Channel Allocation in Multihop Wireless Networks Using MMCPNE

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Abstract- *Channel allocation was extensively investigated in the framework of cellular networks, but it was rarely studied in the wireless ad hoc networks, especially in the multihop networks. In this paper, we study the competitive multiradio multichannel allocation problem in multihop wireless networks in detail. We first analyze that the static non cooperative game and Nash equilibrium (NE) channel allocation scheme are not suitable for the multihop wireless networks. Thus, we model the channel allocation problem as a hybrid game involving both cooperative game and non cooperative game. Within a communication session, it is cooperative; and among sessions, it is non cooperative. We propose the min-max coalition-proof Nash equilibrium (MMCPNE) channel allocation scheme in the game, which aims to maximize the achieved data rates of communication sessions. We analyze the existence of MMCPNE and prove the necessary conditions for MMCPNE. Furthermore, we propose several algorithms that enable the selfish players to converge to MMCPNE. Simulation results show that MMCPNE outperforms NE and coalition-proof Nash equilibrium (CPNE) schemes in terms of the achieved data rates of multihop sessions and the throughput of whole networks due to cooperation gain.*

I. INTRODUCTION

WIRELESS communication system is often assigned a certain range of communication medium (e.g., frequency band). Usually, this medium is shared by different users through multiple access techniques. Frequency Division Multiple Access (FDMA), which enables more than one users to share a given frequency band, is one of the extensively used techniques in wireless networks. In FDMA, the total available bandwidth is divided permanently into a number of distinct sub bands named as channels. Commonly, we refer to the assignment of radio transceivers to these channels as the channel allocation problem. An efficient channel allocation is essential for the design of wireless networks In this paper, we present a game-theoretic analysis of fixed channel allocation strategies of devices that use multiple radios in the multihop wireless networks. Static Non cooperative game is a novel approach to solve the channel allocation problem in single-hop networks, and Nash equilibrium (NE) provides an efficient criterion to evaluate a given channel allocation. Hence, we introduce a hybrid game involving both cooperative game and non cooperative game into our system in which the players within a communication session are cooperative, and among sessions, they are non cooperative.

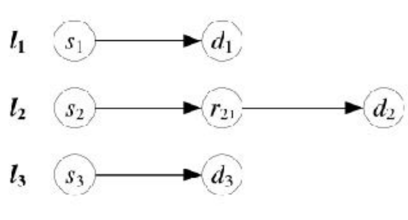
We also define three other equilibria schemes that approximate to MMCPNE, named as minimal coalition-proof Nash equilibrium (MCPNE), average coalition-proof Nash equilibrium (ACPNE), and I coalition-proof Nash equilibrium (ICPNE), respectively. Then, we study the existence of MMCPNE in this game and main result, Theorem 2, shows the necessary conditions for the existence of MMCPNE. Furthermore, we propose the MMCP algorithm which enables the selfish players to converge to MMCPNE from an arbitrary initial configuration and the DCP-x algorithms which enable the players converge to approximated MMCPNE states (e.g., MCPNE, ACPNE, and ICPNE). Finally, we present the simulation results of the proposed algorithms, which show that MMCPNE outperforms NE and coalition-proof Nash equilibrium (CPNE) channel allocation schemes in terms of the achieved data rates of multihop sessions and the throughput of whole networks due to cooperative gain present the simulation results of previous algorithms

II. RELATED WORK

There has been a considerable amount of research on channel allocation in wireless networks, especially in cellular networks. Three major categories of channel allocation schemes are always used in cellular networks: fixed channel allocation (FCA), dynamic channel allocation (DCA), and hybrid channel allocation (HCA) which is a combination of both FCA and DCA techniques. In FCA schemes, a set of channels is permanently allocated to each cell in the network. general, graph coloring/labeling technique provides an efficient way to solve the problems of fixed channel allocation. FCA method can achieve satisfactory performance under a heavy traffic load; however, it cannot adapt to the change of traffic conditions or user distributions. To overcome the inflexibility of FCA, many researchers propose dynamic channel allocation methods .In DCA schemes, in there is no constant relationship between the cells and their respective channels. All channels are potentially available to all cells and are assigned dynamically to cells as new calls arrive in. Because of its dynamic property, the DCA method can adapt to the change of traffic demand. However, when the traffic load is heavy, DCA method performs worse than FCA due to some cost brought by adaptation. Hybrid channel allocation schemes are the combination of both FCA and DCA techniques. In HCA schemes, the total number of available channels are divided into fixed and dynamic sets.

