Throughput Enhancement for Wireless Networks using Coalition Formation Game

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Abstract

With the limited wireless spectrum and the ever-increasing demand for wireless services, enhancing the wireless network throughput is pressing. Coalition formation game as the state-of-art of game theory is proposed to deal with the issue. In this report, we first survey the applications and advantages of game theory in wireless networks researching, and then introduce the coalitional game theory, and then formulate a practical throughput enhancing problem using the coalition formation game. The preliminary results provide the insight of transmission coalition formation under interfering environment and show the correctness of the formulation.

1 Introduction

Wireless networks are everywhere in our life, from the daily used cell phones, to the secured communications on the battlefield; from the micro sensor networks, to the marco satellite communications; from high speed Ultra-Wide Band (UWB) networks, to ultra long distance planet area wireless communications. [1] The study of wireless communications have been carried out for more than a century. Various methods have been used to analyze the wireless networks, including optimization theory, control theory, information theory, game theory etc. [2]

The throughput of a wireless network is a key metric of the network performance. A higher throughput often means a lower transmission latency and a smaller transmission error probability or a higher transmission quality. Improving the network throughput is widely recognized as a very important research topic for wireless networks.

In most previous studies, the main concern is to enhance the performance of wireless networks under a central controller [3]. Take cellphone cellular system as an example, the base station of a cell acts as the central controller or scheduler of the cell. The base station knows the information of every channel between the base station and the cellphone user and allocate resources based on the global information of the cell. In this case, optimization methods are good tools to optimize the performance of the network such as the network throughput and communication delay. However, in practice, it is very difficult if not impossible to know the channel information of all users. In addition, even all the channel information are known by the central controller, the optimization results show that users with poor channel conditions are allocated with

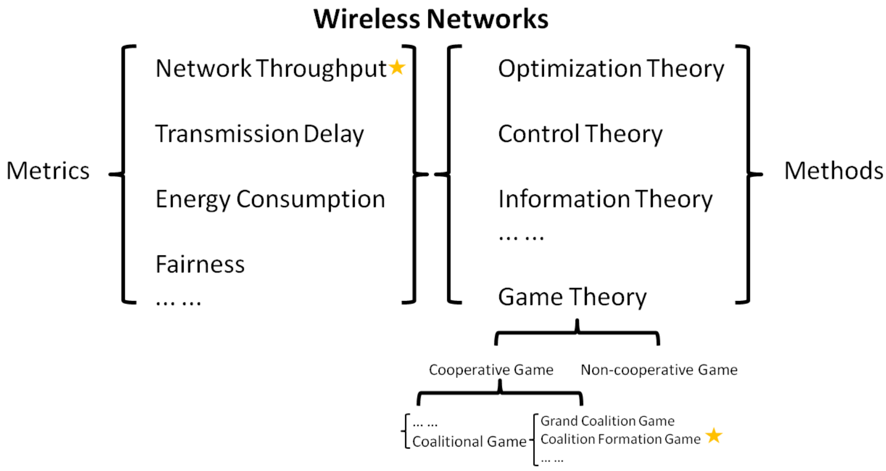

Figure 1: Wireless Networking Research Topics Structure

much less resources in order to optimize the performance of the whole network. It is unfair to the cellphone user with poor channel condition as a self-interest maximizer.

Game theory, as a very useful mathematical theory and tool, has been developed for over 60 years. Game theory provides a formal analytical mathematical frameworks for a large number of areas ranging from engineering, economics, political science, philosophy, etc. [2] In the area of wireless communication networks, game theory is playing a more and more important role in the analysis of the increasing portion of autonomous, distrbuted and mobile wireless networks. Because in such networks, all communication nodes can be modeled as a self-interest agents. These nodes have to share a limited transmission resource that imposes a conflict of interests. To resolve this conflict, the communication nodes can make certain decisions such as transmitting now or later, changing the transmission channel, or adapting their transmission rate and power. [4] The interaction of all the communication nodes can be modeled as games, and can be analyzed with game theory. [5] One of the the benefits of using game theory to analyze is that each agent (communication node) usually only needs to know the local information to make inependent and rational decisions. The feature makes it possible to use low-complexity distributed algorithms to analyze and enhance the performance of wireless communication networks.

