Game Theory Applications in CSMA Methods

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Abstract—As a mathematical tool, game theory has been used for the analysis of multi-agent systems. Wireless networks are typical examples of such systems, in which communicating nodes access the channel through the CSMA method influencing the other neighboring nodes’ access. Different games were examined to model such an environment and investigate its challenging issues. This research reviews different CSMA games presented for wireless MAC and classifies them. Advantages and shortcomings of these games will be recounted and some open research directions for future research, supported.

Index Terms—Game Theory, Multiple Access, CSMA/CA, Wireless Networks, MAC Layer.

I. INTRODUCTION

MATHEMATICAL means for the analysis of wireless Ad Hoc networks have met limited success due to the complexity of mobility and traffic models, varying topology caused by mobility and unpredictability of link quality due to fading and shadowing. However, game theory has gained more attention in Ad Hoc networks because of its ability in the modeling of independent decision makers whose actions affect others’ decisions [1].

The most common application of game theory in distributed algorithms and protocols are the analysis of distributed systems, cross layer optimization and design of incentive schemes. Game theory can investigate the existence and uniqueness of a steady state of networks operating in a distributed mode based on the performance of independent nodes. Considered as a strong tool for the analysis of distributed Medium Access Control (MAC), game theory is widely used in mechanism design aimed at finding the way to engineer incentive methods leading independent and self-interested nodes to operate toward global outcomes, desirable from a system point of view. In the case of wireless MAC, selfish users try to increase their utility by unfair acquisition of channel access, which reduces that of other users. Many studies have been conducted toward the application of game theory in medium access protocols. Authors in [2] have accomplished a comprehensive study on different game models for multiple access wireless networks. The proposed models include contention based and contention free protocols. In the present study, a survey of different proposed games for random CSMA in wireless networks is presented and some open issues are suggested for further research.

The paper is organized as follows: In Section II, various MAC protocols which are used in Wireless Local Area Networks (WLANs) are introduced. Section III is assigned to an introduction of game theory and a presentation of different game models. Game theory application in wireless network is presented in Section IV and Section V considers the specific application of game theory in CSMA/CA based networks. Different solutions for selfish behavior in CSMA games are introduced in Section VI and finally the paper is concluded in Section VII.

II. WLAN MAC PROTOCOL

In broadcast networks such as the popular WLANs standard, IEEE 802.11, nodes compete to access the shared medium called random access or multiple access channels. The most important problem in such networks is the method of selecting nodes for channel access. The MAC layer is responsible for optimal fair channel assignment while preventing collision which occurs if two or more nodes send frames simultaneously. MAC protocols are classified into two general classes: random (based on competition) and deterministic. In random access methods, channel access time is not predictable. Thus a drawback of random access based protocols is the differentiating of QoS support with the absence of any centralized coordinator. Deterministic medium access methods use central or distributed reservation mechanisms. In decentralized coordination methods, collisions may happen, not only in the reservation messages but also in the data packets.

Wireless MAC protocols can be divided into channel partitioning, random access and taking turn protocols. Channel partitioning protocols partition the channel into smaller pieces of time, frequency, code, space and so on to allocate each partition to each node exclusively. Frequency division multiple access (FDMA), Time division multiple access (TDMA), Code division multiple access (CDMA), Space division multiple access (SDMA), Polarisation division multiple access (PDMA), Pulse address multiple access (PAMA) are some examples of such protocols. Taking turn protocols are based on beaconing and polling, centrally or in distributed fashion. In fact, this type of MAC protocol coordinates shared access to avoid collision. In random access protocols, users compete to access the medium channel without any specific pre-assignment of the channel. Random access protocols are divided into carrier sense multiple access (CSMA) and non carrier sense multiple access such as ALOHA and Slotted ALOHA. This taxonomy is shown in Fig. 1.

There are many proposed multiple access channel allocation algorithms; the most well-known contention based protocols namely ALOHA and CSMA will be described here, to overlap the scope of this paper.
A. ALOHA Protocol

In the 1970s, Norman et al. proposed a trusty algorithm named ALOHA to control users’ access to a shared channel [3], [4]. Shortly after, another edition of this protocol named Slotted ALOHA was presented [5]. Very simply, in Pure ALOHA each station is allowed to send data whenever it has any. Obviously, there are some collided frames which are to be discarded. Therefore, a single channel named feedback is used to report collisions and the transmitter will know of collision by listening to this channel. It has been shown that the throughput of ALOHA is low. To increases the channel throughput, Slotted ALOHA is proposed in which time is partitioned into slots. Each active station should wait till the next time slot to send its outstanding packets and in the case of collision the same process will be repeated.

B. Carrier Sense Multiple Access (CSMA) Protocols

The best channel throughput achieved by slotted ALOHA is \(\frac{1}{e}\). The main cause for this nearly low throughput is that each station transmits selfishly, disregarding other stations’ transmissions. In the local area networks, each station can obtain information about other transmissions by sensing the channel using CSMA Protocols. Performance comparisons have shown that CSMA operates much better than ALOHA [6]. In CSMA, simultaneous access to the channel is avoided via two mechanisms: a backoff algorithm based on a Contention Window (\(CW\)) and Persistence Probability. In the backoff algorithm, each node waits for a random time, limited to its \(CW\) before transmission. In the Persistence mechanism, each node maintains a persistence probability. Whenever it finds the channel free, it will access the channel with this probability. If the Persistence Mechanism is implemented, channel access probability will be obtained by (1) [3]–[5], [7]–[12]:

\[
p = \frac{2}{CW + 1}
\]  

CSMA protocols are divided to persistent and non-persistent protocols.

- Non-Persistent CSMA: in this method, an active station senses the channel. Finding the channel idle, it sends its data; otherwise it waits for a random period and repeats the procedure again.
- \(p\)-persistent CSMA: \(p\)-persistent CSMA is proper for time slotted channels. Once a station is ready to transmit, it senses the channel. With the availability of a free channel, the station will send its data with the probability of \(p\) or will postpone its transmission until the next time slot with the probability of \(q = 1 - p\). If the channel is busy, the station waits for the next time slot and repeats the process again.
- Persistent CSMA: in persistent CSMA which is often known as 1-Persistent CSMA, a station, having data to send, attempts to sense the channel first. If the channel is free, data is sent instantaneously. Otherwise, the station waits until the channel is free. Due to the propagation delay and the simultaneous waiting for a free channel, collision is still possible but avoided during the frame transmission. Therefore, the performance of persistent CSMA is more than that of ALOHA. Fig. 2. clarifies the differences between the aforementioned three CSMA protocols.
- CSMA/CA (Collision Avoidance): CSMA/CA is an enhanced version of CSMA in radio environments in which collision detection is almost difficult due to the following reasons:
  - Hidden node problem: this problem is caused by
stations which are hidden from each other due to limited radio coverage. Some transmitted signals will not be sensed by others not in the sender’s coverage area.

- Exposed node problem: this problem is caused by the stations which are exposed to others, erroneously wasting the channel bandwidth. It occurs when a node decides not to transmit to avoid simultaneous transmission with another node with which it will not really interfere.

In order to avoid collision and to resolve hidden and exposed node problems, handshaking is used in this protocol.

802.11 families are considered as the most applicable set of standards for WLANs which may be configured and implemented according to the following schemes:

- Base station based scheme: a key element called AP (Access Point) is responsible for establishing the connection between stations. All of the stations that are served according to this scheme should be in the coverage area of the AP. In this way, channel access procedure will be under the control of AP and the transmissions have to be coordinated under the condition imposed by the AP. In IEEE literature, this is known as the PCF (Point Coordination Function) mode.

- Distributed scheme without any central control: in this scheme which is known as DCF (Distributed Coordination Function), there is no central element for controlling the common channel access procedure. So each station willing to transmit has to enter the contention procedure and resolve the possible collisions. The most complicated part of the channel access algorithm is the distributed characteristic of this scheme which is not supported by any centralized control. In DCF, stations use CSMA/CA as their multiple access control protocol. Ad Hoc networks are good examples for this type of configuration.

According to the IEEE 802.11 standard, PCF and DCF can be used simultaneously in a wireless cell. In the IEEE 802.11 standard, the four independent time durations, which are exploited for both coordination and polling are defined as: Short Inter-Frame Spacing (SIFS), DCF Inter-Frame Spacing (DIFS), Point Inter-Frame Spacing (PIFS) and Extended Inter-Frame Spacing (EIFS). After finding the channel free, all the stations located in a cell modulate their plans according to this time table. DCF uses a backoff algorithm with a contention binary signal, expressing the success or failure of the transmission. Every active node which has a new packet to transmit monitors channel activity. If the channel is free for a DIFS time, the node will start sending data. Otherwise, it will persist on monitoring until the channel is free for DIFS time. Next, backoff random time will be selected by the node based on the following equation:

\[
\text{Backoff Time} = \text{Random}(CW) \times \text{a slot time duration} \quad (2)
\]

Because of simultaneous transmissions, collision is possible in this protocol. Thus, after each unsuccessful transmission, \(CW\) is multiplied by \(\sigma\), which is called the persistence coefficient and the backoff time selection and transmission process will be repeated again. The process will go on till the size of the contention window reaches its maximum value \(CW_{\max} = \sigma^m CW_{\min}\). Once \(CW\) reaches \(CW_{\max}\), it will be preserved till the packet is transmitted successfully, after which the \(CW\) will be set back to \(CW_{\min}\) or the retransmission times reaches to the retry limit \(r\). When the latter happens, the packet will be dropped. An example of \(CW\) changes is depicted in Fig. 3. The most important techniques to modify the backoff algorithm re as follows [13]:

- Backoff control parameter (persistence coefficient \(\sigma\)) setting: while collision occurs, the value of the contention window will be multiplied by this coefficient to decrease the collision probability through the increase of this window. The default of IEEE 802.11 protocol for this parameter is 2. Greedy users are capable of raising their fortune for channel by setting the parameter value close to 1.

- \(CW_{\min}\) value setting: another way to increase channel access fortune is to select a small value for \(CW_{\min}\).

- \(m\) value setting: considering \(CW_{\min}\) and \(CW_{\max}\) as being fixed, the selection of a smaller value for the maximum number of backoff stages leads to a lower \(CW_{\max}\), a higher probability of transmission.

Generally, users are able to set their transmission probability by modifying the above mentioned parameters. In the original version of DCF, each new transmission starts with the minimum value of \(CW\) disregarding the contention level of the network. Hence, in high traffic networks in which no real contention status is considered, the \(CW\) value increases due to continuous collisions leading to low network throughput.
In WLAN, middle nodes are more exposed to collision rather than those which have fewer contending neighbors. Therefore, middle nodes tend to choose longer backoff delay [14], [15]. In order to reach better performance (higher throughput and lower collision) and also the fairness, there is a need for other methods that can adjust the $CW$ or persistence probability via modifying the contention parameters such as $CW_{\text{min}}$, $CW_{\text{max}}$, $m$, $\sigma$, and $r$.

There are two access methods in DCF: the basic access mechanism, and the RTS/CTS access method. In the basic access mechanism, when the backoff timer times out, the station begins to transmit. When a receiver successfully receives the packet, it will send an ACK packet to the transmitter after SIFS as illustrated in Fig. 4. The Network Allocation Vector (NAV), illustrated in Fig. 4., reserves the channel for some time. In fact, the NAV is a timer, which decreases irrespective of the status of the medium, which can be busy or idle. When a frame is received, the NAV is set according to the frame duration field that defines how long the following frame exchange will take. Stations are not allowed to initiate transmissions and they defer their transmissions during the time set in NAV. Thus, upon frame reception, the NAV can be set for a duration that is longer than the transmission duration of this frame, and subsequent frame transmissions are protected [7].

In the RTS/CTS mechanism, which is depicted in Fig. 5, the transmitter station firstly transmits the RTS (request-to-send) packet to the receiver. After RTS reception, the receiver will send the CTS (clear-to-send) packet back to the transmitter. It is worth noting that the CTS will be sent if the channel is free. Data packet transmission will start after the CTS packet is received. And finally the receiver will send the ACK packet to the transmitter if it receives the data packet correctly. So the transmitter will recognize the collision, if it does not receive any CTS or ACK packets.

