Learning Optimal “Pigovian Tax” in Sequential Social Dilemmas

Abstract

In multi-agent reinforcement learning (MARL), each agent acts to maximize its individual accumulated rewards. Nevertheless, individual accumulated rewards could not fully reflect how others perceive them, resulting in selfish behaviors that undermine global performance, which brings the social dilemmas. This paper adapts the famous externality theory in economic area to analyze social dilemmas in MARL, and propose the method called Learning Optimal Pigovian Tax (LOPT) to internalize the externalities in MARL. Furthermore, a reward shaping mechanism based on the approximated optimal “Pigovian Tax” is applied to reduce the social cost of each agent and tries to alleviate the social dilemmas. Compared with existing state-of-the-art methods, the proposed LOPT leads to higher collective social welfare in both the Escape Room and the Cleanup environments, which shows the superiority of our method in solving social dilemmas.

Keywords

Multi-Agent Reinforcement Learning; Sequential Social Dilemmas; Reward Shaping; Externality

ACM Reference Format:


1 INTRODUCTION

Reinforcement Learning [21] has achieved wide success in various tasks [8, 10, 15, 27] and has been successfully expanded into the multi-agent area, especially in fully-cooperative games [13, 24, 25]. However, most recent centralized learning [4, 17, 18, 20] and decentralized learning methods [2, 19, 22] is either not suitable for self-interested agents or have difficulty in dealing with coordination among agents. In many real-world environments with mixed motives, such as those within exclusionary and subtractive common-pool resources [11, 12, 16], selfish agents may fall into social dilemmas because of the temptation to evade any cost, which harms social welfare.

The concept of the social dilemma originates from economics and describes the situations in which individual rationality leads to collective irrationality [9]. In multi-agent reinforcement learning, it is specified as a conflict between agents’ self-interest based on their local rewards and social welfare [11]. Externality theory is proposed to deal with social dilemmas in economics [23], which present whenever the well-being of a consumer or the production possibilities of a firm are directly affected by the actions of another agent [14]. Therefore, it may become a typical tool to measure self-interested agents’ influence on social welfare.

In this paper, we introduce the externality to analysis social dilemma in MARL. Furthermore, motivated by “Pigovian Tax”, which is one of the most popular solutions [3] in non-market economics [1, 3] to deal with externalities, We build a typical reward shaping mechanism to promote social welfare.

Our proposed method is called Learning Optimal Pigovian Tax (LOPT), where a centralized agent, called Tax planner, is built to learn the Pigovian tax/allowance based on the global reward. In learning process, Tax planner aims to maximizes the long-term global reward, which is equivalent to approximating the optimal Pigovian tax. Based on the learned tax/allowance rates, a reward shaping with a distinctive structure, Optimal Pigovian Tax Reward Shaping, is established. As a result, such a reward shaping structure visualizes each agent’s social cost and alleviates the social dilemmas.

2 Method

Externality in MARL: In economics, an externality occurs whenever the activities of one economic actor affect the activities of another in ways that are not reflected in market transactions [14]. In this paper, we expand the definition of externality to the multi-agent reinforcement learning area:
Definition 1. An externality occurs whenever the actions of an agent affect others in ways that are not reflected in local rewards.

We consider a decentralized multi-agent reinforcement learning scenario with an N-player partially observable general-sum Markov game on a finite set of states \( \mathcal{S} \). In each timestep, agents receive their \( d \)-dimensional views from the observation function \( O : s \times \{1, \ldots, N\} \rightarrow \mathbb{R}^d \) based on the current state \( s \in \mathcal{S} \). Then, agents select action \( \{a_{i}\}_{i=1}^{N} \in \{\pi_{i}(a|o_{i})\}_{i=1}^{N} \) from the set of actions \( \{\mathcal{A}_{i}\}_{i=1}^{N} \), which transfers to the next states \( s' \) according to the transition function \( P(s'|a_{1}, \ldots, a_{N}) \). Based on Definition 1, the externality of agent \( i \) can be defined as:

\[
E_{i}(s, a_{-i}, a_{i}) = Q^*(s, a^*) - Q(s, a_{-i}, a_{i}) ,
\]

where \( Q^*(s, a^*) \) is the optimal joint state-action value function and \( Q(s, a_{-i}, a_{i}) \) is the joint state-action value with agent \( i \)'s current action and other agents’ optimal actions. For internalizing the externality and solving the social dilemma, the optimal Pigovian tax based reward shaping is written as follows:

\[
F_{i}(s, a_{-i}, a_{i}) = Q^*(s, a^*) - Q(s, a_{-i}, a_{i}) ,
\]

where \( Q^*(s, a^*) \) is the optimal joint state-action value function and \( Q(s, a_{-i}, a_{i}) \) is the joint state-action value with agent \( i \)'s current action and other agents’ optimal actions. For internalizing the externality and solving the social dilemma, the optimal Pigovian tax based reward shaping is written as follows:

\[
F_{i}(s, a_{-i}, a_{i}) = Q^*(s, a^*) - Q(s, a_{-i}, a_{i}) .
\]

