
Sparse Adversarial Attack in Multi-agent Reinforcement Learning

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Abstract

Cooperative multi-agent reinforcement learning (cMARL) has many real applications, but the policy trained by existing cMARL algorithms is not robust enough when deployed. There exist also many methods about adversarial attacks on the RL system, which implies that the RL system can suffer from adversarial attacks, but most of them focused on single agent RL. In this paper, we propose a *sparse adversarial attack* on cMARL systems. We use (MA)RL with regularization to train the attack policy. Our experiments show that the policy trained by the current cMARL algorithm can obtain poor performance when only one or a few agents in the team (e.g., 1 of 8 or 5 of 25) were attacked at a few timesteps (e.g., attack 3 of total 40 timesteps).

1 Introduction

Many real-world sequential decision problems involve multiple agents in the same environment, where all agents work together to accomplish a certain goal. Cooperative multi-agent reinforcement learning (cMARL) is a key technique for solving these problems. In recent years, cMARL has been applied to many fields, such as traffic light control [31], autonomous driving [25], wireless networking [15], etc.

However, many prior works about adversarial attacks on single agent RL have already shown that the policies trained by most current single agent RL algorithms are not robust enough, thus one cannot use them with confidence in real-world applications. But to the best of our knowledge, there are very few prior works on attacking MARL policies. Lin et al. [10] and Guo et al. [5] showed that a MARL policy can perform awful when one agent behaved adversarially against other agents.

Unlike many prior works which attack RL agents at every timesteps, in this paper we attempt to look further. More specifically, we want to find whether the policy trained by the current MARL algorithm like QMIX can be significantly affected, when only a few agents in the team were attacked at a few timesteps during the whole episode, i.e., *sparse attack*. Here “sparse” has two meanings: sparseness in agent dimension and sparseness in time dimension.

This result is important for judging whether the current MARL policy can be deployed into real-world scenarios, because in many existing cMARL algorithms the team can only guarantee to get a high

reward when all agents execute their optimal policy accurately. But this may not be true for real-world scenarios. For a machine team, the machines may malfunction sometimes; for a human team, the teammates may not be absolutely credible, because the competitors may plant a spy who will sabotage the team.

But of course, if a machine fails frequently, it will be replaced by a better machine soon; and if a spy sabotages the team frequently, he/she will be easy to be spotted and kicked out from the team. Real-world machines may more likely to fail only occasionally, and a spy can only sabotage occasionally to avoid being kicked out. This is why we focus on sparse attack.

Prior sparse attack work mainly focused on single agent RL. Most of them used some rule-based method to get the timestep of the attack, which can be shown to be sub-optimal (see 4.1). In this work, we attempt to use (MA)RL algorithms to learn the optimal sparse attack policy. To the best of our knowledge, our work is the first work about optimal sparse attack in the MARL environment.

Our contributions are summarized as follows:

- We perform adversarial attacks in the MARL environment, and consider both single agent attack and multi agent attack.
- We propose a (MA)RL based optimal sparse attack method in the MARL environment, which outperforms existing rule based sparse attack methods.
- Our experiments show that the current MARL algorithms, at least for QMIX, are not robust enough.

2 Related Work

MARL algorithms Existing cMARL algorithms can be roughly divided into two types: policy-based and value based. Representative policy-based algorithms include COMA [4], MADDPG [12], etc; and representative value-based methods include VDN [29] QMIX [21], QTRAN [26], ROMA [32], Weighted-QMIX [22], etc.

Adversarial attacks in RL Adversarial attacks in RL can also be roughly divided into two types: attack agent (e.g., perturb agent’s observation or action) or modify environment. **1)** For attacking agent, early works like [3, 6] used simple adversarial example algorithm to attack agent’s state. Later works like [30, 23] used RL to learn the perturbation of agent’s state that can minimize agent’s reward. Lee et al. [8] attacked agent’s action directly. Xiao et al. [33], Lin et al. [11], Hussenot et al. [7] tried different adversarial attack task (same perturb across time; mislead agent to certain state). **2)** For modifying environment, Mankowitz et al. [13, 14], Abdullah et al. [1], Zhang et al. [36], Yu et al. [35] provided different kinds of environment modification.

Sparse attack in RL Lin et al. [11], Qu et al. [20], Yang et al. [34] used rule based methods to decide attack steps (based on the “difference” or “entropy” of the agent’s policy or value function). Behzadan and Hsu [2], Qiaoben et al. [19] used RL to learn the attack steps and then applied adversarial example at those steps. Sun et al. [28] used RL to learn both the attack step and the perturbation. All these works are conducted in single agent RL.