III. GAME THEORY

Game theory is a field of applied mathematics which is used to analyze the systems in which multiple participants interact or affect each others’ payoff. In other words, in game theory, a person’s success is based on others’ decisions [16]–[20]. Game theory is a tool not only to analyze the system behavior but also to optimize its process in a multi-agent environment. Optimization theory can not consider interactions between different participants, but game theory is a good approach to study and analyze the behavior of interacting elements [21]–[23]. Because of the competing nature of such an interaction,
the type of problem is called a game and the participants are called players. The players are assumed to be rational, meaning that they try to maximize their payoffs according to their strategies. In order to make a decision, each player should analyze the effect of others’ reactions and decide how to behave to gain the most benefit.

In other words, a game includes a series of players, a series of actions for the players and a series of utilities or payoff benefits, payoff benefit being the subtraction of utility function and user cost. A utility function is a mapping of the player behavior with real numbers and is a measure of user satisfaction. The definition of utility plays an important role in a game. In some researches, however, payoff function and utility have been considered equivalent. The strategy of a player can be an action from his action space or a combination of actions. By maximizing network utility (for example, the sum of all users’ utilities), social welfare is also maximized [24].

There are two forms for the representation of different components (players, actions and payoffs) of a game: the normal or strategic form, and the extensive form.

The extensive form is used to represent the games as time sequenced movements. Games are shown as trees in which each node represents a point of choice for a player. The lines out of a node represent possible actions for that player. And payoffs are specified at the bottom of the tree. The extensive form is the same as the multi-player decision tree [25]. An extensive form game represents the structure of interaction between players, order of movements, dependency of one’s choices on the previous actions of others, and so on. The extensive form can also be used to represent simultaneous-move games and games with imperfect information. For example, in the game shown in Fig. 6, there are two players, Player1 moves first and chooses between $F$ and $U$. Player 2 sees Player 1’s movement and then chooses $A$ or $R$. Suppose that Player1 chooses $F$ and then Player2 chooses $A$. Player1 and Player2 get 5 as their payoffs.

The standard framework of interaction modeling is the strategic form game. A strategic form game consists of a choice set for each player and a payoff function relating the payoffs to the choices. $G = \langle N, A, u_i \rangle$ is a normal form of the game $G$, in which $N = 1, 2, ..., n$ is the set of players, $A_i$ is the action set for player $i$, $A = A_1 \times A_2 \times ... \times A_n$ is the Cartesian product of the sets of actions and $u_i$ is the set of utility functions that each player $i$ wishes to maximize, where $u_i : A \rightarrow R$. For each player $i$, the utility function is a function of the action chosen by player $i$, $a_i$, and the actions chosen by the other players of the game, denoted as: $G = \langle N, \{A_i\}, \{u_i\} \rangle$.

The solution of a game is represented by an array of strategies for a player in the game. Often in game theory, the aim is finding equilibrium, in which each player chooses a strategy that is the best response to the selected strategies of the other players.

The most popular equilibrium is Nash. The Nash equilibrium gives a solution that contains a number of players who cannot gain more benefit via changing their strategies on their own parts. Let $x_i$ be a strategy profile of player $i$ and $x_{-i}$ be a strategy profile of all players except player $i$. When each player $i \in N$ selects the strategy $x_i$, then player $i$ obtains payoff $u_i(x_i)$. The set of $(x^*_i, x^*_{-i})$ is Nash equilibrium if $\forall i, x_i \in A_i, x_i \neq x^*_i : u_i(x'_i, x^*_{-i}) > u_i(x_i, x^*_{-i})$ [19], [22], [26]–[31]. Pareto optimality (efficiency) is obtained when a vector of strategies exists in which one player situation cannot be improved without making another party’s situation worse. Pareto efficiency does not imply equality or fairness. In formal definition, a Pareto optimal Nash equilibrium of a game is any Nash equilibrium $x^* = (x^*_1, x^*_n)$ such that there is no other equilibrium $y^* = (y^*_1, ..., y^*_n)$ with $u_i(x^*) < u_i(y^*)$.

The players’ choice of strategy can be made either in a deterministic or probabilistic manner, which are called pure and mixed strategies, respectively. If players choose a behavior clearly, it is called pure strategy but generally, as players do not have complete confidence in the selection of the opposite player, they choose their strategy probabilistically which is called mixed strategy. Nash proved that if players use mixed strategy, then every game with a finite number of players in which each player can choose from a finite set of pure strategies has at least one Nash equilibrium [21].

The method by which interacting players converge toward equilibrium is called game dynamics. There are many techniques for leading a system toward the Nash equilibrium, the most general being: Best response, Gradient, and Jacobi [32], [33]. The simplest strategy updating mechanism is the best response strategy. Here, in every stage, each node chooses the best response to the behavior of other nodes in the previous stage. Another strategy updating mechanism in comparison with the best response is the gradient strategy that is known as better response. In this mechanism, each node tunes the probability of its action gradually in the direction of the suggested gradient. And finally in the Jacobi mechanism, each node tunes the probability of its action preferably toward the best response.

### A. Classification of Games

In game theory literature there are many game models. The choice of model depends on the problem and its characteristics. Game models are developed to be used for different types of applications. They aim at finding the equilibrium states and deciding whether these states are acceptable for the application or not. They also find the optimization parameters that force the system to reach the desired equilibrium states.

Games are classified into some categories regarding different perspectives. For example, deterministic and stochastic, static and dynamic, cooperative and non-cooperative, complete information and incomplete information, iterating and non-iterating games as illustrated in Fig. 7.
1) Deterministic vs. Stochastic: A game is called deterministic if the players’ actions uniquely specify the outcome, but if the outcome of at least one player depends on an additional variable with a known probability distribution, then the game is called stochastic.

2) Static vs. Dynamic: In static games, the users choose their strategies simultaneously and even if they adopt the strategies in different times, they do not have any information about other users’ strategies. While in the dynamic games, the players make alternative decisions and every player is informed about the strategies previously selected by other players. Repeated games are a subset of dynamic games in which a fixed strategic game \( G \) is played periodically. At the beginning of each period, players see the past history of choices and then make a decision, accordingly. In these games, payoff is the summation of payoffs gained from previous periods.

3) Complete vs. Incomplete: A game is a complete information game if the descriptions of the game (including the players, the objective functions, and the corresponding probability distributions (if stochastic)) are known for all players; otherwise it is called an incomplete information game. An incomplete information game model can be assumed as an extension of the Bayesian learning approach. A probability distribution is used to express uncertain information regarding players or nodes. Then the solution in terms of equilibrium is obtained. A Bayesian game is generally composed of a set of players, a set of actions, types of players, payoff function for each player, and probability distributions associated with the types. The equilibrium solution of such a game is called the Bayesian Nash equilibrium (BNE). A Bayesian Nash equilibrium can be obtained for each player by choosing a strategy that maximizes the expected payoff regarding the beliefs about the types and strategies of other players [34].

4) Perfect Information vs. Imperfect Information: An important subset of sequential games are the games with perfect information. In a game with perfect information, all players know the actions previously chosen by all other players. Only sequential games can be perfect information games because in simultaneous games, every player does not know the actions of the others. Perfect information is often confused with complete information. A complete information game requires that every player know the strategies and payoffs of the other players but not necessarily the taken actions.

5) Cooperative vs. Non-cooperative: Game theory can be divided into two main branches: cooperative and non-cooperative.

In the first case, players cooperate with each other to optimize the social welfare. In a cooperative game, players try to reach an agreement which maximizes their benefits, through collective decision making, bargaining, dealing, and discussion. In optimization problems, cooperation of the nodes is needed too and in most cases, players gain the best result. The prevalent criterion for expressing equilibrium utilization in cooperative games is Pareto optimality. Pareto optimality means that a user cannot increase her/his utility without any decrease in the utility of at least one other player. In other words, a game is cooperative where all players are concerned about the overall benefits not their individual benefit. A game is cooperative if the players can form commitments. For example, a legal system forces them to adhere to their promises. In non-cooperative games this is not possible. Sometimes it is assumed that communication among players is allowed in cooperative games, but not in non-cooperative ones. However, this classification based on two binary criteria has been sometimes rejected.

Cooperative games include bargaining and coalitional games. Nash bargaining deals with situations in which a number of players need to agree on the terms under which they cooperate but coalitional game theory deals with the formation of cooperative groups or coalitions. In fact, given several cooperation incentives and fairness rules, cooperative game theory in both forms provides tools that let the players choose whom to cooperate with and under what terms.

Another kind of game is the non-cooperative. In such games, each decision maker chooses his strategy selfishly. In fact, in non-cooperative games each player chooses his strategy without the coordination of others. In this case, equilibrium, if any, will be the Nash equilibrium. In general, Pareto utilization is a favorable operation point for a system but non-cooperative equilibriums are inefficient in general situations. Non-cooperative game theory can be used to analyze the decision making processes of a number of independent entities, i.e., players, which have interests over the outcome of a decision affected by their actions. It is considerable that non-cooperative games do not always imply the players’ cooperation, but it may mean that, any cooperation must be self-enforced without any direct communication or coordination. In Competitive or non-cooperative games, every user is mainly concerned about his individual payoff and all of his decisions are made competitively and, moreover, selfishly. Most of 2-player games are good examples of this type.

Hybrid games include cooperative and non-cooperative elements. For instance, coalitions of players are formed in a cooperative game, but they play in a non-cooperative way. Most cooperative games are presented in a characteristic function form and the extensive and normal forms are used to define non-cooperative games. Potential games and Super Modular games are two kinds of non-cooperative game models which are used frequently. In Potential games, a Nash equilibrium is determined by maximizing a single function (called the potential function). The potential function is a useful tool for analyzing the equilibrium properties of games, since the goals of all players are mapped into one function, and a set of pure NE can be found by simply locating the person-by-person optima of the potential function [18]. Super modular games are those characterized by strategic complementarities which means that the players want to follow each other’s decisions and act similarly. In other words, super modular games are characterized by increasing best response. They are interesting for the following reasons. First, they include many applied models. Second, many solution concepts reach the same predictions [18], [35], [36].

B. Utility Functions

Utility is a criterion for measuring the proportional satisfaction of a user. The utility function is a reward (reward
minus cost) that is expected to be obtained by each player after action. Users have different utility functions with respect to the kind of services they offer. With the maximization of network utility (for example, total utility of all users) the social welfare of the system is also maximized. On the other hand, utility functions can be interpreted as handles for controlling the trade off between performance and fairness.

In medium access games, reverse engineering models of the available protocols, reverse engineering of the desirable point, and forward engineering and heuristic methods have usually been used to determine the utility function. Usually in forward engineering, an optimization problem is taken into account and the utility function and payoff are formulated according to the player’s actions. Convergence and consistency features, derivability and convexity of these functions are necessary. As heuristic and mathematical models can introduce various functions as utility and payoff, the forward engineering process accepts a larger class of utility functions. Reverse engineering is a development method to access the available protocols that have been devised innovatively and have been based on the detection of mathematical problems with respect to the dynamism of the network. This means that it starts from specific descriptions of a pre-devised protocol and then an underlying optimization problem that should be solved by this protocol, is examined. Reverse engineering is used for solving the defects and increasing the abilities of the available protocols and eliminating the imperfections as well. This model makes full recognition of a protocol performance, acquisition of technological knowledge of available protocol, utilization and retrieval of other important information possible. And it is also a self motivator for the protocols to re-design themselves using forward engineering [37].

The choice of the utility function is an important challenge in game theory to analyze the performance of wireless networks; in this paper the important issues in utility function definition are covered. This survey collects the application of game theory in the CSMA method, emphasizing the comparison of payoff and utility function designing.