The fixed set contains a number of nominal channels that are assigned to the cells as in the FCA schemes, whereas the dynamic set is shared by all users in the system to increase flexibility. Recently, channel allocation problem is becoming a focus of research again due to the appearance of new communication technologies, e.g., wireless local area networks (WLANs), wireless mesh networks (WMNs and wireless sensor networks (WSNs).Using weighted graph coloring method, Mishra et al. propose a channel allocation method for WLANsin, InWMNs, many researchers have considered devices using multiple radios. Equipping multiple with radios in the devices in WMNs, especially the devices acting as wireless routers, can improve the capacity by transmitting over multiple radios simultaneously using orthogonal channels. In the multiradio communication context, channel allocation and access are also considered as the vital topics. By joint considering the channel assignment and routing problem.

In the above cited work, the authors make the assumption that the devices cooperate with the purpose of the achievement of high system performance. However, this assumption might not hold for the following two reasons. In one hand, players are usually selfish who would like to maximize their own performance without considering the other players' objective. In the other hand, the full cooperation of arbitrary devices is difficult to achieve due to the transmission distance limitation and transmission interference of neighboring devices.



Game theory provides a straightforward tool to study channel allocation problems in competitive wireless networks. As far as know, game theory has been applied to the CSMA/CA protocol to the Aloha protocol and the peer-to-peer (P2P) system. Furthermore, on the basis of graph coloring, Halldorsson et al. use game theory to solve a fixed channel allocation problem. Unfortunately, their model does not apply to multiradio devices. In wireless ad hoc networks (WANETs), using a static non cooperative game.

However, their results can be only applied to single-hop wireless networks without considering multihop networks. In this paper, we extend the results to the wireless networks with arbitrary hops.

III. SYSTEM MODEL AND GAME FORMULATION

3.1 System Model

We assume that the available frequency band is divided into M orthogonal channels of the same bandwidth using the FDMA method (e.g., 24 orthogonal channels in case of the IEEE 802.11a protocol). In our model, we assume that there exist L communication sessions,1 including multihop and single-hop sessions. We further assume that each user participates in only one session, either being a ending user or a relaying user, and thus, we can divide all users into L disjoint groups.

We assume that all sessions reside in a single collision domain, which means that each session will interfere the transmission of all other sessions if they are using the same channel. Note, however, that the users within a session may reside in different collision domains, e.g., in a multihop session. We assume that each user owns a device equipped with two independent sets of radio transceivers, which used to transmit and receive the data packets, respectively. Each transceivers set contains K <jCj radio transceivers, all having the same communication capabilities. 2 We assume that the communication between two users is bidirectional and they always have some packets to exchange.

Due to the bidirectional communication, transmitter's and receiver's are able to coordinate, and thus, to select the same channels to communicate. We assume that there is a mechanism that enables the multiple radios with transceivers set to communicate simultaneously by using orthogonal channels. We further assume that the total available bandwidth on channel c is shared equally among the radios using that channel. This fair rate allocation is achieved, for example, by using a reservation- based TDMA schedule on a given channel. Even if the radio transmitters are controlled by selfish users in the CSMA/CA protocol, they can achieve this fair sharing.

3.2 Game Formulation

We refer to each communication link as a selfish player. A communication link is defined as a direct connection of two users. It is obvious that each N-hop session contains N links and each link contains K pairs of radios. In the example of Fig. 1, there are four communication links, i.e., s1 $ d1, s2 $ r21 , r21 $ d2, and s3 $ d3, where i $ j denotes a direct connection of users i and j. For the simplicity of presentation, we rewrite player as the user at left-hand side of the link. Thus, the players set, denoted by U, can be defined as the set of all senders and relaying users. We denote the number of radios of player i using channel c by ki;c for every c 2 C. We further denote the set of channels used by player i by Ci. For the sake of suppressing coradios interference in device, we assume that the different radios within a transceiver set cannot use the same channel, i.e., ki;c 2 f0; 1g for arbitrary player i 2 U and channel c 2 C. Each player's strategy consists of the number of radios on each of the channels.

