcome efficiency issue and the NE existence. For a potential game, the following holds:

- Every finite potential game possesses at least one pure strategy NE [17].
- All NE are either local or global maximizers of the utility function [17].
- There are well-known learning schemes to reach these function maximizers in the literature, namely *best response* and *better response* [2].

A potential game is defined as a game in which a *potential function* $P : \mathbf{S} \rightarrow \mathbf{R}$ exists

$$P(\mathrm{s}^{'}, \mathrm{s}_{-\mathbf{i}}) - P(\mathrm{s}^{''}, \mathrm{s}_{-\mathbf{i}}) = U_i(\mathrm{s}^{'}, \mathrm{s}_{-\mathbf{i}}) - U_i(\mathrm{s}^{''}, \mathrm{s}_{-\mathbf{i}}) \ \forall \ i, \mathrm{s}^{'}, \mathrm{s}^{''} \tag{5}$$

where $\mathrm{s}^{'}$ and $\mathrm{s}^{''}$ stands for two arbitrary strategies.

[3]According to game-theoretic conventions *players* should be referred to with *female* pronouns

Lemma 1. *CoCAG is a potential game.*

Proof: It is straightforward that the network utility function (3) itself is a potential function for CoCAG. For the process of identifying if a given utility function is a potential function, we have the following definition from [16]. A coordination game is defined when all users have the same utility function. That is to say, $U_i(\mathbf{\Psi}) = P(\mathbf{\Psi})$. Since CoCAG is a coordination game, we thus conclude that (3) is a potential function for this game. □ ■

Hence, we have:

$$P = U_i(\mathbf{\Psi}) = U_{NET}(\mathbf{\Psi}), \forall i \tag{6}$$

Making use of NE and potential games, we guarantee that our CoCAG will converge to an agreement among players and this point will be a utility function maximizer. In the literature, there are two famous learning schemes to accomplish this purpose, namely best response (7) and better response (8). In the former scheme, during her turn to choose a strategy to play, the player searches her entire strategy space and selects the one that yields the best outcome considering the other players' strategy. This scheme provides a fast convergence. On the other hand, it requires intensive processing that grows exponentially according to the number of players. In the latter scheme, during its turn, each player selects a random strategy and keep it as long as it generates a better outcome than the previous one. Thus, better response provides less intensive computation at the cost of a slower convergence to the equilibrium.

$$\mathbf{s_i^{t+1}} = \arg\max_{\mathbf{s_j} \in \mathbf{S_i}} U_i(\mathbf{\Psi}) \tag{7}$$

$$\mathbf{s_i^{t+1}} = \begin{cases} \mathbf{s_i^{\text{rand}}} & \text{if } U_i(\mathbf{s_i^{\text{rand}}}, \mathbf{s_{-i}}) > U_i(\mathbf{s_i^t}, \mathbf{s_{-i}}) \\ \mathbf{s_i^t} & \text{otherwise} \end{cases} \tag{8}$$

Nevertheless, the equilibrium may happen at the local optimum of the utility function, instead of the global optimum. In this case, the system performance will be trapped in a sub-optimal state and, since this is one NE, no player will be able to increase her utility function by changing her strategy.

We propose the following negotiation based algorithm that converges to NE. We assume identical MRs, and each of them has an unique identification parameter a_iID for routing purpose. In addition, we generalize the finalization criteria (T). The finalization criteria can be met following different parameters, few possibilities are exemplified. In this article we will employ the maximum number of negotiations as finalization criteria.

- maximum number of negotiations;
- timely limited;

- utility function threshold.

Algorithm 1 Near-optimal Partially Overlapping Channel Assignment (NPOCA)

$\mathbf{s_i} = \{0\}\ \forall a_i \in \mathbf{A}$
while $T =$ false **do**
    Randomly select a_i with prob. $1/N$
    $\mathbf{s_i^{rand}} \leftarrow$ random strategy $\{k_{i,1}, \ldots, k_{i,c}, \ldots, k_{i,|C|}\}$
    while $\mathbf{s_i^{rand}} \neq$ valid strategy **do** ▷ Examine Interference constraints
        $\mathbf{s_i^{rand}} \leftarrow$ random strategy
    end while
    if $\mathbf{s_i^{t+1}} > \mathbf{s_i^{t}}$ **then** ▷ Eq. (8)
        $\mathbf{s_i^{t+1}} \leftarrow \mathbf{s_i^{rand}}$
    else
        $\mathbf{s_i^{t+1}} \leftarrow \mathbf{s_i^{t}}$
    end if
    Broadcast $a_i ID$ + $\mathbf{s_i^{t+1}}$
    Update T
end while