IV. GAME THEORY APPLICATION IN WIRELESS NETWORKS

Game theory was mainly applied to economics, political science, biology and sociology. But in the early 1990s, engineering and computer science have been added to this list. Because of the increasing research in the area of distributed computing in computer science, in mid to late 1990s, game theory became a major topic of interest. Game theory generalizes the decision-theoretic approach, which was already widely adopted by computer scientists [16]. Game theory examines the decision making in a common environment with other decision makers who have various objectives in mind. As the nodes of a network are good examples of such a situation, game theory is highly applicable for the wireless networks, specifically for the Mesh and Ad Hoc communicating [18–20], [28], [29], [38], [39]. Since optimization theory is unable to consider players’ interaction, game theory has shown that it is a suitable substitute for studying and analyzing the behavior of complex and interactive systems [24]. When a telecommunication system is modeled by using game theory, there are some important issues, such as: Is there Nash equilibrium? Is it unique? Does the system converge to the equilibrium point? Is it also a global optimum of system, i.e. does it maximize the social welfare?

Game theoretic research regarding Ad Hoc networks has also been focused on the cooperation of the nodes. There are various mechanisms introduced to prevent selfishness and to encourage cooperation [40].

Mathematical analysis has experienced limited success in wireless networks because of the complexity of mobility and traffic models, and also the dynamic topology and the unpredictability of link quality in such networks. The ability of game theory in the modeling of individual and independent decision makers, whose actions affect others, makes it attractive to analyze the performance of Ad Hoc networks.

Current wireless networks consist of a large number of users with different Quality of Service (QoS) requirements (such as bandwidth, delay, and power). To decrease management complexity, distributed control of such networks is preferred leading to distributed (or at least partially distributed) network domains, in which end-users take independent decisions regarding their network usage and based on their individual preferences. This framework can be categorized as a non-cooperative game.

Network resources are often limited in wireless networks which might be fully used by greedy users; therefore, self-interested user behavior cannot be very useful and the greed of even one user for accessing the channel to improve his QoS may lead to network throughput collapse. Game theory can
analyze the decision making process in a shared environment by users with different goals. Hence, this technique is applied in wireless networks especially in mesh and Ad Hoc networks as given in Table I [1], [28], [29], [38], [39].

In recent years, game theory has been widely used for some problems like routing and resource allocation in competitive environments. The main advantages of using game theory in wireless networks are the analysis of distributed systems, cross layer optimization and designing of encouraging methods for avoiding selfish behaviors [38]. The application of game theory, its models and challenges in wireless networks have been studied in [26], [34], [40]–[44]. In MAC games, selfish users try to increase their utility by unfair acquisition of shared channel reducing the ability of other users to access the channel. Many studies have been conducted on the application of game theory in medium access models. Game theory can address some of the limitations of the aforementioned approaches in a multi-player environment for optimizing the network performance, specifically when the resources are shared among multiple nodes with different objectives. Several games are proposed to solve the MAC layer problems such as: game model for random channel access, channel allocation, power control and cognitive radio. Authors in [2] performed comprehensive study on different game models for multiple access in a wireless media. The proposed models include contention-based and contention-free protocols. A complete survey on different game models proposed for random CSMA in wireless networks and some open directions for further research are presented in this paper.

V. APPLICATION OF GAME THEORY IN CSMA METHODS

Medium access control is a distributed approach which shares the wireless channel among competitive nodes. Since wireless networks use a shared transmission medium, collision is possible because of simultaneous transmissions by two or several nodes that exist in an interfering domain. As randomness in CSMA protocols depends on the network congestion, in order to control contention between different transmissions, avoiding the collision, increasing the performance of system and fairness in sharing the resources, it seems necessary to use a distributed medium access protocol. Game theory can be used to design CSMA protocols in wireless networks as a distributed interactive system. Different proposed CSMA games can be categorized as shown in Fig. 8.

In random access games, wireless nodes share a common channel and want to maximize their utilities independently. Using game theory and Nash equilibrium concept, it has shown that the current IEEE 802.11 standard does not work well in such a scenario as it is based on random access. A selfish node may choose to wait for a smaller backoff interval to increase its chance of accessing the medium and hence reducing the channel access chance of well behaved nodes [46]. Among the first works showing the application of game theory in CSMA model, [47], [48] can be mentioned which consider the misbehavior in MAC layer. Cagalj et al. studied the effect of selfish behavior of some users in the network and have shown that even the presence of few selfish users may lead the network to collapse which can be assumed.
and infinite backlog for nodes have proposed a static game and a dynamic game to adapt the contention window with the purpose of throughput maximization. 802.11 DCF can be modeled as a 2-player game, in which, the competing nodes for the channel are the players with two strategies: Transmit and Wait [15], [49], [50]. The non-cooperative game presented in [15] is one of the first researches proposing a fair non-cooperative game model for DCF 802.11 mechanism. This basic model is depicted in Fig. 9.

![Fig. 9. The DCF game with two nodes [15]](image)

$u_s$, $u_t$ and $u_f$ are the payoffs when a node transmits successfully, stay idle and fails to transmit, respectively, where $u_f < u_t < u_s$. In this game there are two Nash equilibria (Transmit, Wait) and (Wait, Transmit) as well as a Nash equilibrium with mixed strategy. If user $i$ transmit data with $\tau_i$ probability, the DCF game can be defined as $< N, \tau, \tau_{-i}, U_i >$ and the payoff function can be defined as the following in which $n$ is the number of competing nodes.

$$U_i = \tau_i \left( u_s \prod_{j \neq i} (1 - \tau_j) + u_f (1 - \prod_{j \neq i} (1 - \tau_i)) + u_t (1 - \tau_i) \right)$$

To maximize the payoff function, the necessary condition is $\frac{\partial U_i}{\partial \tau_i} = 0$. So this payoff function has the following unique solution which is the best response of node $i$.

$$\tau^* = 1 - \left( \frac{u_t - u_f}{u_s - u_t} \right)^\frac{1}{\tau}$$

It is stated that $u_t$ represents the delay sensitivity where the lower $u_t$ shows that the traffic is more delay sensitive. $u_s$ is an increasing function with respected to data frame length. And finally $u_f$ is a decreasing function of data frame length since an error in transmission of longer frames is more harmful.

Although DCF does not consider different traffic priorities and also length of data frames, proper DCF game models can be defined to consider the effect of these parameters on the network performance through adjusting $u_f$, $u_s$ and $u_t$ [15].

Contention control through reverse engineering approach as a distributed iterated feedback system is studied in [33], [51], [52]. Reverse engineering offers a mathematical model for the studying selfish behavior in MAC protocols as well as a high vision toward the performance and protocol performance. Hence, it guides designers toward planning and improving of new protocols with forward engineering. In fact, medium access control as a distributed algorithm can be modeled for updating the strategy to reach the equilibrium of the random access game. For example, DCF has a backoff algorithm that results in a channel access probability and can be modeled by a function like $F_i$. This algorithm responds to occurrence of collision and hence the measure of contention $q_i(t)$ in 802.11 DCF is the collision probability whose dependence on the channel access probability vector $p(t)$ can be modeled by a function like $C_i$. Performance of MAC protocols like throughput, fairness, and collision is heavily depended on equilibrium and stability of this dynamic system.

$$p_i(t + 1) = F_i(p_i(t), q_i(t))$$

$$q_i(t) = C_i(p(t))$$

Therefore, MAC protocols can be reverse engineered and studied within the game theory framework. A vector of channel access probability $p$ is equilibrium, if for the given network contention, no node is willing to change. It has been shown that exponential backoff protocol can be modeled with a non-cooperative game in which links try to maximize their utility function in the form of reward for successful transmission [37], [53]. Through reverse engineering of 802.11 protocols, it has been shown that sufficient feedback information cannot be provided for the competing nodes to solve the selfishness problem which can result to maximize the social welfare by solving the selfishness problem. In [37] the utility function obtained by reverse engineering is as follows:

$$U_i(p) = R(p_i)S(p) - C(p_i)F(p), \forall l$$

Where $S(P)$ and $F(P)$ are obtained directly from the definition of success and failure probabilities. $R(P)$ and $C(P)$ are resulted from reverse engineering of Exponential Backoff (EB) protocol and are the reward and cost of transmission respectively. Utility of each link depends not only on its persistent probability but also on transmissions of other users due to collision. Moreover there is no clear and evident feedback from network. Therefore, for EB protocol, non-cooperative game is more suitable than global optimization model and it has been shown that without any nodes’ coordination, selfish behaviors reduce the network performance. After proving the existence of Nash, it has been shown that the obtained Nash equilibrium may not be unique and steady [37], [53]. So it becomes a motivation for designing a new MAC protocol by forward engineering. In forward engineering, a cooperative network utility maximization (NUM) problem has been formulated according to persistence probability of each node for the purpose of improving medium access protocol [37], [53].

With the exchange of contending prices, the best coordination for balancing the nature of non-cooperative EB towards the best converging point can be obtained. Convexity feature is necessary for designing an optimal distributed algorithm and convex utility functions are therefore of much attention. Along the forward-engineering direction, in [37], [54] it has developed a NUM framework to achieve desired efficiency, fairness and their trade off by appropriately adjusting the utility function and solving the resulting NUM problem. In the NUM framework, there are two interpretations of each source utility function. It can be interpreted as the satisfaction level gained by a user as a function of resource allocation. Each user may have a different utility function depending on its type of service. The social welfare of the system will be maximized by maximizing the network utility (i.e., the sum of all user utilities). Efficiency of resource allocation algorithms
can be evaluated by measuring the obtained network utility. Utility functions, in fact, can control the trade off between efficiency and fairness. Different shapes of utility functions result in different types of fairness. For example, a family of utility functions parameterized by \( \alpha \geq 0 \) is:

\[
U^\alpha(x) = \begin{cases} 
(1 - \alpha)^{-1}x^{1-\alpha} & \text{if } \alpha \neq 1 \\
\log x & \text{else}
\end{cases}
\]  

If \( \alpha = 0 \), NUM leads the system to maximize its throughput. If \( \alpha = 1 \), proportional fairness among nodes is achieved and if \( \alpha \to \infty \), then max-min fairness is obtained. In random access games, the strategy of a player is usually transmission probability or equivalently, the size of contention window and its payoff function is a combination of the channel access gain and the packet collision cost. In these games, users estimate their collision probabilities through observing idle time slots between transmissions as well as unsuccessful transmissions and accordingly can adjust their persistence probability [33], [52], [55]. Studying the previous works has shown that contention window, transmission power and data rate are most frequently used parameters in the strategy definitions. From the players’ strategy point of view, the CSMA games can be divided to contention control, power control, jointly power and access control and jointly power and rate control games as mentioned in Fig. 8. In the following, proposed CSMA games, cooperative and non-cooperative ones have been investigated and then researches around selfishness and the punishment of users in CSMA networks have been studied.

A. Cooperative CSMA Games

In cooperative games, players interact with each other and choose their strategies after some agreements. Usually implementation of cooperative solutions is difficult as it requires interaction of agents with each other, regularly. But generally cooperative games achieve better performance than non-cooperative ones. The cooperative games proposed in the literature can be divided into complete information and incomplete information games. In the following section, first complete cooperative games are investigated. Then the incomplete frame work is introduced and some example games will be explained.

1) Complete Cooperative CSMA Games: A game is a complete information game if the description of the game is known to the players. Based on this definition, authors of [56] propose robust random-access protocols for wireless networks in fading environments, where each terminal operates in Nash equilibrium of a random-access game. In [56], it is supposed that each node knows its channel SNR, number of existing nodes as well as the probability distribution of channel conditions of other nodes. Then based on this assumption a CSMA game has been proposed. In this game, the action space of the users is defined by \( A = \{1, K, K + 1\} \) in which \( k \in \{1, \ldots, K\} \) represents transmission of packet in the \( K^{th} \) slot and \( K + 1 \) represents no transmission. By considering \( h_i \) as the channel SNR for player \( i \), the node’s payoff \( (Q_i) \) is defined as the difference of its utility \( (U_i(h_i)) \) and the cost function \( (C_i(h_i)) \) as functions of SNR \( (s_i(h_i)) \) if its transmission is successful. In the case of unsuccessful transmission, the node gains nothing and only pays the cost. And the payoff will also be zero if the node decides not to transmit (9).

