An Overview of Game Theoretic Approach to Intrusion Detection System in IoT

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Abstract

Security is a vital role in modern world. Its usually provided in the three phases such as intrusion prevention, intrusion detection and intrusion tolerance. However, the network security problem is far from completely solved. Researchers have been exploring the applicability of game theory approaches to address the network security issues. This paper reviews some existing game theory solutions which are designed to enhance network security in the intrusion detection phase.

Keywords: Intrusion detection,game theory,IoT,Security

Game Theory: A Brief Overview

Game theory is an advanced branch of intelligent optimization. The model of game theory represents a game between player groups that choose to behave cooperatively or non-cooperatively and try to promote their benefits (payoffs) through the used strategy executed through the cumulative players actions. [1,2] survey the fundamental definitions of game parameters, which can be summarized as follows:

Definition 1. A game is a description of the strategic interaction between opposing, or cooperating, interests where the constraints and payoff for actions are taken into consideration.

Definition 2. A player is a basic entity in a game, which is involved in the game with a finite set of players denoted by N that is responsible for taking rational actions denoted by A_i , for each player i. A player can represent a person, machine, or group of people within a game.

Definition 3. The Utility/Payoff is the positive or negative reward to a player for a given action within the game denoted by $u_i : A \rightarrow R$, which measures the outcome for player i determined by the actions of all players A.

Definition 4. A strategy is a plan of action within the game that a given player can adopt during game play denoted by a strategic game hN,(A),(u_i)i.

Game theory [3], a new branch of applied mathematics, is a subject to study optimal solutions in the context of conflicts. Game refers to the procedure that some people, groups or organizations choose and carry out the strategies that they choose from their action sets synchronously or successively, once or repeatedly under certain environments and rules. Corresponding payoffs are achieved after all players choose strategies.

In order to describe a game, there are some essential elements, including players, actions, information, strategies, payoffs, outcome and equilibrium. The definitions of these elements are given as below. Player is the entity involved in a game, namely the decision maker who chooses actions to maximize its utility or payoff in the game. What is more, the player can be an individual, a company, a nation, and so on. Strategy is a player's plan of action that specifies which action to take based on its knowledge of action history. Strategies can be pure or mixed, which could be dynamically changed. There are two more terms that need to be noticed. One is strategy set or strategy space, which is the set of a player's all possible action. The other is strategy profile that is a set composed by strategies from which all players choose. After all players have taken actions in the game, each of them will get either a negative or a positive return. The return of each player is its payoff. Apparently, the player's payoff not only depends on its own action, but also is impacted by other players' actions. Different combinations of players' strategies result in different outcomes.

Information means the knowledge that the players know, especially the characteristics and the actions of other players. The characteristics of the aforementioned strategy space, payoff and players consist of the information structure of a game. Equilibrium is a combination of all players' strategies where each player's strategy is the best response to the strategies of other players. Equilibrium is one kind of stable outcomes.

Nash Equilibrium (NE) is one kind of equilibrium that can be applied to come up with the solution of a game. It is noticeable that the definition of equilibrium cannot ensure solution uniqueness, and the lack of unique solution is exactly the main problem of game theory. What is more, we may counter an adverse problem that a game does not have an equilibrium, which means that the modeler cannot find a reasonable strategy profile. A game model with no equilibria or with multiple equilibria is an underspecified model, in which the modeler does not give a comprehensive and precise prediction about what is going to happen.

Typical Game Models

Gift-giving game contains two kinds of players. One is an employer who provides works (or wages) and the other one is a worker who decides whether accept the wages or not. If there is no workers accept the wages, the benefits of both of them are zero. If a worker accepts the wage, he should choose the level of his efforts. The more he contributes, the more the benefits the worker can obtain.

Bayesian Game, which is also called a game with incomplete information, is a game where the players have incomplete information about other players' strategies or payoffs. But they know the probability distribution of the others' strategies. The equilibrium of Bayesian Game is called Bayesian Nash Equilibrium (BNE). If $T > R > P > S$, then this situation is called the prisoner's dilemma. The best outcome of a player is unilateral defection (defect while the other player chooses to cooperate) while the equilibrium of this game is mutual defection due to the higher potential benefits of defection. Zero-Determinant (ZD) strategy was first proposed by Press and Dyson [4] to solve 2-player iterated prisoner's dilemma. A player with ZD strategy can make its own payoff have a linear relationship with the other's payoff. The other player has no idea about this ZD player. Thus the ZD player can take this advantage to force the opponent to choose the strategy that the ZD player wants the other player to choose (e.g., cooperation) by setting the relationship properly. What is more, recent research shows this strategy can be extended to larger application scenarios with multiple players [5].