IV. NASH EQUILIBRIA

4.1 Non cooperative Game NE

In single-hop networks, the payoff of player i is equivalent to its utility Ri and the multiradio channel allocation problem can be formulated as a static non cooperative game.

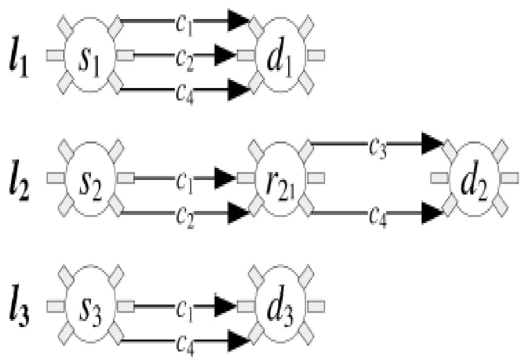


TABLE 1
Notations

I	The set of communication sessions (sessions)
G	The set of player groups, each corresponding to a communication session
Q	The set of coalitions, each corresponding to a communication session
S, R, D	The set of all senders, relaying users and destinations, respectively
U	The set of players in game, i.e., $\mathbf{U} = \mathbf{S} \bigcup \mathbf{R}$
Ψ_t, Ψ_r	The sets of transceiver radios in each device, each contains K radios
$\mathbf{C}^+, \mathbf{C}^-$	The set of channels choosed by relatively more players and less players, respectively
δ^+, δ^-	The number of radios deployed on the channel in $\mathbf{C}^+$ and $\mathbf{C}^-$, respectively
$k_{i,c}$	The number of radios of player i deployed on channel c
k_b, k_c	The total number of radios deployed on channel b and c, respectively, i.e., $k_c = \sum_i k_{i,c}$
k_i	The total number of channels used by player i, i.e., $k_i = \sum_c k_{i,c}$
k_i^+, k_i^-	The number of radios of player i deployed on $\mathbf{C}^+$ and $\mathbf{C}^-$, respectively
$R_{i,c}$	The bandwidth occupied by player i on channel c
R_i	The total bandwidth (utility) occupied by player i
R_i^e	The end-to-end rate (payoff) of player i
$\delta_{b,c}$	The difference of radios umber between channel b and c

4.2 Cooperative Game CPNE

In single-hop networks, the payoff of player i is equivalent to its utility Ri and the multiradio channel allocation problem can be formulated as a static non cooperative game. In order to study the strategic interaction of the players in such a game, we first introduce the concepts of Nash equilibrium.

Definition 1 (NE). The strategy matrix XX_ ¼ fx_ 1; . . . ; x jUjg defines a Nash Equilibrium, if for every player i 2 U, we have

$$R_i\left(\mathbf{x}_i^*, \mathbb{X}_{-i}^*\right) \geq R_i\left(\mathbf{x}_i', \mathbb{X}_{-i}^*\right),$$

for every strategy x0 i, where RiðXXÞ denotes the utility of player i in strategy matrix XX. The definition of NE expresses the resistance to the deviation of a single player in non cooperative game. In other words, in an NE, none of the players can unilaterally change its strategy to increase its payoff. An NE solution may be inefficient from the system point of view. We characterize the efficiency of the solution by the concept of Pareto optimality.

Definition 2 (Pareto Optimality). The strategy matrix XXop is Pareto-optimal if there does not exist any strategy XX0 such that the following set of conditions is true:

$$R_i(\mathbb{X}') > R_i(\mathbb{X}^{op}), \quad \forall i \in \mathbf{U},$$

This means that in a Pareto-optimal channel allocation XXop, one cannot improve the payoff of any player without decreasing the payoff of at least one other player.