We can divide game theory into two branches in general: non-cooperative game theory and cooperative game theory. In non-cooperative game, the players have potentially conflicting interests. Each player aims at improving its own utility. Most part of game theory we studied in the course CPSC532L is for non-cooperative games. Several solution concepts exist such as the famous Nash equilibrium. Most of the existing work for communication networks used non-cooperative games to deal with problems such as power control, resource allocation and spectrum sharing. [6, 7, 8] The advantage of using non-cooperative game theory to analyze communication problems is as follows. In non-cooperative games, each player (communication node) only considers how to maximize his/her own utility. The assumption of pure competing relation among all player makes the problem relative simple to analyze. The user-level fairness is improved. However due to the pure competing relasionship among players, the global optimum may be less likely to be achieved and the system-level performance may be degraded.

Cooperative game theory studies the actions of rational players when they cooperate. In cooperative game, the group of cooperated players form a coalition, the game becomes a competition among coalitions of players (e.g. communication nodes), rather than among individual players. The name of such major cooperative game is coalitional game. Coalitional games have been in different areas as well, such as economics or political science. The idea of cooperation in wireless networks design is a very hot topic recently. Cooperations bring benifit more than cost. The idea of using coalitional game in wireless networks analysis and design is proved to be powerful. [9, 10, 11, 12]

In this report, we first briefly introduce the research of wireless networks and the applications of using cooperative and non-cooperative game theory to analyze wireless networks. In chapter 2, we will introduce the basic concept of coalitional game and its applications in wireless network research. In chapter 3, we focus on the specific type of coalitional game-coalition formation game. In chapter 4, we show the basic idea of using coalition formation game to enhance the network throughput. In chapter 5, we show the analytical result of throughput improvement of using coalition formation game. In Chapter 6, the conclution and future work is stated.

2 Coalition Formation of Coalitional Game

A coalitional game consists of a finite set of players in total, denoted by $\mathcal{N}$. Each player in the game can choose to form a coalition with other players in the game. If the player choose no other player to form a coalition, the player itself is a coalition. Assume we have a coalition $\mathcal{S}$, and the member of $\mathcal{S}$ is a subset of $\mathcal{N}$, i.e. $\mathcal{S} \subseteq \mathcal{N}$. We can define the value of the coailtion $\mathcal{S}$ as $v(\mathcal{S})$. A coalitional game with $\mathcal{N}$ players and defined coalition value v can be represented as coaltional game $G(\mathcal{N}, v)$.

We can divided a coalitional game into Transferable Utility Coalitional Game (TUCG) or Non-transferable Utility Coalition Game (NTUCG). For Transferable Utility Coalition Game, it means that the measure of each player is the same and the utility of a coaltion can be freely distributed among all the players in the coalition. It also means that just a single value is needed to represent the utility of a coalition. In many scenarios, it is reasonable to assume that utillity is transferable. In the scenario of my work of improving the network throughput, it is also reasonable to assume that the utility is transferable since the transmission rate of wireless transmission depends on the transmission bandwidth. The transmission bandwidth can be distributed freely among all communication nodes in the network like money. Therefore, we assume the coalitional game in the rest of the report is utility transferale coalitional game.

The next questions are which coalition should be formed. To answer the question, we can first recheck the motivation of forming coaltions in a coalitional game. That is to improve the coalition utility by cooperating with other players in the game. Therefore, we can say that a coaltion will form if the coalition utility is improved by forming the coaltion. Otherwise, the coaltion will not form. Before introducing the important solution concept for grand coalitional games–the core, we need the defintion of the superadditive game. A game $G(\mathcal{N}, v)$ is superadditive if for all $\mathcal{S}, \mathcal{T} \subset \mathcal{N}$, if $\mathcal{S} \bigcap \mathcal{T}$ = $\emptyset$, then $v(\mathcal{S} \bigcup \mathcal{T}) \geq v(\mathcal{S})$+$v(\mathcal{T})$. The meanning is that if a game is superadditive, the added value of any subset coalition is equal or greater than the summation of the value of all the subsets. Therefore, if a game is superadditve, the value of the grand coalition with all players in it is greater than the added value of other formation of the coalition. Thus, the players have an incentive to form the grand coalition with all player in the coalition. By definition, a payoff vector x is in the core of a coalitional game $G(\mathcal{N}, v)$ if and only if $\forall \mathcal{S} \subset \mathcal{N}$, $\Sigma x_i \geq v(\mathcal{S})$. According to the definition, the core is the set of utility allocations that guarantees that no group of players has an incentive to leave the grand coalition to form another coalition. So far, the question which coalition will form for the superadditive game has been answered, that is the grand coalition achieves the greatest coalition value if the core is not empty.