Our algorithm has a distributed coordination and in order perform likewise the following mechanism should be met. The algorithm has two distinct steps, namely negotiation and operation phases. In the negotiation phase, all nodes operate using a common channel to exchange the messages, which guarantees the distributed coordination of the algorithm. This is necessary to avoid deafness problems, i.e., nodes trying to exchange control messages but, since they are operating in different channels, the message would not be detected by the destination nodes. During the negotiation phase, for each decision, in other words, selecting a strategy, the nodes have a conservative 200 ms window to broadcast their decisions. After the finalization criteria is met, the algorithm switches to operation phase. And just at this point, the nodes actually switch channels on the radios.

Consider the following scenario in order to illustrate the algorithm's execution. The scenario consists of a WMN backbone containing N MRs. As previously mentioned, during the negotiation phase all MRs should be assigned to a common channel, for instance, channel 1. Initially, all MRs set their strategy vector $\mathbf{s_i}$ to zero. Then the gateway will randomly calculate the sequence in which each MR will play its strategy, and broadcast it. During its turn, each MR will play the game following the better response learning scheme. In other words, a MR randomly selects one CA for its radios, $\mathrm{s_i^{rand}}$, and checks if $\mathrm{s_i^{rand}}$ will not cause adjacent channel interference considering the strategy of all other players or self-interference. In case this strategy causes interference, another random strategy should be selected. Then, a_i verifies if $\mathrm{s_i^{rand}}$ yields a higher value for the utility function (3) than the previous strategy, $\mathrm{s_i^{t}}$. In the affirmative case,

a_i will decide on the random strategy as his playing strategy ($\mathbf{s_i^{t+1}} \leftarrow \mathbf{s_i^{rand}}$), or it will remain with the previous strategy ($\mathbf{s_i^{t+1}} \leftarrow \mathbf{s_i^{t}}$), otherwise. Finally, a_i will broadcast its decision $\mathbf{s_i^{t+1}}$ to all other MRs. This loop of each player selecting an improving strategy or maintaining the previous one will occur until the finalization criteria T is met for the negotiations. Thereupon, all MRs will start the operation phase, in which they actually switch the channels on the radios according to the final selected strategy.

Other then having a distributed coordination function, note that NPOCA is also scalable and resilient. Negotiations to improve the network performance can restart whenever the algorithm is triggered. For instance, radio failure or addition of a MR. In case of failures, the strategy vector of each player should not be cleared to zero unless the failure caused a network partition. As for addition of MRs, there will be no necessity of clearing the strategy vector. By using the current CA when restarting the algorithm, a faster convergence can be achieved and there will be no deafness problem, since the MRs are already able to successfully send and receive broadcast messages.

V. Performance Evaluation

In this section, we evaluate the game theoretical CA that we will call from now on as NPOCA (Near-optimal Partially Overlapping Channel Assignment). We also add one more CA protocol called Hybrid Multi-Channel Protocol (HMCP) [18], which uses the non-overlapping CA, in order to compare our results. We evaluate both algorithms' performance using numerical analysis. The simulation scenarios were created using Java. A grid topology is constructed on the backbone.

A. NE and better response

In Fig. 1 we illustrate the negotiation process reaching the NE. This is a small topology containing just 5 nodes, we estimate the global optimum using a centralized brute force algorithm. The nodes were placed using a squared topology. Four nodes at the corners and one positioned at the center. The gateway is positioned at the corner to stimulate a multi-hop topology. MCS 6 Mbit/s is set as link data rate. After optimum estimation, we simulate NPOCA. We set T=50 iterations and repeat the simulation using 100 random seeds to calculate the average.

From the results depicted in Fig. 1 we can visualize the negotiation steps, in which the nodes are selecting random strategies. The utility function maintain its value when a random strategy yielded a worse channel strategy, since the nodes decide to maintain the previous strategy, as expected from eq. (8). The curve NPOCA_{100} represents the average after 100 simulations. Our algorithm is classified as near-optimal because although it sometimes reaches global-optimum, it may also generates sub-optimal results when node find themselves trapped in a local optimum NE.