This game is an opportunistic CSMA game based on user’s channel condition. Since any Nash equilibrium deviation will penalize the terminal, the network will become more robust by preventing a selfish terminal from violating the access protocol. It is shown that the strategies in symmetric equilibrium of the game cause the terminals with better channel state to access the channel more. The proposed game is a complete game; therefore, cost, probability distribution, and utility functions are defined similar for all users. This is far different from practical environment and needs further studies. Also users’ traffic, QoS, and condition of users’ queue have not been considered as well in this model [56].

A cooperative random access game to maximize total throughput, from the network point of view is presented in [57]. It is assumed that the nodes voluntarily cooperate with each other by exchanging interference information. A tax mechanism is added into the game which causes the users an incentive to intelligently avoid interference. By solving each node sub-problem based on super modular game, each node computes its persistence probability in a distributed manner. Authors of [58], [59] continue the work of [57] and formulate a random access game at the MAC layer, under which each user maximizes its own payoff function. According to the received prices \( e_j, j \in N_{from}^f(n) \) and with the consumed power \( p_n \) consideration, a cooperative game is defined by following the global payoff function (10). Where \( c_j = \frac{\partial u_j(f_j(q))}{\partial f_j} \) and \( N_{from}^f(n) \) denotes the set of nodes whose receivers are interfered by node \( n \) transmission. And \( N_{to}^f(n) \) represents the set of nodes interfering with the reception of \( r_n \), the receiver of node \( n \). \( f(q) \) is the probability that a node \( n \) makes a successful transmission which is given by:

\[
f_n(q) = q_n \prod_{k \in N_{to}^f(n)} (1 - q_k)
\]  

\[
Q_i(s_i(h_i), s_{-i}(h_{-i}); h_i) = \begin{cases} 
U_i(h_i) - C_i(h_i) & \text{if } s_i(h_i) < s_j(h_j), \forall j \neq i \\
0 - C_i(h_i) & \text{if } s_i(h_i) \leq s_j(h_j), \forall j \text{and } \exists i' \text{'s.t. } s_{i'}(h_{i'}) = s_{i'}(h_{i'}) \\
0 & \text{otherwise}
\end{cases}
\]  

\[
U_n(q_n; c_{-n}, p_n) = u_n(f_n(q)) + \log (1 - q_n) \sum_{j \in N_{from}^f(n)} c_j - p_n q_n
\]
By this assumption, the following payoff function is proposed
\[
\pi(x_n) = \text{continuous in } x_n, \text{ twice continuously differentiable, non-decreasing and uniformly strictly concave in } x_n.
\]
In this game, with the objective of optimizing the total payoff, nodes adjust their channel access probability \(q_n\).

In [60], bandwidth allocation in MAC layer of Ad Hoc networks has been considered as an optimization problem and as a repetitive cooperative game. The model considers two separate channels for control and data. In control channel, each node calculates an initial flow rate based on gradient method in a distributed manner and makes the one hop links aware of its new flow rate. The initial flow rate is calculated regarding the price information received from other users. Then nodes adjust their contention window regarding the calculated initial flow rate in their data channels. In WMNs, periodic exchange of game state is difficult for nodes and results in higher energy and bandwidth consumption. But since each node is always sensing the channel to receive the probable packets, it is able to estimate the game state by listening to the channel. However because of the dynamism, the exact and on time estimation of game state is not always possible. In most of the proposed CSMA games, each node does not have complete information about the other nodes, therefore, they are considered as incomplete cooperative games.

2) Incomplete Cooperative CSMA Games: Because of the nodes’ mobility, joining of new nodes and leaving of some old nodes, the wireless networks have a very dynamic nature. Therefore, gathering the neighboring nodes information is too complex. For all these reasons, an incomplete cooperative game could be a suitable candidate to optimize the performance of MAC protocol in wireless networks [61].

In [62], it is assumed that when accessing the channel, a transmitter costs a fixed amount of payoff \(C\), where \(0 < C < 1\). By this assumption, the following payoff function is proposed for the cooperative game presented in [62] for WSNs:
\[
u_i = p_i \prod_{t=1, t \neq i}^{n}(1 - p_t) \times (1 - C) - p_i[1 - \prod_{t=1, t \neq i}^{n}(1 - p_t)] \times C
\] (12)
\[
u_i = p_i[ \prod_{t=1, t \neq i}^{n}(1 - p_t) - C]
\] (13)

Where, \(p_i\) is the transmission probability of node \(i\). Suppose that all nodes have the same structure, it is proved that there is a mixed-strategy Nash equilibrium point as follows:
\[
1 - p_i = C^{\left(\frac{1}{n-1}\right)}
\] (14)

In order to solve the problems of low throughput and high collision rate for WSNs, a new backoff algorithm which is expected to improve the network performance at the same power consumption is proposed as (15) [62]. In (15), \(Nb\) is the number of nodes tried to access the channel. The initial value of \(Nb\) is 0 and \(d\) represents the nodes backoff rate.
\[
d = 1 - p_i = \frac{CW}{CW_{max}} = C^{n-1}
\] (16)

In the proposed delayed backoff algorithm, if a sensor node continuously has sent the packets successfully, its backoff time is decreased slowly instead of instant decrements of \(CW_{min}\). And the Nash equilibrium point limits the surplus of \(CW\), which releases the delay time oscillation. If a node keeps \(CW > C^{\frac{1}{n}}CW_{max}\), other nodes will decrease their \(CW\) to achieve a higher access rate. In order to prevent others from getting more benefit, a node will not increase its \(CW\) from the amount obtained at the Nash equilibrium point. When a node fails twice, it will agree that the ceiling of Nash equilibrium point will no longer exist.

Hatami [46] uses a static game to model cheaters’ interaction based on the idea of Idle Sense. The idea of Idle Sense is that each node estimates the number of consecutive idle slots between two transmission attempts and uses it to compute its contention window [63]. To find the game solution, Nash bargaining solution from cooperative game theory is used [46]. According to [63], maximizing throughput is equivalent to minimizing the following cost function:
\[
Cost(P_a) = \frac{T_{SLOT} P_e + P_i}{P_t}
\] (17)

Where \(P_a\), \(P_c\), \(P_i\), \(P_t\) are transmission probability, collision probability, idle probability and successful transmission probability, respectively. \(T_c\) is the average collision duration, and \(T_{SLOT}\) is the slot duration. General framework of incomplete cooperative games [13], [15], [64]–[66] includes three elements namely detector, estimator, and adjuster as depicted in Fig. 10.

The detector gets some information from different layers through listening to the channel and recording them. Such information includes physical layer information such as SNR, MAC layer information such as transmission probability \(T\) and conditional collision probability \(p\) as well as TCP/IP layer information e.g. TCP datagram drop rate. The estimator evaluates the game state based on the detector recorded information. In most researches the number of competing users is considered as the game state. Having the information provided by detector and estimator, adjuster chooses the strategy by tuning contention parameters like TCP sliding window, size of contention window, transmission rate, duration of transmission, transmission power and etc. Cross layer detection, estimation, and adjustment are necessary to acquire the game state and adjust the strategy in each time slot. The main point in this class of games is the exact and on time estimation of game state. After estimating the current game state, each node changes its equilibrium strategy by tuning its local contention parameters. The game is repeated finitely to get the optimal
performance. To implement a distributed game, cross-layer design is introduced for simultaneously estimating the PHY-specific and MAC-specific game states (e.g., bit rates and the number of competing nodes), and adjusting the strategy (e.g., by tuning the minimum contention window) for the estimated game state. In an incomplete cooperative game, each node can estimate the game states by reading the corresponding information in the MAC and PHY headers of all received frames. Simulation results show that the estimation method is valid and the game performs much better than DCF in terms of throughput, delay, jitter, and bit drop rate. The simulation results show that this game can increase system throughput, and decrease delay, jitter and bit drop rate [64], [67]–[69].

Mehta in [61] uses the concept of incomplete cooperative game theory [64] to model an energy efficient MAC protocol for WSNs. The game is modeled as a stochastic game, which starts when there is a data packet in the node’s transmission buffer and ends when the data packet is transmitted successfully or discarded. As each node can try to transmit an unsuccessful data packet for maximum retry limit, the game is finitely repeated. Players have three strategies [61]: transmitting, listening, and sleeping. The probabilities of selecting these strategies are defined by \( P_{\text{Tran}}, P_{\text{List}}, \) and \( P_{\text{Sleep}}, \) respectively.

\( P_{\text{Tran}}, P_{\text{List}}, P_{j} \) and \( P_{w} \) are the payoffs of listening, successful data packet transmission, failed transmission and sleeping mode, respectively. Whatever the payoff values are, but their explicit relationship between the defined payoff values is given by: \( P_{j} < P_{s} < P_{w} < P_{s} \). By defining \( \tau_{1}, \tau_{2} \) and \( w_{1}, w_{2} \) as the transmission and sleeping probabilities of player 1 and player 2, respectively, according to Table II, there are three strategies for both players. In this game, player 1 transmits with probability \((1 - \tau_{1})(1 - w_{1})(1 - w_{2})\tau_{1}\) and payoff \( P_{s} \). Player 1 can choose listening strategy with probability \((1 - \tau_{1})(1 - w_{1})(1 - w_{2})\) and payoff \( P_{s} \). The third strategy of player 1 is sleeping with probability \( w_{1}(1 - w_{2}) \), and payoff \( P_{w} \). Finally, if both of players transmit simultaneously, their payoffs are \( P_{j} \) and \( P_{j} \), when every node has to play its strategies with some probabilities.

In such games, the optimum equilibrium is in mixed strategy form. In mixed strategy equilibrium, it is not possible to achieve an optimum solution with one strategy and players have to mix several strategies probabilistically. In such games, players can reach their optimal response by cooperating each other. Here, the players can obtain the mixed strategy-based optimum response by choosing contention window as the tuning parameter to adjust the transmission probability of a node by Improved Backoff mechanism (IB) [70]. Comparing to traditional backoff scheme, IB scheme uses a small and fixed CW.

In IB scheme, nodes choose a non-uniform geometrically increasing probability distribution \( P \), for selecting a slot in a contention window. In fact, nodes pick a slot \( t_{r} \) in the range of \((1, CW)\) with the probability distribution \( P \) while \( CW \) is a fixed contention window. A node will be successful in getting access to the channel if it is the only node to choose \( t_{r} \). The distribution is defined as [61]:

\[
P = \frac{(1 - \alpha)\alpha^{t_{r}}} {1 - \alpha^{t_{r}}}, \quad \text{for} \ t_{r} = 1..CW.
\]

Here, \( 0 < \alpha < 1 \) is a distribution parameter. IB scheme does not defer similar to IEEE 802.11, so it saves energy and reduces latency in case of collision. The problem with IB is its fairness, but in WSNs, overall network performance is more important than of an individual node while all nodes do not always have data to send. Therefore, fairness is not a serious problem. Because of the complexity of the neighboring nodes information gathering, incomplete cooperative games can be a suitable candidate to optimize the performance of MAC.
protocols in wireless networks. In incomplete cooperative games, each player estimates some information about the game states and chooses its strategy accordingly.

3) Number of competing users Calculation: Many studies have shown that DCF performance is very sensitive to the number of competing nodes which try to transmit their packets on the shared media, simultaneously [71], [72]. DCF analysis indicates that the number of competing players is a function of conditional collision probability $p$ and transmission probability $\tau$. With respect to the incompletely cooperative framework, each node can measure $p$ and $\tau$ through several counters independently: Transmitted-Fragment Counter that counts the total number of successful transmitted data frames, ACK Failure Counter that counts the total number of unsuccessful transmitted data frames, Slot Counter that counts the total number of experienced time slots. Supposing an ideal channel (free of noise or interference) the number of competing nodes can be obtained from the (19) [72].

In [72] a clear statement of $n$ against $p$ and contention parameters like $CW_{\text{min}}$, $m$ and $\sigma$ has been derived, but no re-transmission bound has been considered. With re-transmission bound consideration, $\tau$ can be obtained from (20) [71]. However, Vercauteren et al, has shown that (19), (20) are only correct in the saturated situations in which each node has always a packet to transmit, so they do not work properly for bursty traffic in [73]. To resolve this problem, [71] proposes two mechanisms for estimating the operation time, ARMA and Kalman filters; these two methods are accurate even in unsaturated situations but their implementation in mesh nodes is very complicated.