Definition 3 (CPNE). The strategy matrix XXcp defines a coalition-proof Nash Equilibrium, if for every coalition _x 2 Q, we have

$$R_i(\mathbb{X}^{cp}_{\sigma_x}, \mathbb{X}^{cp}_{-\sigma_x}) \geq R_i(\mathbb{X}'_{\sigma_x}, \mathbb{X}^{cp}_{-\sigma_x}), \quad \forall i \in \sigma_x$$

for every strategy set XX0

This means that no coalition can deviate from XXcp such that the utility of at least one of its members increases and the utilities of other members do not decrease.

Definition 4 (MMCPNE). The strategy matrix XXmm defines a novel coalition-proof Nash Equilibrium, if for every coalition _x 2 Q, we have

$$\min_{i\in\sigma_x} R_i\left(\mathbb{X}^{mm}_{\sigma_x}, \mathbb{X}^{mm}_{-\sigma_x}\right) \geq \min_{i\in\sigma_x} R_i\left(\mathbb{X}'_{\sigma_x}, \mathbb{X}^{mm}_{-\sigma_x}\right)$$

for every strategy set XX0

Definition 5 (MCPNE).

The strategy matrixXXm defines a special coalition-proof Nash Equilibrium, if for every player.

$$\min_{u\in\sigma_x} R_u\left(\mathbf{x}^m_i, \mathbb{X}^m_{-i}\right) \geq \min_{u\in\sigma_x} R_u\left(\mathbf{x}'_i, \mathbb{X}^m_{-i}\right)$$

for every strategy x0 i, where _x is the coalition player i belongs to, i.e., i 2 _x

Definition 6 (ACPNE).

The strategy matrix XXa defines a special coalition-proof Nash Equilibrium, if for every player.

Definition 7 (ICPNE).

The strategy matrix XXs defines a special coalition-proof Nash Equilibrium, if for every player i 2 U, we have

$$\min_{u\in\sigma_x} R_u\left(\mathbf{x}^s_i, \mathbb{X}^s_{-i}\right) > \min_{u\in\sigma_x} R_u\left(\mathbf{x}'_i, \mathbb{X}^s_{-i}\right)$$

Obviously, players within a coalition can select their strategies independently to achieve the above three approximated MMCPNE situations, and thus, the computations increase linearly to the size of coalition.

	x_i^1	x_i^2	x_i^3	x_i^4	x_i^5	x_i^6
R_i	2	1.5	1	1	0.5	0.5
R_j	1	0.5	3	2.5	5	0.5

Fig. 4. The resulting utility for player i choosing xni

or

$$\begin{cases} \min_{u\in\sigma_x} R_u\left(\mathbf{x}^s_i, \mathbb{X}^s_{-i}\right) = \min_{u\in\sigma_x} R_u\left(\mathbf{x}'_i, \mathbb{X}^s_{-i}\right) \\ R_i\left(\mathbf{x}^s_i, \mathbb{X}^s_{-i}\right) \geq R_i\left(\mathbf{x}'_i, \mathbb{X}^s_{-i}\right) \end{cases}$$

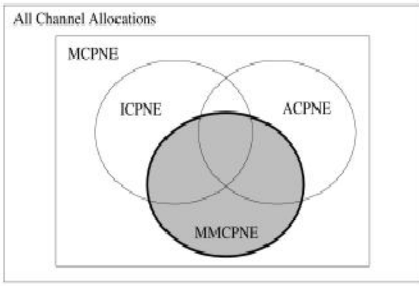
.

for every strategy x0i.