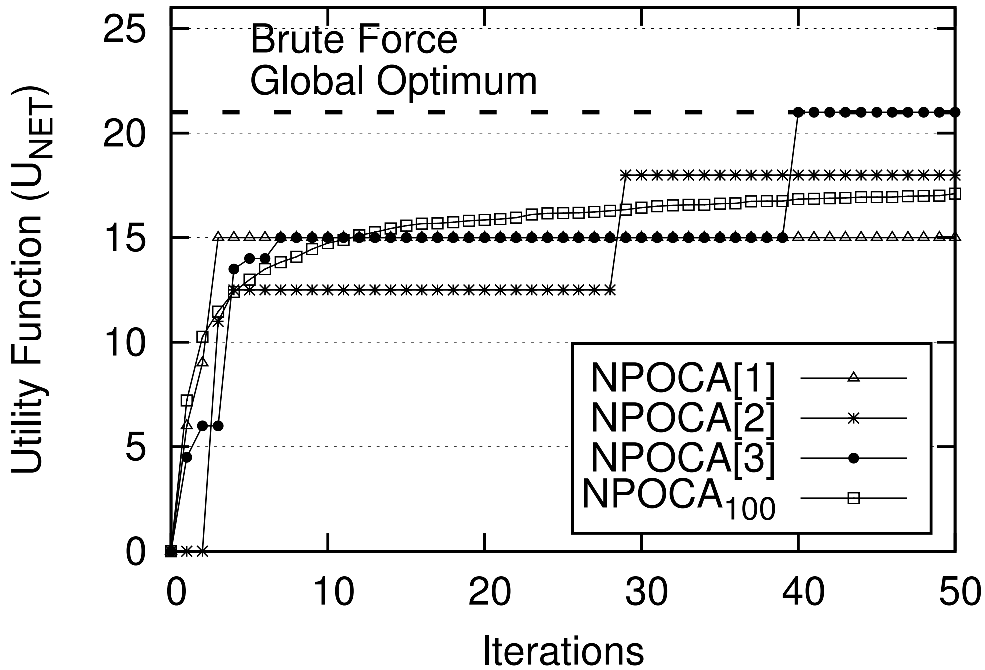

Fig. 1. NPOCA: 5 nodes topology

B. Random Topology

As mentioned previously in this work, the processing cost for the simulations exponentially increases with the number of players as a result of the exponential growth for existing game profiles (Ψ). Consequently, estimating the global optimum using brute force algorithm for topologies containing various nodes becomes unfeasible. However, considering the results from the five nodes topology, we can assume that the following results generated by NPOCA are near optimal channel assignments.

In this section, we evaluate NPOCA's performance in random topologies. In this scenario, nodes are randomly placed in a field with squared dimensions of 100, 200, 300 and 400 m. The gateway is also randomly selected, hence it can be positioned any where in the field which yields that at a given simulation the gateway might be distant from most of the other nodes in the backbone. This occurrence is severely minimized as the number of nodes increases. We simulate topologies containing 10, 15, 20, 25 and 30 nodes. Since these scenarios contain more nodes, we increase the iterations (T=100), but we maintain the 100 random seeds.

First we analyze the results from the node axis' perspective. From Fig. 2 we notice that when there are 5 player, a field size of 100x100 m yields the best performance, hence this was the better node density for this experiment. Once the field size increases the nodes become to sparse degrading the network performance due to (dis)connectivity issues. On the other hand, regarding this simulation parameters, the bigger the field, the better performance we can observe for 30 nodes. Analyzing the results from the field

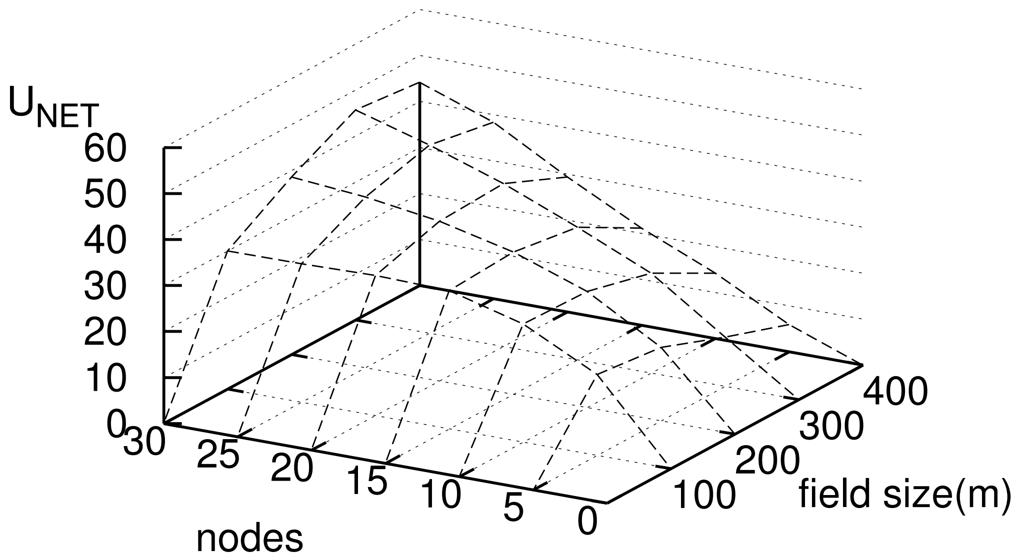

Fig. 2. NPOCA: random topology

size axis' perspective, we note that for 100 and 200 m, we reach a maximum desirable concentration of 20 nodes, since from this point on, increasing the number of nodes, do not increase the network overall performance. Although for 300 and 400 m field size, the network would improve its capacity if more nodes were added.