Hence, in [66] a model called V-CSMA/CA has been proposed that works like CSMA/CA but only manages virtual frames. Of course, scheduling of such frames is similar to real frames and their difference lies in the fact that in VCSMA/CA when a node decides to transmit a virtual frame, no frame is transmitted. V-CSMA/CA estimates the collision probability by assuming real transmission of virtual frame. After the virtual frame transmission, the node examines the channel in the next time slot; if it finds the channel idle or no other node is transmitting real frames in the channel, it means that its virtual frame has been transmitted successfully. Otherwise, if other nodes are transmitting and if the channel is busy, it means that its virtual frame has experienced collision. Collision detection is done using a timer in CSMA/CA standard. If no confirmation is received in response to a transmitted frame before timer expiration, CSMA/CA supposes that a collision has occurred and the frame will be retransmitted. Of course, V-CSMA/CA does not detect collision in this way. Collision of a virtual frame is detected when other nodes transmit their real frames in the same time slot. In the case of collision, V-CSMA/CA will go into backoff process. Since no real frame is transmitted in VCSMA/CA, it has no effect on contention of other nodes and also no consumption of bandwidth and extra energy will occur [66]. Hence in this game, nodes follow hybrid CSMA/CA to estimate game state and to determine the number of competing nodes.

The channel contention process of the nodes is modeled as a dynamic Bayesian game, called a multiple access game. According to the Nash equilibrium of the game, a novel MAC scheme, called G-DCF is obtained. Under saturation conditions in which all nodes have packets to send, each node adjusts its local contention parameters for data transmission according to the current game state (i.e. the number of competing nodes), and thereafter updates the game state through the transmission feedbacks; but under unsaturated condition, a virtual frame scheduling mechanism, called VFS, should be incorporated in G-DCF to keep the idle nodes state in a consistent state. This process is finitely repeated to reach the optimal performance. If the node has no packet to transmit, it estimates the game state through CSMA/CA. Therefore, nodes have always packets, either virtual or real, to transmit; in other words, they are always in the saturation mode and they can use the above mentioned relations to estimate the number of competing nodes and to adjust their strategies with dynamic game state and to compete for accessing the channel with optimal strategy when transmitting their real packets. With this method, nodes are always ready to transmit their real packets and to make use of the channel efficiently [66].

4) Incomplete Cooperative CSMA Games Based on the Number of Competing Nodes: As mentioned in previous sections, optimal value of $CW_{\text{min}}$ depends on the number of nodes. In [49], [50], the channel contention between nodes is modeled as a dynamic Bayesian game. Zhao et al. have proposed cooperative games with above mentioned framework for WMNs, WSNs and Ad Hoc networks [13], [49], [50], [64]–[69], [74], [75]. In these games each node estimates the number of competing nodes ($n$) and then adjusts its minimal contention window as follows:

$$CW_{\text{min}} = \begin{cases} \lfloor n \times \text{rand}(6, 7) \rfloor & n \leq 5 \\ \lfloor n \times \text{rand}(7, 8) \rfloor & 6 \leq n \end{cases}$$

(21)

Where $\text{rand}(x, y)$ returns a random value between $x, y$ and $\lfloor z \rfloor$ is the largest integer not more than its argument. The simulation results have shown that the incompletely cooperative games are appropriate tools to improve throughput, decrease delay, jitters, and packet loss ratio. Since all nodes are able to

$$\tau = \begin{cases} (21-2p)(1-p)^{m+1} & r \leq m \\ (21-2p)(1-p)^{m+1} + CW_{\text{min}}(1-2p)(1-p^{m+1}) & r > m \end{cases}$$

(19)
obtain the number of competing nodes, they form a cooperative game and nodes with fewer numbers of competitors tune a smaller $CW_{\text{min}}$. In [66] mesh routers estimate the game state based on an incomplete cooperative game and broadcast this information to the clients. Then all clients perform a cooperative game based on estimated game state and obtain the optimal equilibrium strategy. The best strategy for nodes with more competitors is the selection of a larger $CW_{\text{min}}$ to reduce the collision probability. One advantage of [64], [65], [68], [69], [74] games compared to other games is that there is no need to exchange any information like SNR [15]. If distribution function of the payload size of frames is known, the optimal $CW_{\text{min}}$ will be a function of bit rate and number of competing nodes. In [67], it is suggested that each node estimates the number of its opponents $(n - 1)$, before tuning its $CW_{\text{min}}$ as follows:

$$CW_{\text{min}} = \begin{cases} 
  \lfloor n \times \text{rand}(6, 7) \rfloor & \text{bitrate} = 11\text{Mbps} \\
  \lfloor n \times \text{rand}(6, 7) \rfloor & \text{bitrate} = 5.5\text{Mbps} \\
  \lfloor n \times \text{rand}(6, 7) \rfloor & \text{bitrate} = 2\text{Mbps} \\
  \lfloor n \times \text{rand}(6, 7) \rfloor & \text{bitrate} = 1\text{Mbps}
\end{cases} \quad (22)$$

Simulation results show that packet drop ratio in this game, is much lower than DCF. In this game, each node adjusts its equilibrium strategy regarding the game state, it can transmit its packet successfully before the retransmission time reaches the retry limit, and no packet will be discarded. A game-theoretic EDCA (G-EDCA) to improve QoS in WLANs is proposed in [65], [75]. In a wireless network, each node can receive all the frames transmitted by its neighboring nodes. Therefore, it can obtain the source MAC address and the subtype field in the received data-frames. By counting the number of data-frames with different source MAC addresses, the player estimate the number of competing nodes of the four Access Categories (ACs), $(n_i, \text{where } i \text{ denotes a particular AC})$. After that, it adjusts its equilibrium strategy namely the size of contention window for each traffic class as follows:

$$CW_{i,\text{min}} = \lfloor n_i \times \text{rand}(7, 8) \rfloor, i = 3, 2, 1, 0 \quad (23)$$

Also (24) is used to adjust the current value of contention window for the $i^{th}$ traffic class:

$$CW_{i,j} = \begin{cases} 
  CW_{i,\text{min}} & j = 0 \\
  2CW_{i,j-1} & 1 \leq j \leq m_i \\
  2^{m_i}CW_{i,\text{min}} & \text{else}
\end{cases} \quad (24)$$

Where, $j$ denotes the number of consecutive failed attempts to transmit and $m_i$ is the maximum backoff stages of the $i^{th}$ class. The simulation results show that G-EDCA is an appropriate tool to improve throughput, and to decrease delay, jitter and packet loss ratio. It is obvious that the main weak point of CSMA/CA is the $CW$ increasing in response to consecutive collisions in the networks with high traffic load. Another simple protocol called (G-CSMA/CA) that calculates $CW_{\text{min}}$ after each packet transmission to maintain the real contention level is presented in [66]. This scheme is similar to what is done in [13], [66]. In this way, each node does not start the next process of contention with nominal $CW_{\text{min}}$. But in case of successful transmission of previous packet, the ultimate value of previous $CW$ is considered and the node adjusts $CW_{\text{min}}$ as $CW_{\text{min}} = CW/2$ in order to use the channel more efficiently. If the previous packet has been discarded, the best strategy to reduce the collision of the given node is to adjust the contention window as $CW_{\text{min}} = CW_{\text{max}}$. Furthermore, when a player is idle, she/he adjusts his strategy by transmitting a virtual packet (either successful or unsuccessful) and makes herself/himself ready to transmit her/his real packets. In this way G-CSMA/CA can be implemented easily in every mesh node (25) [64], [66], [68], [69].

With respect to particle swarm optimization, a game called (G-PSO) for WMNs is suggested as follows [76]: in this game, mesh routers estimate the game state via complicated mechanisms like ARMA and Kalman filters, more accurately and broadcast it across the networks. Thus, a cooperative game is shaped regarding the estimated condition to reach the global best ($p_{\text{best}}$). For example, each node adjusts its minimal contention window based on data rates after it became aware of the number of nodes as (22) which, here, is defined as $CW_{\text{min}}^g$. But if a node cannot obtain game state accurately and on time, it can adjust its strategy like G-CSMA. In fact it selects its personal best ($p_{\text{best}}$), so $CW_{\text{min}}^p$ is defined as (25). Therefore, in (G-PSO) each node adjusts its contention window as follows [76]:

$$CW_{\text{min}} = \begin{cases} 
  CW_{\text{min}}^p & \text{a node does not know the game state.} \\
  CW_{\text{min}}^g & \text{a node knows the game state.}
\end{cases} \quad (26)$$

G-PSO simulation results in better performance, compared to DCF and G-CSMA. It has shown that G-PSO increases throughput and decreases delay, packet drop ratio, and jitter. Despite the fact that cooperative algorithms are more efficient and optimal, their update process requires some massages to be passed, up to two hop neighbor nodes. Hence, non-cooperative games have drawn the attentions toward themselves. The next section deals with examining some non-cooperative CSMA games. As mentioned before, wireless nodes usually are not exactly aware of the number of nodes in the network and each node can obtain limited information about the channel state (collided packets, busy or idle state of channel). In such conditions, the best way is to optimize node’s personal goals and to tune its behavior according to the limited acquired information. Therefore, to model such a situation, non-cooperative game model is the best choice.

### B. Non-cooperative CSMA Games

Although cooperative games perform better than non-cooperative games, they need much signalling. Therefore
attention is attracted toward non-cooperative and distributed games. In this section non-cooperative CSMA/CA games are categorized into four essential groups: contention control games, power control games, joint power and access control games and joint power and rate control games.

1) Contention Control Games: In these games, players adjust their transmission probability to access the shared medium. Defining the utility (payoff) function is crucial in analyzing the strategies of selfish nodes [77]. Most papers that are modeling DCF in the presence of selfish behavior assume that each node wants to maximize its bandwidth share as well as its throughput. In [33], [52], [55], there are some examples of how utility functions are designed including the determination of contention criterion through reverse engineering of existing protocols or the desirable performance points (according to throughput and fairness) and also through forward engineering in a heuristic manner. For example, (27) represents a utility function which is defined through forward engineering, heuristically:

$$U_i(p_i) = \frac{1}{a_i} \left( \frac{(a_i - 1)b_i}{a_i} \log(a_ip_i - b_i) - p_i \right)$$  \hspace{1cm} (27)

Where $0 < b_i < 1, a_i > 1$ and $p_i$ is the transmission probability $p_i \in [2b_i/(1 + a_i), b_i]$. In these games each node keeps a constant transmission probability (or contention window) that is determined by Nash equilibrium of the random access game. In this game, convergence of asynchronous random algorithms is obtained by gradient method. Due to lack of knowledge about number of network users and also the obtained estimation in designing the utility function, dynamic algorithm may not converge to desirable performance point. Therefore, an algorithm for equilibrium selection, to lead these algorithms toward the desirable point, is presented [52], [78]. In [51] besides modeling the interaction between nodes as a non-cooperative game similar to [52] and [78], service differentiation has also been provided by defining different utility functions for different traffic classes with various weights. There is no need of definite exchange of channel access probabilities to calculate the payoff function in random access games presented in [51], [52], [55], [78]. Therefore, the games can be implemented in a distributed manner. In most researches including [51], [52], [55], [78] only cellular wireless local networks have been taken into account, in which each node hears transmissions of other nodes. Also it is assumed that all nodes are saturated, channel is error free and packet drop occurs only as a result of collision. Although direct learning of others channel access probabilities is difficult for wireless nodes, each node learns about the extent of network contention by observing some contention criteria that are functions of nodes channel access probabilities. The non-cooperative game presented in [15] is among the first researches that proposed a fair non-cooperative game model for interpretation of DCF mechanism. Authors of [33], [51], [52], [55], [79] define a general game-theoretic model, called random access game, to capture the distributed nature of contention control and wireless nodes interaction in such a contention-based medium access. They proposed a medium access method derived from CSMA/CA, in which each node estimates its collision probability and adjusts its persistence probability or contention window according to a distributed strategy update mechanism to achieve the Nash equilibrium. The payoff function of random access games can be interpreted as the net gain of utility from channel access decreased by contention cost. Hence, the equilibrium (or steady-state) properties of a contention control protocol can be designed through the specification of the utility function and the contention measure (e.g., collision probability). Their specification defines the underlying random access game whose equilibrium determines the steady-state properties such as throughput, fairness, and collision of the contention control protocol. The adjustment of channel access probability can be specified by different strategies to reach the equilibrium of the game. The medium access control problem is modeled as a non-cooperative game GMAC:

$$U_i = p_i \prod_{j \in N \setminus i} (1 - p_j) - c_ip_i$$ \hspace{1cm} (28)

In the utility function, node $i$ gets payoff 1 for a successful frame transmission, and the transmission of a frame also incurs the transmission cost $c_i$ (e.g. in terms of energy). Each player $i$ selects its channel access probability $p_i \in A_i = [0, 1]$ to maximize its utility.