Nash equilibrium with a judiciously designed objective function, rather than coalition-proof Nash equilibrium of cooperative game. We show the difference of MCPNE, ACPNE, and ICPNE by an example of two-player coalition . Without loss of generality, we assume that there are six strategies for player. and the resulting utility for selecting one of the strategies. For MCPNE, each player would like to choose the strategy which maximizes the minimal utility of players within the coalition, and thus, the best strategies for player. While for ACPNE, each player would like to choose the strategies which maximize the minimal utility and further maximize the average utility of players within the coalition. Similarly, for ICPNE, each player would like to choose the strategies which maximize the minimal utility and further maximize its own utility. Thus, for ACPNE and ICPNE, the best strategies of player. In order to provide an intuitionistic impression, we show the previous channel allocation schemes by properties. The fact of MMCPNE being a subset of MCPNE can be proved by contradiction as follows: Assume that there exists an MMCPNE strategy matrix XXmm which is not an MCPNE, then according to Definition 5, there exists at least one player (say i) who can improve the minimal utility of its coalition (say x) by changing its strategy, which implies that there exists a coalition, i.e., x, that can improve the minimal utility of its members by changing its member i's strategy. According to Definition 4, XXmm cannot be an MMCPNE, which leads to a contradiction. Thus, we declare that an MMCPNE must be an MCPNE.

V. EXISTANCE OF MMCPNE

In this section, we study the existence of Nash equilibria and min-max coalition-proof Nash equilibria in the single collision domain channel allocation game. It is straightforward to see that if the total number of radios is smaller than or equal to the number of channels, then a flat channel allocation, in which the number of radios per channel does not exceed one, is a Nash equilibrium.



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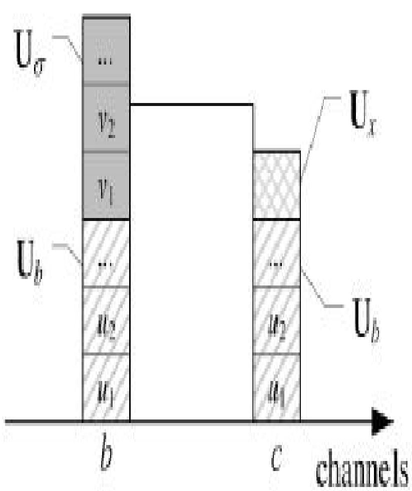
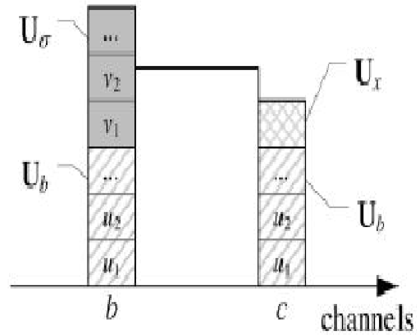
5.1 NE in Multihop Networks

The first condition shows that a player cannot assign two radios with the same channel due to the coradios interference in device, and the second condition shows that a selfish player would like to use all of his radios in order to maximize his total bandwidth. The first two conditions provide the necessary conditions for NE from the aspect of individual players. The third condition shows that the whole system will achieve load-balancing over the channels in an NE. The third condition provides the necessary condition for NE from the aspect of whole system. We divide the channels in NE into two sets: Cþ, which contains the channels selected by relatively more players which contains the channels selected by relatively less players. We denote the number of radios deployed on the channel.

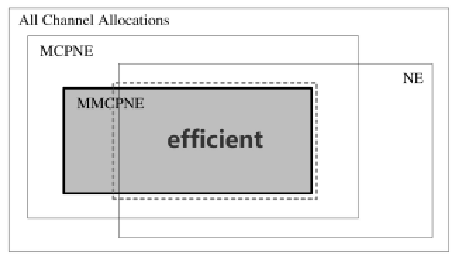
Fig. 6. An example of MMCPNE channel allocation corresponding to Proposition.





However, that Nash equilibrium is not suitable for the multihop wireless networks as mentioned previously.

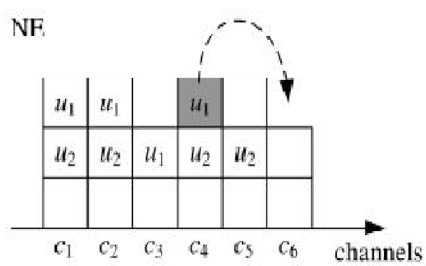
Fig. 7. Summary of MMCPNE and NE channel allocations with different properties.