C. NPOCA and HMCP

In our last evaluation, we consider the improvements of our proposed CA against HMCP. In this scenario we use grid topologies to evaluate both protocols. The grid step is set to 120 m, which is the distance between adjacent nodes. The node positioned in the bottom right corner is assumed to be the gateway. MCS 6 Mbit/s is set as link data rate. In our experiments, we vary the grid size using 3x3, 3x4, 4x4, 4x5, and 5x5 arrangements that we will refer to as 9, 12, 16, 20, and 25 topologies, respectively. In this scenario we used T=100 and 100 random seeds.

In Fig. 3, we can notice a significant performance issue due to co-channel interference that occurs between nodes when HMCP is used. NPOCA, as expected, generates better results due to extensive negotiation iterations, in which at every iteration the nodes agree upon an improved CA topology. In addition, by using POCs, NPOCA is able to achieve a better spatial channel reuse factor compared to the traditional three orthogonal channels approach.

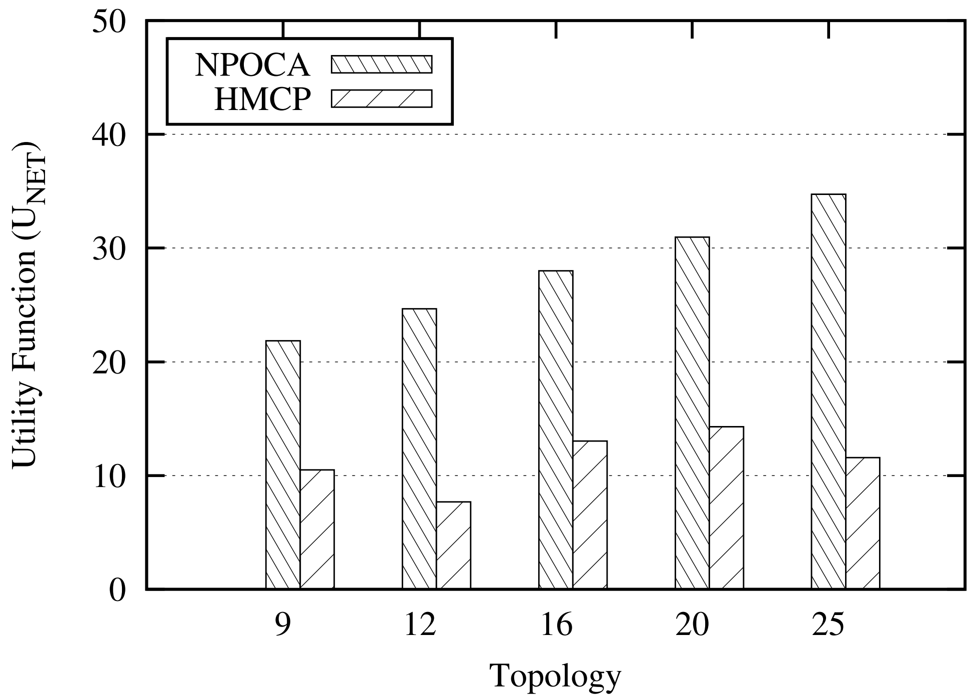

Fig. 3. NPOCA vs. HMCP: grid topology

VI. Conclusion

In this article, we developed a novel game-theoretical CA algorithm with near optimal performance for WMNs. In our algorithm, we exploited POC assignment following the latest research trends in the field. From the simulation results and analysis, we conclude that if well managed, overlapping channels can clearly overcome the overall performance of the common CA strategies using just the three orthogonal channels. Such improvements can be measured as network throughput, channel spatial re-use, non-interfering links.

Although our algorithm reaches near-optimal performance, it still can be improved. For example, in many simulations the algorithm reached low levels of performance, considering our utility function. One open issue in our research is how to devise a method to ensure that the nodes do reach these low level performance with very low probability during the strategy negotiation phase, hence our average performance would increase, approximating even more to the global optimum.

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