Along the utility function definition, [80] defines a novel utility function to capture node’s gain from channel access. The payoff of this game, Game-Theoretic Contention Resolution(GCR), is defined similar to the previous games as follows:

$$u_i = U_i(p_i) - p_iq_i(p)$$ \hspace{1cm} (29)

$p_i, (0 < v_i \leq p_i \leq w_i < 1)$, is transmission probability and $q_i(p)$ is the conditional collision probability:

$$q_i(p) = 1 - \prod_{j \in N \setminus i} (1 - p_j)$$ \hspace{1cm} (30)

Where, $p_iq_i$ is the cost of channel access and the utility function is defined as:

$$U_i(p_i) = p_i - \alpha_ip_i + \frac{\ln(p_i)}{\beta_i}$$ \hspace{1cm} (31)

Where, $\beta_i = 1/v_i - 1/w_i$, $\alpha_i = \ln \frac{v_i}{w_i}$. Note that the utility function does not correspond to a physical quantity like throughput, delay, etc. but after an investigation, it has been designed to satisfy a desirable property such as having a unique non-trivial NE: $U_i(p_i^*) = q_i(p^*)$. GCR is played repeatedly by the nodes, as, it is a multi-stage game. Each stage includes a sequence of $K$ transmissions for a fixed $K > 1$. After $K$ transmissions, each node observes the cumulative effect (in the sense of conditional collision probability) of the players’ action in the previous round and updates its strategy. This method does not have any need to message passing or network-wide information. It is also observed that the utility functions in [80] outperforms DCF and also the comparable functions in [55]. The authors of [80], in another research [81] proposed a different utility function as:

$$U_i(p_i) = \frac{p_i[\ln w_i - \ln p_i + 1]}{\ln r_i}$$ \hspace{1cm} (32)

Where, $r_i = \frac{\alpha_i}{\beta_i}$. In this iterative and multi-stage game, each node observes the collective effect of all users by sensing
the collision probability in the previous stage: then each node chooses its strategy for the next round regarding the obtained information. This method also involves high throughput, low overhead and results in a good short-term fairness. Authors of [82] have proposed a non-cooperative and contention-based medium access game (CAG) with an initial framework similar to [51] and with selfish users. In CAG the number of users is pre-determined and constant. And each node estimates the medium access game (CAG) with an initial framework similar to [51], this Non-cooperative Random Access scheme (NRA) uses a general increasing and twice differentiable function \( J_n(.) \) instead of the linear collision cost, to express different levels of service tolerances of transmission failure due to collision.

Authors of [83], [84] establishes a MAC protocol with selfish users who are energy constrained and are able to change their contention window as a repeated non-cooperative game, GMAC. In GMAC, all network nodes are selfish, rational and do not cooperate in managing their communication. Each node \( i \) chooses its \( CW \) value (\( W_i \)) to maximize its own benefit described by a utility function defined as:

\[
u_i = \frac{\tau_i[1-(1-p_i)g_i-e_i]}{T_{slot}}\]

where \( g_i \) the gain of node \( i \) when successfully transmitting a packet, \( e_i \) is the cost of transmitting a packet, \( T_{slot} \) is the average slot length, \( u_i \) expressed as the expected gain during a slot time divided by the slot length, can be regarded as the expected payoff per unit time. Players use TFT FOR TAT (TFT) strategy as the best strategy in such an environment. In this approach, each user takes its decisions based on previous movement of other nodes. It has also designed a Markov chain model with respect to selfish users and has extended the game to a multi-stage game. In each stage \( k \), each player \( i \) measures the \( CW \) value of any other player \( j \) in the last stage and set its \( CW \) as follows:

\[
W_i^k = \min_{j \in N} W_j^{k-1}
\]

It has been shown that the game converges toward a Nash equilibrium that may not be globally the best. Therefore, selfishness does not always lead to network destruction but it
It has been shown that there are infinite Nash equilibria in this game, all of which do not result in fairness. Hence, in a non-cooperative game, implementation of some restrictions seems necessary. Therefore, for fairness establishment, users are required to consider the following relation in which \( w_i \) is the weights of users regarding their traffic features.

\[
\frac{p_1/(1 - p_1)}{w_1} = \ldots = \frac{p_i/(1 - p_i)}{w_i} = \ldots = \frac{p_n/(1 - p_n)}{w_n} = 1/K
\]

(46)

Based on its received SNR in wireless sensor networks, the Contention Window Select Game (CWSG) is formulated as a non-cooperative game in [88]. Each player selects the content window to control the access probability to maximize its utility. The utility function is defined as obtained throughput to access channel successfully. Simulation result shows that the utility is maximized at NE point. If \( C \) denotes the throughput of the wireless sensor network, the throughput can be described as follows according to the Shannon equation:

\[
C = B \log_2 (1 + SNR)
\]

(47)

And the utility function of a cooperative player \( i \) is defined as:

\[
U_i = P_i C
\]

(48)

Where \( P_i \) is successful access probability of player \( i \) which is defined as:

\[
P_i = \tau_i (1 - \tau_i)^{K-1}
\]

(49)

Here \( \tau_i \) and \( K \) are transmission probability and the number of sensors in the system, respectively. In distributed CWSG, the players cannot be obliged to obey the rule. But all of the players must be self-enforced to cooperate in the network. Hence, a penalizing mechanism based on repeated game is proposed to prevent the misbehavior of cheaters. On the other hand, since in cooperative game proposed in [57], there is not enough feedback and little information is exchanged across the network, a non-cooperative random access game with pricing(NRAP) is proposed [89]. In this game, the link utility function captures its demand for successful transmission and the pricing of persistence probability is used to improve efficiency for medium access. Each link tries selfishly to maximize its throughput through some local information. Limitation of nodes transmitting power has been also added to the conditions. Price of each link reflects the interference it gets from others. At first, a pricing function as a linear function of \( \beta_l \) is proposed in [89]. In this game, the link utility function captures its demand for successful transmission and the pricing of persistence probability is used to improve efficiency for medium access. Each link tries selfishly to maximize its throughput through some local information. Limitation of nodes transmitting power has been also added to the conditions. Price of each link reflects the interference it gets from others. At first, a pricing function as a linear function of \( \beta_l \) is proposed in [89].

\[
U_l(q, \beta_l) = W_l(f_l(q)) - \eta \beta_l q_l
\]

(50)

Where \( \eta \) is the cost function for user \( l \). Also \( \eta > 0 \) is the constant price coefficient, \( \beta \) are positive scalars and \( q_l \) is persistent probability. In equilibrium point, transmission probability, throughput, and packet collision probability, all depend on the constant price coefficient. Compared to standard protocols, the proposed algorithm resulted in rapid convergence and also effective and fair allocation of resources with less collision. Using the best response method, it has been shown that non-cooperative random access algorithm with
constant price gives better fairness compared with other BEB protocols. However, adaptive pricing method provides flexible trade off between performance and implementation overhead. From the network’s point of view, when the transmission environment is under low contention, the network should set a low price and allow the users to enjoy more chance to access the channel. But, when contention increases, it should set a high price. A good measure for the transmission environment experienced by a user is its conditional collision probability. So another non-cooperative random access game with adaptive pricing called NRA\(^5\)P is proposed to use an adaptive price setting based on the measurement of network conditions. The adaptive pricing scheme can lead to a Pareto dominant NE and enables higher link rates with lower persistence probabilities.

\[
\max_{q \in Q_i} U_{i}^{ad}(q) = W_i(f_i(q)) - (1 - \prod_{k \in L_i} (1 - q_k))\beta q_i \quad (51)
\]

Unlike the work in [37], these two non-cooperative random access schemes do not require each wireless link to announce its strategy to other links. It is shown that the non-cooperative random access scheme with fixed prices can allocate bandwidth more fairly compared to standard BEB algorithm. And the adaptive pricing scheme can achieve a better trade off between performance enhancement and implementing overhead compared to the fixed price proposed schemes [89]. Although the performance of non-cooperative games does not equate the cooperative ones but in non-cooperative games message exchange cost decreases.

In [90], Park et al. presents a distributed non-cooperative carrier sense update algorithm (NCUA) to adjust the physical carrier sense, \(s_i\). Physical carrier sense characterizes the spatial reuse level. In fact, a sender listens to the channel before each transmission and determines whether the channel is busy or not by comparing the received signal strength with its carrier sense threshold. If the received signal strength is above the carrier sense threshold, the sender considers the channel busy and defers its transmission. Otherwise, the sender starts its transmission. In this game, firstly the collision probability of each node is derived regarding the essential feature of physical carrier sense, and then its carrier sense threshold is updated. When a node increases its carrier sense threshold, the chance of channel access will increase as it will care for fewer nodes. To address this property, [90] introduces a non decreasing concave function for each node’s carrier sense threshold as a utility function \(U_i(x_i, x_{-i})\). And to balance out the effect of interference from the node on the others, a pricing function \(P_i(x_i, x_{-i})\) is defined according to the collision probability of each node. The Nash equilibrium of the game is computed by minimizing the following cost function.

\[
J_i(x_i, x_{-i}) = P_i(x_i, x_{-i}) - U_i(x_i, x_{-i}) \quad (52)
\]

NCUA does not require any information exchange; and it is also adaptive to the network environment changes. By considering the collision probability in the cost function, NCUA improves the overall network capacity compared to the standard CSMA. However in this analysis, the effect of dynamic contention resolution algorithm, such as BEB algorithm used in IEEE 802.11 DCF, has not been considered. By explicitly incorporating the carrier sense threshold and transmit power into [90], the problem of maximizing CSMA throughput is investigated in [91] and an analytical relation between MAC throughput and system parameters is derived. In this game, each node needs to consider not only its own throughput \(T_i\) (as profit), but also a certain penalty \(G_i\) (as price) for its adverse impact on other nodes. So it has to solve the following optimization problem:

\[
\max_{(x_i, P_i)} [T_i(x_i, P_i) - G_i(x_i, P_i)] \forall i \in N \quad (53)
\]

Where \(x_i\) is its carrier sense threshold and \(p_i\) is its transmit power. The obtained optimal carrier sense range is smaller than the one computed to cover the entire interference range. An interference-aware MAC protocol, which considers concurrent transmitting nodes in nearby clusters, is formulated in [92], both in the static and dynamic game settings. It is assumed that the proposed game is a non-cooperative, simultaneous-move game where nodes cannot communicate or even share information. Moreover, due to the fluctuating nature of the physical channel, this game is one of the incomplete information games. In the static setting, the proposed strategy is a Bayesian Nash Equilibrium (BNE) in which nodes choose to transmit regarding to a SNR threshold to determine the best trade off points between throughput and power consumption. BNE strategy ensures a stable outcome where nodes have no intention to deviate from the symmetric equilibrium. In the dynamic setting, a practical best-response dynamic procedure is presented for the nodes to easily find equilibrium of the static game. In this game, the action space of players is Transmit, Backoff. The player’s payoff functions are defined as follows:

\[
\prod_i(\text{Backoff, } a_{i-1}) = 0 \quad (54)
\]

\[
\prod_i(\text{Transmit, } a_{i-1}) = r_i(a_{i-1}) - \beta \quad (55)
\]