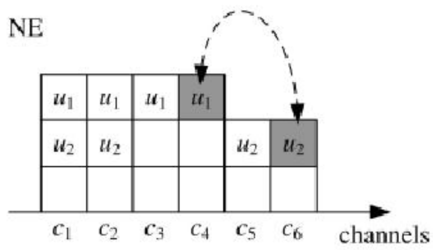


5.2 MMCPNE in 2-Hop Networks

In this section, we study the MMCPNE in short-path networks in which each session contains at most 2 hops, i.e., each coalition contains at most two players. It is easy to see that all players in 2-hop networks reside in a single collision domain. Although none of the players can unilaterally change its strategy to increase its payoff in NE, it is possible that a player changes its strategy to improve the utility of another player he is in a coalition with, e.g., u1 and u2 in Fig. 3.

Fig. 8. An example of NE channel allocation





5.3 MMCPNE in N-Hop Networks

In this section, we study the MMCPNE in long-path networks in which at least one session contains N >2 hops. We will show that through the judiciously designing of scheduling scheme, the existence of MMCPNE in N-hop networks can be transformed into the problem in 2-hop networks.

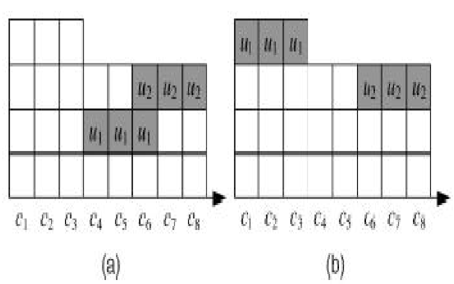
Fig. 10. An example of a 3-hop communication session.

VI. SIMULATION RESULTS

6.1 Simulation Setup

We implemented the previous algorithms in MATLAB and with a special focus on wireless IEEE 802.11a protocol. For multiradio device, the adjacent 802.11a channels interfere in practical communication (although they are theoretically orthogonal), but nonadjacent channels do not interfere.

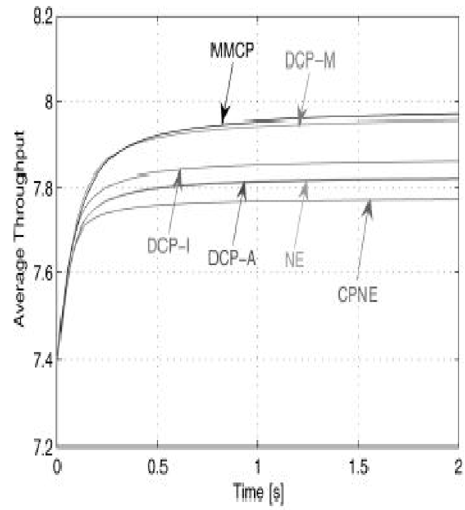
Fig. 11. An example for (a) a best case and (b) a worst case of NE channel allocation in terms of the payoff of coalition _x ¼ fu1; u2g, where
jCj ¼ 8, jUj ¼ 9, and K ¼ 3.



6.2 Performance of Networks

We investigate the performance of the whole networks in different equilibrium states. To evaluate the performance of the networks, we introduce the concept of networks throughput.

Fig. 17. Average throughput versus time using W ¼ 15, jCj ¼ 8, jUj ¼ 5, K ¼ 4, and _x ¼ fu1; u2g.



VII. CONCLUSION

In this paper, we have studied the problem of competitive channel allocation among devices which use multiple radios in the multihop networks. We first analyze that NE and CPNE channel allocation schemes are not suitable for the multihop networks due to the poor performance of achieved data rate of the multihop sessions. Then, we propose a novel coalition-proof Nash equilibrium, denoted by MMCPNE, to ensure the multihop sessions to achieve high data rate without worsening the performance of single-hop sessions. We investigate the existence of MMCPNE and propose the necessary conditions for the existence of MMCPNE. Finally, we provide several algorithms to achieve the exact and approximated MMCPNE states. We study their convergence properties theoretically. Simulation results show that MMCPNE outperforms CPNE and NE schemes in terms of the achieved data rates of multihop sessions and the throughput of whole networks due to cooperation gain.

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