Stochastic game [6], which consists of finite or infinite number of stages, refers to a dynamic game with probabilistic transitions played by one or more players. In each stage, the game begins at an uncertain state, and then its players choose their strategies and obtain payoffs according to a current state and the strategies they choose. The state of each stage does not have to be the same and if they are the same, the game is a repeated game. If the number of players in a stochastic game is finite and the number of possible states in each stage is finite, it must have a NE, which may not be the optimal strategies for both players. Stochastic game is also called Markov game.

Potential game [7] is a very helpful game in designing schemes and instructing players in choosing strategies. The most important notion in the potential game is potential function, which is a global function related to each player's payoff function. A significant property of potential game is that the NE must exist and it can achieve maximize overall profits.

Differential game [8] is a kind of cooperative game, where players interact with each other continuously to achieve their own optimal objectives. It can be widely used in addressing optimal control problems.

Colonel Blotto game [9] is a zero-sum game within two players who distribute their limited forces to some battlefields at the same time. Each player has no idea about the strategies of another. In each battlefield, the player who allocates more forces will win. They need to figure out the most optimal allocation plan in order to win as more battlefields as possible.

Behavioral game [10] is different from traditional games that assume players to be rational and unwilling to believe in others. However, behavioral economists proved that traditional games are impractical in modeling actions of humans. Behavioral game takes irrational factors into consideration and makes a game model more socialized. This kind of game can be used to model interactions with many human participations. In most research, players are assumed to be overly reasoning, which is not reasonable in some practical scenarios. Players in evolutionary game are bounded rational. A player with bounded rational will not change its strategy until its benefit decreases significantly. Evolutionary game takes various factors that may influence a player's decisions into consideration and analyzes the evolution of player actions. Evolutionarily Stable Strategy (ESS) is a strategy adopted by most members of the population. When most players in a system choose the ESS, the system is strong enough to resist small turbulence.

Shapley value [11] is a concept in cooperative game. It is a value to evaluate the contribution of each player. With the help of Shapley value, the overall utility of all players can be distributed to a coalition fairly. Sealed-bid auction is a type of auction process where every buyer (e.g., worker) submits its sealed bid to an auctioneer (e.g., a platform) simultaneously, and then the auctioneer sells its product (task) to the buyer who has offered the highest bid and publishes it to the public after comparison. Vickery–Clarke–Groves (VCG) mechanism is one kind of sealed-bid auctions. This mechanism can alleviate players to tell the truth and distribute the items bided optimally.

Motivation To Use Game Theory In Intrusion Detection

Motivation to Use Game Theory in Intrusion Detection With the increasing development of network technology, network security issues are receiving more and more attention. The Intrusion Detection System (IDS) is the firewall for data encryption and other traditional security measures that protect the security of the new generation of technology. However, because the invasion and the continued expansion of the scale of the network are constantly burgeoning, IDSs based on the traditional pattern matching is no longer useful. The game-theory-based intrusion detection system will effectively solve this problem, it is the third-generation intrusion detection pattern matching technology that can meet the needs of the new IDSs.

All of these methods are subject to the following problems: They continuously use additional resources in the system they are monitoring, even without any intrusions occurring. As the components of the intrusion detection system are put into effect as separate processes, they are subject to tampering. An intruder can disable or modify the programs running on a system potentially, so that the intrusion detection system is useless or unreliable. Instead of depending mainly on heuristic solutions, there have been increasing interests and efforts devoted recently to analytical methods for researching security problems, especially to unleash the theoretical performance behaviors, and expected requirements to design practical systems.

Game theory is used to establish a mathematical model to capture behavior in strategic situations. After the intrusion detection system detects an attack, it will respond to minimize the loss of the system. For single-stage attacks, the process of finding the defenders' best responsive action to a detected attack and maximizing payoffs is a majorization problem.

However, since attackers usually launch multistage attacks in reality and the defenders do not know the attackers' full strategies when making decisions to minimize the loss, the problem becomes finding the best strategy using game theory. The second reason for using a game model is that it is more accurate in analyzing the attacker and the defender's payoff, which can intuitively explain a series of problems brought by the network intrusion. Furthermore, due to the rigor and accuracy of the game theory, we can get an optimal choice compared with other methods, as long as the right game model is established.

We can analyze the Nash equilibrium through the process of the game and get the optimal strategy of the game, which is what the other intrusion detection system cannot achieve. Finally, the process of the game is both sides, not unilateral. This is another big advantage of game theory. We can use the payoffs of both offensive and defensive to judge whether the invasion (or defense) is successful or not.