Where \(\beta\) is the cost of consuming transmission power, and \(r_i(a_{i-1})\) is the network throughput as (56). In [77], [93]–[95] a game theoretic approach is proposed for defining a generalized medium access protocol for slotted contention-based channels in infrastructure networks, when all the stations have a desired ratio between uplink and downlink throughput. It is assumed that each station tunes its access probability according to a best response strategy. Since the utility of each station depends not only on its own throughput but also on the Access Point (AP) throughput, no station is motivated to transmit continuously. Tinnirello et al. define uploading throughput \(s^i_u\) and downloading throughput \(s^i_d\) as follows:

\[
s^i_u(s_i, p_i) = \frac{\tau_i(1 - p_i)(1 - \tau_{AP})P}{P_{idle}\sigma + [1 - P_{idle}]T} \quad (57)
\]

\[
s^i_d(s_i, p_i) = x_iS_{AP}(p_{AP}) = x_i \frac{f(p_{AP})(1 - p_{AP})P}{P_{idle}\sigma + [1 - P_{idle}]T} \quad (58)
\]

Where \(P\) is the fixed frame payload, \(\sigma\) and \(T\) are the empty and busy slot duration, respectively. \(P_{idle}\) is the probability that neither the stations, nor the AP transmit on the channel. \(\tau_{AP}\) and \(p_{AP}\) are the transmission and collision probabilities
In [45] an Incentive Compatible Medium Access Control (ICMAC) is presented. It provides incentives for the players in a wireless network to optimize the overall utility using a Bayesian game formulation. First of all, based on the Vickrey auction, bids are collected from the various stations, then transmission time slots are assigned to the stations based on the highest bids. The price paid by the winning station represents the opportunity cost. ICMAC is robust to greedy behavior, and it does not show any degradation in performance with respect to IEEE 802.11 for realistic network size. ICMAC is a Time Division Multiple Access (TDMA) based MAC protocol that is robust to contention window misbehavior. The authors prompt the nodes to cooperate each other by a game theoretic approach using the Vickrey auction mechanism [45]. Another non-cooperative game-theoretic approach to study selfish MAC-layer misbehavior is presented in [96]. In this game, the obtained bandwidth shares are considered as payoffs and nodes choose backoff slots to maximize their long-term throughput. A forced mechanism is used to prevent the backoff attacks of misbehaving nodes. To obtain a better solution a repeated game is proposed in which a node considers the effect of its current action on the future actions of other nodes. The number of stages is finite and also large enough to reach the steady state values. Nodes can choose between standard or non-standard backoff configurations (i.e., fair or more-than-fair bandwidth share, respectively) to maximize their long-term payoffs. To prevent the backoff attack and to reach a fair Pareto optimal, a strategy profile called Cooperation via Randomized Inclination to Selfish/greedy Play (CRISP) is introduced. A misbehaving node deviating from CRISP will obtain lower bandwidth than that of nodes playing CRISP [96]. In non-cooperative contention control, each node tries to maximize its access to wireless channel by adjusting its transmission probability. In these games, nodes do not usually exchange information. So to prevent selfishness, it is necessary to define proper payoff functions which consist of utility and cost functions. In fact, each non-cooperative node must consider the effect of other nodes’ strategy on its access probability by considering the collision probability in the cost function.

2) Power Control CSMA Games: In [97]–[99], channel contention problem has been implemented as a non-cooperative power control game called GMAC. GMAC uses a shared channel for data and control. A linear pricing factor of power consumption is used in the definition of utility function.

\[ r_i(a_{-i}) = \begin{cases} \log(1 + \alpha \sum_{j \in S_i} h_{ij} h_{ij}^{-1} + \sigma^2) & \text{if } \alpha \sum_{j \in S_i} h_{ij} h_{ij}^{-1} \geq SNR_{th} \\ 0 & \text{else} \end{cases} \]  

(56)

In this game, \( \gamma_i \) denotes the SINR at the receiver, \( p_i \) is the transmission power of transmitter \( i \) (to be computed) and \( p_{-i} \) represents the transmission powers of all other links. Power control decisions are made for each packet. Simulations have shown that GMAC makes more concurrent transmissions possible and improves power consumption. GMAC uses RTS/CTS control packets for spreading interference information. And in this way, all terminals receiving RTS are locally synchronized. Nodes that intend to transmit data show their tendency by exchanging controlling packets in Access window (AW). AW allows neighbor terminals to exchange their controlling packets with each other. AW includes several access slots with constant lengths, but the number of slots changes dynamically according to network load.

After completion of data transmission, GMAC sends ACK packets continuously with maximum power, \( P_{max} \). The order of ACK transmissions is according to the order of their appearance in AW. In this game, each node can be in either three possible states: contention-free, contention, and transmission. When a node has a packet to transmit, it should wait until the start of a slot in the next AW. Then it senses the channel and if no carrier is sensed, the related terminal changes its state from contention-free to contention state with \( p_i \) probability and \( p_i \) is updated. Then the terminal waits for a random time \( B_i \) that has a uniform distribution in \([0, B]\) where \( B \) is a constant system parameter. If terminal \( i \) senses the channel busy during waiting time, it switches from contention to contention free state and \( p_i \) is updated; otherwise, it switches to the transmission state. In power control CSMA/CA games, each node adjusts its transmission power by considering the effect of the increased power on the others and also their reciprocity probability in increasing their transmission power.

3) Joint Power and Access Control CSMA/CA Games: In [100], [101], a distributed power-aware MAC algorithm called PAMG has been modeled for Ad Hoc networks, using static non-cooperative game idea. In this game, each active link has been considered as a player and its strategy vector are two-dimensional including transmission power and transmission probability. According to their location in the network and also their received feedback from channel, players selfishly tune their transmission probability and transmission power, simultaneously. Each link makes a decision based on optimality of its payoff function that has been defined on two-dimensional strategy space. Payoff function of this game includes utility and cost functions. The utility function is defined from optimization perspective and the cost function is also calculated through message passing. Payoff function for each link is as follows where \( \delta_j, \lambda_j \) are appropriate constants [101]:

\[ u_j(q_j, p_j, q_{-j}, p_{-j}) = \log(q_j) + \delta_j \log(\gamma_j - \beta) - \lambda_j q_j p_j \]  

(61)

Here, \( q_j \) and \( p_j \) are transmission probability and transmission power of link \( j \). \( \beta \) and \( \gamma_j \) represent the minimal accept-
able SINR and the average SINR, respectively. Each link can improve its data rate through increasing its power and transmission probability. The defined payoff function includes three terms, the first two represent utility of link and the third statement represents the transmission cost. The first statement shows that the more transmission probability of a link is, the more the utility of that link will be. The second statement in payoff function shows the effect of links transmission power on the utility and has been defined to guarantee the minimal SINR for the user. But the cost function, \( \lambda_j / q_j p_j \), increases with transmission power and transmission probability. The cost coefficient \( \lambda_j \), should be selected proportional to the number of links in the network. This constant coefficient is the same for all users [101]. This assumption is useful for easy implementation without message passing or when previous network topology information does not exist. But in [100], the constant coefficient is determined by message passing between players. Also according to PAMG, a distributed channel-aware MAC algorithm has been presented which is asynchronous in message passing. In the proposed algorithm, each active link broadcasts a control message simultaneous with its data transmission in each time slot. It also listens to the channel in each inactive time slot and receives the messages of other active links and updates its cost coefficient accordingly. Simulations have shown that this algorithm results in better performance compared to the models that only control the transmission power.

In [102], the issue of joint random access and power control design in wireless Ad Hoc networks is addressed with the use of game theory. The goal of the proposed joint random access and power control game (JRPG) is to minimize average transmission cost of links to support a given rate of the links. Using super modular game theory idea, the existence and uniqueness of Nash equilibrium are established. To ensure the feasibility of the game and also the network stability, an admission control algorithm has been considered.

A cross layer optimization problem for power allocation by controlling the contention window size in sensor networks is formulated in [103]. Utility function is considered as the reciprocal of time delay. Time delay is closely related to the transmission probability, successful probability and also the reciprocal of time delay. Time delay is socially optimal. The suggested procedure is distributed and simple to be applied in the existing IEEE 802.11 MAC protocol. In [104], it is specified how to use local transmit power efficiently and assign the transmission rate optimally with the use of a non-cooperative game-theoretic approach. For this purpose the utility function for a user is defined as the ratio of the user’s good put \( C_n \) to its transmit power \( P_n \) as (64).

\[
U_n = \frac{C_n}{P_n} \quad (64)
\]

Where \( C_n \) is the number of bits that are successfully transmitted per second (goodput) with rate \( R_n \) and it is defined as follows:

\[
C_n = \frac{R_n M_n}{M_n + R_n \epsilon_n} \quad (65)
\]

\( M_n \) is the number of bits needed to be transmitted by a user and \( M_n + R_n \epsilon_n \) is the number of overhead bits [104]. By this scheme, it is shown that game theory is an appropriate tool for examining the performance of the music file sharing, in a trade off between goodput and energy efficiency. A summary of investigated CSMA games is given in Table III.

### VI. Selfishness in CSMA Games

Study of the proposed cooperative and non-cooperative models for the purpose of improving CSMA method, leads toward the fact that the desirable solution for CSMA games should be unique, fair, and Pareto optimal. In cooperative games, the mentioned condition can be obtained by using different techniques such as bargaining, dealing, discussion and etc. But in non-cooperative games, these techniques are not suitable to reach the desirable result and some other techniques like punishment should also be used [2]. Users can implement greedy strategies at the driver level to increase their bandwidth share at the expense of hurting the other users. In CSMA games, cheating nodes usually tune their contention window to the minimum value to use the wireless resources more. Such a scenario is similar to a game in which nodes try to maximize their utility. Based on [83], a short-sighted player has negative impact on the network as it can degrade the network performance or even leads the network to collapse. Unlike selfish players, malicious players aim at collapsing the network. Hence, they have no incentive to operate on the efficient NE. They will surely deviate from equilibrium to reach their goal. Therefore, it is shown that a game theoretical

\[
\begin{align*}
\min_{z^k_i} & \ T_{d,i}^k(z^k_i) \\
\text{s.t.} & \ R_i^k(z^k_i) = \log (1 + z^k_i \sigma_i^k) \geq R_{th} \\
0 & \leq z^k_i \leq \bar{p}, i \in V, V = \{1...N\}
\end{align*}
\]

Where \( R_i^k \) is the data rate constraint, \( \bar{p} \) is the power constraint, \( R_{th} \) is the desired data rate and \( \sigma_i^k \) is the node \( i \)'s channel gain at time \( k \). Each sensor node uses its power to maximize its utility and also to satisfy the desired data rate. In joint games, each node has to tune two strategies. The goal of joint random access and power control design in wireless networks is to support a given rate in conjunction with minimizing the average transmission cost of the links.

4) Joint Power and Rate Control Games: power and rate control problem in IEEE 802.11 WLANs, is formulated as three specific non-cooperative games: the fixed-rate power control game GNPC, the fixe-power rate control game GNRC and the joint power and rate control game GNJPRC [78]. It is proven that the NE of the joint power and rate control game is socially optimal. The suggested procedure is distributed and simple to be applied in the existing IEEE 802.11 MAC protocol.

In [104], it is specified how to use local transmit power efficiently and assign the transmission rate optimally with the use of a non-cooperative game-theoretic approach. For this purpose the utility function for a user is defined as the ratio of the user’s good put \( C_n \) to its transmit power \( P_n \) as (64).
analysis of user interactions is necessary to prevent unfair resource sharing or resource collapse [77]. Cheating nodes are divided into penitent and recidivist cheaters. Penitent increase their contention window after being punished by other nodes so their throughput will reduce. Therefore they are punished just one time. But recidivist cheaters continue cheating even after being punished [105]. Among the first works that studied the application of game theory in CSMA access model, [47], [48] can be mentioned which studied the misbehaving nodes in MAC layer. In these researches, Cagalj et al. studied the effect of selfish behavior of some users and have shown that even the presence of few selfish users may lead the network to collapse, which itself is a motivation to encourage the users to cooperate. Authors of [47], with the assumptions of static nodes, similar traffic and infinite backlog for nodes, have proposed a static and a dynamic game to tune the contention window to maximize the throughput. Studies have proved the need of introducing penalty mechanisms to have acceptable performance in the presence of selfish stations. Queseth, in [106], has shown that in CSMA games which are performed only one time, the best strategy is to transmit which results in network collapse. But when a game is repeated several times, cooperative users can punish the misbehaving user and lead the game to an equilibrium point. The main difference between iterating and non-iterating games is that in non-iterating games, users do not have any motivation to cooperate; but in iterating games, it is possible to punish the other users and this feature prompts the users to cooperate. In a repeated game, a punishment method can be designed to motivate the users to follow the system rules and the cheaters who do not obey the rules, will be punished by other cooperative players. An assumption in iterating games is that in non-iterating games, users do not have any motivation to reward the other users and the cheating player will increase its contention window. Two reasonable reactions to selfishness behavior of cheating users are frame jamming and refusing ACK frames. In frame jamming, every node jams the data frame of misbehaving node, but in refusing ACK frames scheme, the node which is the receiver of the frames transmitted by misbehaving node, refuses to send ACK frames [83].