However, intresting enough, when the game is not superadditive, the grand coalition is no more the solution of the coalitional game. The property of superadditive can be justified if the players are always independent to each other. We can see that the worst case of having a new player in the coalition is that the new player doesn't cooperate, in this case, if the players are independent, non-cooperative players bring zero value and the superadditivity remains. However, if the coalition value is not independent to other players or coalitions in the game, similar to the situation that the transmission rate of wireless communication link is interferenced by other communication nodes, the game is not superadditive and the value of grand coalition can be smaller than some subset coalitions. In this case, a new kind of coalitional game need to be introduced–the coalition formation game.

Different from grand coalitional games, a coalition formation game is not superadditive in general and the optimal coalition is not the grand coalition. The key problem of coalition formation game is to study how to form and stablize the coalitions other than the grand coalition. There is usually cost that is not negligible when forming a coalition. [13, 14] When the cost of having new players in the coalition is greater than the benifit the new players bring, forming a new coalition with the new players will degrade the value of the former coalition, so that the new coalition should not be formed. Several papers talk about the merge and spilt rule of the coalition formation with dynamic algorithms. The basic idea is to check the coalition's utility if merge or spilt, merge if the utlity is increased, spilt if the utility decreased.

3 Throughput Enhancement using Coalition Formation

In this section, we introduce the sytem model of our problem and formulate the problem as a coalition formation problem.

The objective is to use coalition formation formulation to enables the communication nodes to cooperate, by forming coalitions, and enhance the network throughput by minimizing their mutual interference within each coalition

We consider a network with $2N$ active nodes randomly deployed in a square area. N nodes are saturated senders belong to set S, and the rest are receivers belong to set R.

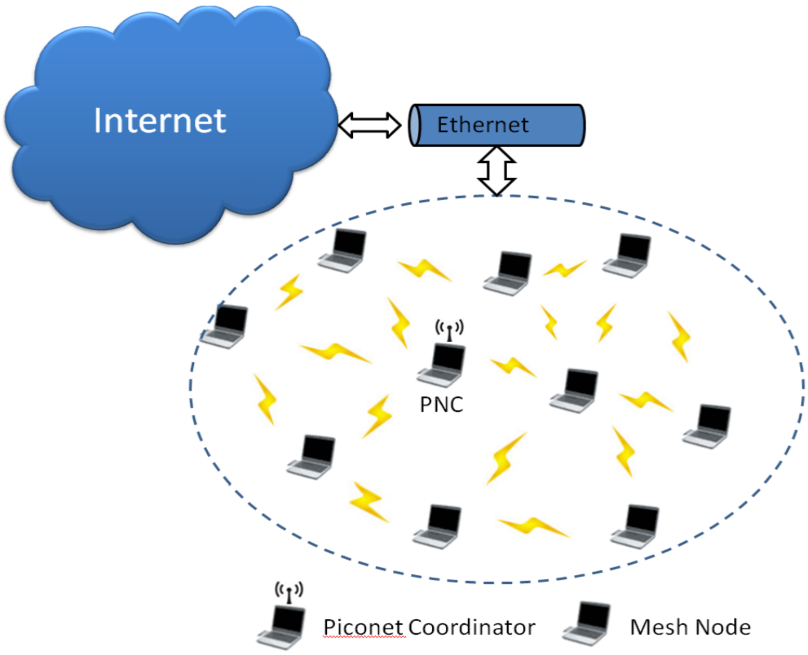

Figure 2: Piconet network structure for coalition formation

The i-th sending node $s_i \in S$ and the i-th receiving node $r_i \in R$ form a transmission pair (s_i, r_i) for flow i. The sender-receiver association does not change during the coalition formation and transmission period. The above mesh network setting can be observed in many occasions, such as in home networks and wireless access networks.

We follow the IEEE 802.15.3a standard, which is the standard for Ultra-wideband (UWB) Wireless Personal Area Network (WPAN). According to the standard, wireless devices can autonomously form a piconet. One node is selected as the piconet coordinator (PNC). Resource allocation in the piconet is based on a superframe structure. Each superframe begins with a Beacon Period (BP) for network synchronization and control message broadcast. The BP can be used as coalition formation period. After the BP, the communication coalition is fixed and devices use the carrier sensing multiple access/collision avoidance (CSMA/CA) MAC protocol to send request to PNC during the contention access period (CAP). The remaining channel time of the superframe is the contention-free channel time allocation period (CTAP) for data transmission. During CTAP, we let transmission links in each coalition share the coalitional subband and transmit in a time division manner.