Game Theory Applications In Iot

The rapid development of Internet of Things (IoT) technology makes it possible for connecting various smart objects together through the Internet and providing more data interoperability methods for application purpose. Typically, IoT is expected to offer advanced connectivity of devices, systems, and services that goes beyond machine-to-machine communications and covers a variety of protocols, domains, and applications. The interconnection of these smart devices is expected to usher in automation in nearly all fields while reducing the need of human interventions. The future vision of IoT has evolved due to a convergence of multiple technologies, ranging from wireless communication to micro-electromechanical systems. This means that all traditional technologies have contributions to enable the IoT [12, 13, 14].

Recently, information cascades over IoT systems can deeply influence the patterns of social behaviors. Indeed, we have become increasingly aware of the fundamental role of the coupled socio-physical network as a medium for the spread of information. Socio-physical approach considers jointly the interaction and integration of the social and physical views of IoT systems and yields meaningful qualitative and quantitative differences when compared with approaches that focus on the social and physical views in isolation. During IoT system operations, this collaborative approach provides services to both people and technical systems while realizing the vision of future pervasive computing environments [15,16].

In IoT systems, individual devices locally make control decisions to maximize their profits. This situation can be seen a game theory problem. Game theory is a decision-making process between independent decision-making players as they attempt to reach a joint decision that is acceptable to all participants. The standard application of game theory requires each player to form a utility function that quantifies the benefit that accrues to it as a consequence of the actions that it and all other players may take. In the traditional game theory, a solution concept is a rule that defines what it means for a decision vector to be acceptable to all players in the light of the conflict/cooperation environment [17].

Usually, game theory implicitly assumes that players have complete information about the game situation throughout the time period. Therefore, many game models assume that players are on perfect rationality and can have enough abilities to act according to their preferences. However, this assumption is obviously not satisfied under the real-world environment; experiments have shown that players do not always act intelligently [17]. In addition, traditional game methodologies attempt to optimize individual player's profit. However, the game players' group interest is generally not optimized and perhaps not even well served if each individual player optimizes his own behavior. This is because optimization is an individual activity that is based on the doctrine that each individual is committed to maximizing its own satisfaction without concern for the welfare of others [18].

To overcome the limitations of traditional game theory, behavioral science is a newly discovered research approach. It is the idea that in decision-making, the rationality of individuals is limited by the information they have, the cognitive limitations of their minds, and the finite amount of time they have to make a decision. In real-world situations, decision-makers lack the ability and resources to arrive at the optimal solution. Therefore, the decision-makers are seeking a satisfactory solution rather than the optimal one. It is an alternative way of traditional optimal decision-making, which views decision-making as a fully rational process of finding an optimal choice given the information available. To understand the complex social behavior, behavioral science has become very popular and of growing interest in social sciences [19].

A newly developed behavioral learning game involves the idea that players take reasonable strategies that may lead to suboptimal decision-making. Therefore, players engage in mapping the decision strategies that players use in order to help increase the effectiveness of decision-making process. During the behavioral learning game operations, players iteratively negotiate with each other and adaptively modify their strategy selections in an attempt to reach a mutually acceptable decision vector. As a new solution concept of behavioral learning game, the observed agreement with behavioral development is introduced. Such an agreement in decision-making, if reached, is called behavioral learning equilibrium. During game operations, game players may not realize how their learning experience would have been different if they had chosen to behave differently. Therefore, they may adjust their behavior when experience contradicts their beliefs. The novel solution concept of behavioral learning equilibrium presents a dynamic learning interpretation to justify their behaviors.

Recently, IoT technology has been widely explored in many fields. IoT is the interconnection of uniquely identifiable network agents or smart objects within the existing internet infrastructure.

The rapid IoT development makes it possible for connecting various smart objects together through device-to-device communications and providing more data interoperability methods for application purpose [20]. However, there is much room left to exploit diverse social interactive relationships among agents for networking optimization, and it is of great interest to explore the continuum space [21, 22, 23]. Motivated by the facts presented in the above discussion, in this paper, we design a new IoT communication control scheme based on the behavioral learning game model. With considering the socio-physical relationship, we take into account both the agents' social relationships and physical coupling.

Conclusions

In this article, we proposed a game-theory-based attack-defense game model to improve the energy consumption and detection rate for ESNs in IDS. The key feature in this attack-defense game model is using mixed strategies (δi, σi) to fairly achieve optimal performance. Furthermore, attackers and defenders can change their own strategies periodically to reach their maximum payoffs, respectively. Simulation results showed that the proposed game model can lead to a more fairly competitive environment for the IDS, where the model can increase the IDS's payoffs, reduce energy consumption, and improve stability. Therefore, the game-theoretic IDS can be applied to an embedded scenario to protect the data and further ensure the safety of ESNs in CPESs.

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