Supposed that $r_i$ and $r_j$ denote the average throughput of the cooperative player $i$ and the cheating player $j$, respectively. During the measure time $N_d$, If

$$\frac{r_j}{r_i} > 1 + \epsilon$$

(66)

where $\epsilon$ is the tolerance threshold, other cooperative users start to punish the cheater $j$ for a duration of $N_p$ time slots. Of course, it should be noted that throughput measurement of others is not an easy task.

In [106] compared to [47], a simpler model has been proposed to detect the misbehaving nodes. In the proposed method, each user who sends five packets without leaving the channel is considered as greedy and will be punished. Hatami, in [46] uses the number of data packets in a network as an indicator of misbehaving nodes existence. In fact, each node counts the data packets of every other node, including itself. This is indeed feasible due to the broadcast nature of the wireless medium. Then, each node calculates the mean, variance, and standard deviation of the whole data. If the number of packets of a certain node in the network is greater than the sum of both derived mean and standard deviation, it is assumed as a cheating node.

### B. Punishment

When a selfish user is detected in CSMA games, it will be punished by the others and got aware of its punishment and consequently it will increase its contention window. Two reasonable reactions to selfishness behavior of cheating users are frame jamming and refusing ACK frames. In frame jamming, every node jams the data frame of misbehaving node, but in refusing ACK frames scheme, the node which is the receiver of the frames transmitted by misbehaving node, refuses to send ACK frames [83].

In [88], [105], [107], [108], cheating users is punished by jamming its communication in a punishment period. In [106] the punishment is also suggested as jamming for the time needed to transmit five packets. In [107], during the punishment time that lasts $N_p$ time slots, all cooperative players switch to the jamming mode one by one and block the transmission of cheating $j$ with a short signal. In such a case, the packet of node $j$ cannot be properly recovered at the receiving terminal. Hence, the payoff of node $j$ will decrease to zero. In other words, during the punishment, confirmation of proper reception of the traffic transmitted by a cheater to a

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**TABLE III**

**SUMMARY OF CSMA GAMES**
function

Hatami proposes a dynamic game in which the cheater’s utility which each node changes channel access probability by tuning its contention window to reach the equilibrium. The payoff function of cheating users is formulated as follows [47], [48]:

\[ J_i = U_i - P_i \] (67)

\[ P_i = k_i(\bar{\tau}_i - \bar{\tau}), \bar{\tau}_i \geq 0, \bar{\tau} \in (0, 1) \] (68)

In this game, \( U_i \) is the utility function, \( P_i \) is the punishment function and each user is punished proportional to its throughput violation of the threshold limit. Author of [105] has considered a scenario with respect to [48] in the presence of a specific number of users with different QoS requirements and has modeled the traffic priority in this CSMA network using game theory. Each node labels its traffic with a specific traffic class and these classes do not change. In this model, it is expected that nodes with higher priorities access the wireless medium with lower values of contention window. Nodes with lower priority should not reduce their contention window to eliminate the higher priority nodes action. Each time throughput of a node is estimated, punishment mechanism will be done for the nodes which have violated the expected throughput.

\[ f_i = U_i - P_i = r_i - P_i \] (69)

\[ P_i = \begin{cases} r_i - r_j & \text{if } \tau_i > \tau_j \\ 0 & \text{otherwise} \end{cases} \] (70)

Where \( \tau_i \) is node \( i \)'s throughput.

Hatami proposes a dynamic game in which the cheater’s utility function \( U_i \) is as follows [46]:

\[ U_i = R_i - G_i \] (71)

Where \( R_i \) is the throughput of player \( i \) and \( G_i \) is its penalty function. \( G_i \) is defined as:

\[ G_i = k_i \left( \frac{1}{n_i} - \frac{1}{n_i^{opt}} \right), k_i > 0, n_i > 0 \] (72)

\( k_i \) and \( n_i^{opt} \) are constants and \( n_i \) is the average number of consecutive idle slots between two transmission attempts.

In addition, Cagalj et al. propose an incentive mechanism to guide multiple selfish nodes to a Pareto optimal Nash equilibrium in CSMA Ad Hoc networks by controlling their contention window [48]. But the convergence of their incentive algorithm is a bit slow.

A selfish backoff attack in a simplified form, whereby the configuration of the backoff scheme at each station is restricted to greedy, selfish and honest states, is studied in [109]. The stations success rate is considered as users’ payoff. It is shown that a non-cooperative CSMA game characteristic is similar to that of a Prisoners’ Dilemma. The unique NE of such a game is inefficient and the success rates decrease as the number of attackers increase. This fact permits to design a simple strategy for the repeated CSMA game, called Selfish Play to Elicit Live-and-Let-Live (SPELL). Assuming that the stations are rational players and wish to maximize a long-term utility, SPELL prevents a single attacker to play in the greedy or selfish manner.

The problem that a station can maliciously change the Access Category (AC) of its application to gain a higher utility is investigated in [108]. The authors use the technique of mechanism design in game theory to tackle this problem in random access WLANs. Mechanism design is a sub-field of microeconomics and game theory that studies the implementation of an optimal system allocation with self interested players, who aim to maximize their own payoffs. They also propose the Vickrey-Clarke-Groves (VCG) mechanism as a kind of mechanism design to motivate each station to inform the access point (AP) truthfully, about the required AC of its application. Groves mechanism and its subfamily named VCG mechanism are among the most efficient mechanisms that not only tackle dishonesty, but also guarantee achieving maximum social welfare. The AP will then inform each station about its persistent probability and the price it needs to pay for the offered service. Simulation results show that the use of mechanism design can lead to a higher aggregate utility and prevents malicious users from gaining an unfair share of network bandwidth.

In conclusion, it is shown that in a communication system which uses CSMA for medium access control, greedy behavior can be discouraged by punishment. However, in a real system it is not always possible to punish a misbehaving user. In other words, because of the time consuming process of misbehavior detection, moving nature of the nodes that move from one cell to the another and also the time limitation of punishing the cheating user, implementation, detection, and punishment of misbehavior users in a radio environment is a difficult task. This is discouraging since finding a cooperative solution generally requires the ability to punish the other users. But by enacting a large set of regulations that users are required to obey, it is possible to enforce users to cooperate [106]. Once it is detected that a user is greedy, he/she can be punished as long as she/he stays within the cell. It is of course possible to imagine that when the user moves to the next cell, the well behaved users tell the new cell users to watch out for this guy.

VII. CONCLUSION AND FUTURE WORKS

In recent years, application of game theory in wireless communications gained many attentions. Application of game theory in data link layer is concerned with medium access control problem. In these games, selfish users try to maximize their performance by unfairly accessing the channel which reduces the ability of other users to access it. Users have to overcome the collision incurred because of limited transmission resources.

Game theory is a powerful tool to analyze and improve the contention-based protocols. Numerous games have been proposed for modeling such environment in which users can select to transmit or to wait using a transmission probability. In cooperative games, each player has some knowledge about other players’ actions and makes her/his decision accordingly. As this assumption is not always valid in wireless networks, it must be investigated that how the characteristics of wireless networks influence the decision making process of players and the resulting equilibria.

The researches have shown that cooperative random access games can use radio resources more efficiently and fairly than...
non-cooperative ones. Thus to achieve an efficient and fair system with low collision, reception of control messages from other nodes seems necessary. It should be noted that message passing between nodes is based on cooperation assumption with the purpose of acquiring a system with a global goal. Game theory mechanisms help to reward the generous users and punish the selfish users to obtain the global goal. When nodes misbehave and try to monopolize the wireless channel, they are punished. Punishment mechanism has been presented to lead the system act around a Nash equilibrium that is also Pareto optimal.

According to previous sections, some open research directions regarding the application of game theory in CSMA can be briefly mentioned as follows:

- The transmission probability can be modified by tuning the contention parameters like $CW_{\text{min}}, CW_{\text{max}}, m, \sigma$ and $r$. In most of proposed CSMA games, the transmission probability is adjusted by tuning $CW_{\text{min}}$.
- It seems more logical to use multi-dimensional strategy vector considering other parameters like duration of transmission opportunity, transmission power, transmission rate, modulation method, spatial reuse in addition to transmission probability. So studying of joint strategy CSMA games may be attractive.
- Many different payoff functions are proposed in CSMA games. Comparing these utility functions in terms of performance and effectiveness seems necessary.
- The intended fairness for service differentiation, better contention control and consequently higher throughput can be achieved by specifying proper utility functions. Therefore, the payoff function that including utility and cost functions is very important in random access games. In most researches, however, this function has been defined heuristically without sufficient explanation. Most of the introduced utility functions have been only based on transmission probability, estimated collision or transmission power. But a proper utility function should take into account system parameters. These parameters include QoS requirements, user’s priority, user’s queues status, channel conditions, power limitations, priorities of packets and etc. To design proper payoff functions which are convergent toward optimal equilibrium point, it is suggested to use reverse engineering, forward engineering or heuristics. Therefore, proposing a general framework to design utility and cost functions in CSMA games is another challenge that needs further research.
- In CSMA networks, users usually have little information about the state of each other, make them to decide based on estimation of partial information. Collecting more useful information improves the efficiency of the decision making process. Therefore, developing simple ideas for gathering more information will also be useful. Using Bayesian learning and Bayesian games to gain more accurate information about unreliable and dynamic wireless environment can also be profitable to study CSMA games under incomplete information.
- Researches show that the connections between game theory and artificial intelligence are deep and they originate from similar roots. Therefore, combination of game theory, artificial intelligence and learning models in case of acceptable degree of complexity can be effective in estimating the game state.
- Most of the proposed games assume that all the users are within the same radio range hearing each other and they do not consider the effect of hidden nodes. Investigating the effect of hidden nodes on the game dynamics is one of the open issues.
- In most of the papers, the users are considered saturated and their arrival traffic distribution is assumed to be Poisson, while this is not correct for bursty traffics. Hence, study of CSMA with self similar traffic may be of research interest.
- Typically, the number of nodes has been considered constant and their movements have been ignored. Considering the nodes mobility and topology changes in study of CSMA problem is another subject for further research.
- Study of equilibria other than Nash equilibrium may be interesting. In fact, most of CSMA games only study Nash equilibrium as the solution concept. But it is evident that Nash equilibrium does not always provide the best performance. Therefore, other equilibrium concepts such as Nash bargaining solution and correlated equilibrium need to be investigated, too.
- Moreover, most of punishment models are based on jamming that reduces the channel utilization. Therefore, presentation of simple and new mechanisms for punishment can also be effective in improving CSMA games performance.
- Studying the interaction between physical carrier sense and contention resolution in a game-theoretic framework can be another research topic.
- Investigating the coexistence of the access methods and 802.11 DCF, to understand how the resource is shared among wireless nodes with the use of different medium access methods is considerable.
- Networks in which some players are selfish, and others are socially responsible can be modeled as a hybrid (cooperative and non-cooperative) game. Proposing new hybrid game models for CSMA networks is another issue that deserves to be investigated.
- Cooperation binding mechanisms, planning mechanisms for avoiding multiple access attack and multiple access in heterogeneous environments are some examples of open research directions which interested readers can be referred to [2] for more details.

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