Regard the coalition formation game as $G(\mathcal{N}, v)$, where the N transmitters are the players of the game. and v is the value of a coalition. For a coalition $\mathcal{S}$, the value $v(\mathcal{S})$ represent the total network throughput of the coalition. According to the famous Shannon theory in wireless communication, the total throughput of the coalition $\mathcal{S}$ is given as follows,

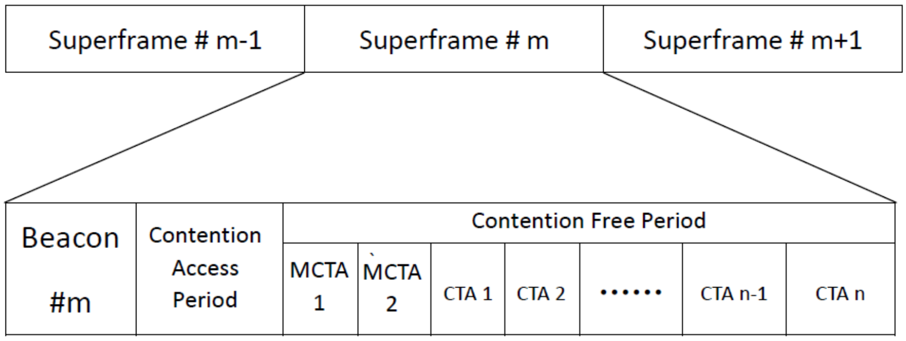

Figure 3: 802.15.3 superframe structure

$$v(\mathcal{S}) \quad = \sum_{i=1}^{S} R_i(\boldsymbol{P}) = \sum_{i=1}^{S} \eta W \cdot \log_2(1 + \frac{P_i \kappa G d_{i,i}^{-\gamma}}{N_0 + b\sum_{j\neq i} P_j \kappa G d_{j,i}^{-\gamma}}),$$

where W is the allocated bandwidth, $\eta \in (0, 1)$ is a coefficient describing the efficiency of the transceiver design, P_i is the transmission power of s_i, the G represents the fading gain, $d_{i,i}$ is the distance between s_i and r_i, N_0 is the background noise power. We assume that with-in a coalition, the interference item is negligible since the time division scheduling.

Note that the cost of form a coalition is not counted above. [15, 16] The cost of using power to transmit coalition formation information from the communication node to the farest node in the coalition is P, if the power is greater than the maximal power allowed, we need to set the value of the coalition as

$$v(\mathcal{S}) = 0 \tag{1}$$

In a coalitional game, we also need to consider the utility x_i of a single player i. Since we assume that the utility is transferable in the wireless networks, in this problem, we use the Egalitarian Fair method for utility division. That is, the extra value given by the coalition formation is equally distributed among the players in the coalition. Therefore, the uility of the player i can be represented as follows,

$$x_i(S) = \tfrac{1}{S}\left(v(\mathcal{S}) - \textstyle\sum_{j\neq i} v\{j\}\right) + v\{i\} \tag{2}$$

Up to now, we have formulated the throughput enhance problem as a coalition formation game. We have given the value of the coalition as the total throughput of the coalition and the utility of each player (communication node) in the coalition. By solving the coalition formation problem, we are supposed to get the optimal coalition formation that each coalition maximized its own throughput.

4 Preliminary Results and Discussion

In this section, the preliminary results are shown and some thoughts and discussions are presented.

Intuitively, the solution of the coalition formation problem formulated in the last section is not the grand coalition. Because the utility becomes zero when the coalition forming cost (the power to exchange coalition information) is larger than the maximum power allowed. A method developed by [] using the novel concept of recursive core is able to solve the kind of coalition formation problem. It's really a pity that due to the time limitation, the coding job I tried to implement still has some problem to accomplish the goal of the algorithm. To verify the correctness and effectiveness of the problem formulation, I tried to form the coalitions manually by computing the value of all possible coalition combinations under the following simple scenario. Three communication pairs are in a network, two of them are very close and one is far away from the other two comunication pairs. The result shows that when the near two forms a coalition, and the other one forms a coalition, the summation of coalition value is maximized. The result shows that the transmission pairs which introduce strong interference to each other forms a coalition. The insight agrees with a great amount of insights in previous literature and verified the correctness of the problem formulation. Of course, further algorithm implementation and simulation is needed.

5 Conclusion and Future Work

In this course project, I mainly accomplished three tasks. Firstly, I surveyed the applications and advantages of game theory in wireless networks researching. Secondly, I learned the knowledge of the cooperative (coalitional) game theory besides the non-cooperative game theory we learned in class. Finally, I used the state-of-art coalition formation game theory to formulate a practical throughput enhancing problem that is non-superadditive and verified the correctness of the formulation.

There are a great amount of very interesting work to do in the future, including finishing the implementation of the recursive-core algorithm and considering about more accurate channel model. The computational complexity of finding the optimal coalition formation is also is very interesting and diffulct problem.

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