It can further be reshaped as follows:

\[
F_{i}^{2}(s', a_{-i}', a_{i}') = \sum_{j=0}^{N} r_{j}(s', a_{-i}', a_{i}') - \sum_{j=0}^{N} r_{j}(s', a_{-i}', a_{i}') .
\]

Learning Optimal Pigovian Tax (LOPT) method is proposed to learn the optimal Pigovian tax based reward shaping. In LOPT, we design the Pigovian tax reward shaping within percentage tax/allowance formulation as:

\[
F_{i}^{3}(s', a_{-i}', a_{i}') = -\theta_{i}(s', a_{i}') r_{i}(s', a_{-i}', a_{i}') + \delta_{i} s_{i}^2 \sum_{j=0}^{N} \theta_{j}(s', a_{j}') r_{j}(s', a_{-i}', a_{i}') .
\]

where \( \theta \) is the tax rates on all agents, \( \theta_{i} \) is the specific tax rate for agent \( i \), while \( \delta \) is the allowance rates on all agents, \( \delta_{i} \) is the specific allowance rate for agent \( i \). They are treated as functions based on the current joint state and action. Learning the optimal Pigovian tax reward shaping needs to learn \( \theta \) and \( \delta \) so as to let all \( F_{i}^{3}(s', a_{-i}', a_{i}') \) equal to the \( F_{i}^{3}(s', a_{-i}', a_{i}') \).

From Figure 1, The LOPT uses a centralized tax planner for learning Pigovian tax-based reward shaping functions. It can be described as a centralized reinforcement learning agent: \( \langle S_{P}, O_{P}, A_{P}, R_{P} \rangle \), where \( S_{P} \) is the global state space for the tax planner, and \( O_{P} \) is the observation function to get observation \( o_{P} \) from its global state, \( A_{P} \) is its action space, and \( R_{P} \) is the reward function for it. Typically, the observation in timestep \( t \), \( o_{P}^{t} = (s', a') \) includes these general agents’ joint state and action in the same timestep, while the action in timestep \( t \) includes the tax rates and allowance rates for all general agents \( a_{P}^{t} = (\theta_{i}^{t}, \delta_{i}^{t}) \). In the training process, we use the approximate state action function \( Q_{P}(o_{P}, a_{P}) \) to replace the cumulative global reward (Social Welfare), the gradient loss for the tax planner is:

\[
\mathbb{E}_{\pi_{P}} \nabla_{\pi_{P}^{\phi_{P}}} \log \pi_{P} \left( a_{P}^{t} \mid o_{P}^{t} \right) Q_{P} \phi_{P} \left( o_{P}^{t}, a_{P}^{t} \right) + \eta f \phi_{P} \left( o_{P}^{t} \right) ,
\]

where function \( f(\phi_{P}) = \sum_{t=0}^{T} \sum_{s=0}^{T} F_{t}^{3}(s', a_{-i}', a_{i}') \), which is the entropy to maintain the balance on tax and allowance. In light of the learning process of the tax planner, other general agents are trained within the approximated optimal Pigovian tax reward shaping as follows:

\[
\mathcal{L}(\phi_{i}) = \mathbb{E}_{\pi_{i}^{\phi_{i}}} \nabla_{\pi_{i}^{\phi_{i}}} \log \pi_{i} \left( a_{i} \mid s \right) Q_{i}^{\phi_{i}} \left( s, a_{i} \right) ,
\]

where function \( Q_{i}^{\phi_{i}}(s, a_{i}) \) is defined as:

\[
Q_{i}^{\phi_{i}}(s, a_{i}) = r_{i}(s, a_{i}) + F_{i}^{3}(s', a_{-i}', a_{i}') + \gamma \max_{a_{-i}} Q_{i}^{\phi_{i}}(s', a_{i}') .
\]

3 EXPERIMENT

To benchmark LOPT we use Cleanup [6], a set of environments with social dilemmas. We compare LOPT with LIO [26], IA [6], MOA [7], SCM [5], and common reinforcement learning algorithms in previous works [5–7, 26]. Figure 2 LOPT can reach better social welfare, especially in more complex Cleanup(N = 5) scenarios.

4 CONCLUSION

In this paper, the externality theory is first introduced to analysis social dilemmas in MARL. Based on it, Learning Optimal Pigovian Tax method is proposed to deal with social dilemmas. In LOPT, the tax planner learns each agent’s tax/allowance allocation policy. Pigovian tax reward shaping internalizes each agent’s externality to encourage them to promote social welfare. Experiments have shown the superiority of the proposed mechanism for alleviating social dilemmas in MARL. In the future, we aim to build a decentralized Pigovian tax/allowance mechanism to learn the reward shaping to internalize agents’ externality with lower computation complexity.
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