Adversarial attacks and adversarial training in MARL Lin et al. [10], Guo et al. [5] attacked one agent in the cMARL environment. Pham et al. [17] used model based method to attack cMARL agents. Li et al. [9], Sun et al. [27], Nisioti et al. [16] did mini-max adversarial training in the cMARL environment, which assumed some agents may behave adversarially against other agents. All these works assumed agent(s) can behave adversarially at any timestep.

3 Problem Formulation

A standard cooperative MARL system contains n agents that can be described as a multi-agent Markov decision processes (multi-agent MDP, MMDP) $(\mathcal{S}, \{\mathcal{A}_i\}_{i=1}^n, \{\mathcal{O}_i\}_{i=1}^n, R, P)$. Here \mathcal{S} is the environment’s global state space. Each agent i has its own action space \mathcal{A}_i and observation space \mathcal{O}_i . At each time step t , agent i first observes $o_{i,t} \in \mathcal{O}_i$ based on the current global state $s_t \in \mathcal{S}$. The

observation $o_{i,t}$ can be the same as s_t if the environment is fully observable, or be different if the environment is partially observable. After that, agent performs action $a_{i,t}$ based on its policy $\pi_i(\cdot|h_{i,t})$, $h_{i,t}$ is agent i 's all historical information until t . The team receives reward $r_t = R(s_t, a_{1,t}, \dots, a_{n,t})$, and then the environment transfers to next state $s_{t+1} \sim P(\cdot|s_t, a_{1,t}, \dots, a_{n,t})$. The team's goal is to maximize its expected total reward $\mathbb{E}_{s_0 \sim p_0, \mathbf{a}_t \sim \pi, s_{t+1} \sim P} [\sum_t R(s_t, \mathbf{a}_t)]$.

To simplify the notation, we may use \mathbf{a}_t to refer to $a_{1,t}, \dots, a_{n,t}$, use $\mathbf{a}_{\{i,j,k\},t}$ to refer to agent $\{i, j, k\}$'s action, and use $\mathbf{a}_{-\{i,j,k\},t}$ to refer all except agent $\{i, j, k\}$'s action.

For partially observable environments, we may assume the global state s_t is known during MARL's training period, but not during its testing period. The MARL algorithm can use global state information to help agents learn its policy, but each agent must be able to perform its policy only with its own observation. This is a common setting in many existing cMARL algorithms.

If the attacker decide to attack $m \in [1, n]$ agent(s) in the team (denoted by $\mathbf{k} = \{k_1, \dots, k_m\}$, $k_i \in [1, n]$ for $i \in [1, m]$), the sparse adversarial attack task can be formulated as a constrained optimization problem:

$$\begin{aligned} & \min_{\mathbf{a}_{\mathbf{k},t}} \mathbb{E}_{s_0 \sim p_0, s_{t+1} \sim P} \left[\sum_t R(s_t, \mathbf{a}_{\mathbf{k},t}, \mathbf{a}_{-\mathbf{k},t}^*) \right] \\ & \text{s.t. } \sum_{i=1}^m \sum_t 1_{[a_{k_i,t} \neq a_{k_i,t}^*]} \leq N. \end{aligned} \quad (1)$$

where a^* is the optimal policy without attack, and N is the maximum number of attack steps. This optimization problem is a constrained (MA)RL problem.

Moreover, since our goal is to find out "whether MARL policy can be significantly affected by a little modification", the maximum number of attack steps, i.e., N , is also a hyper-parameter that needs to be tuned. Instead of solving the constrained (MA)RL and tune the hyper-parameter N , we can just relax the hard constraint $\sum_{i=1}^m \sum_t 1_{[a_{k_i,t} \neq a_{k_i,t}^*]} \leq N$ into a soft regularization:

$$\min_{\mathbf{a}_{\mathbf{k},t}} \mathbb{E}_{s_0 \sim p_0, s_{t+1} \sim P} \left[\sum_t R(s_t, \mathbf{a}_{\mathbf{k},t}, \mathbf{a}_{-\mathbf{k},t}^*) + \lambda \sum_{i=1}^m \sum_t 1_{[a_{k_i,t} \neq a_{k_i,t}^*]} \right]. \quad (2)$$

The soft regularized problem is enough for our goal. In the regularized problem, λ can be used to control the sparsity of attack indirectly, large λ leading to less attack.

Most existing works on adversarial attack on RL policy were targeted on attacking state or observation. Unlike this, we make a stronger assumption: the attacker can directly modify agent's action. This assumption is reasonable under sparsity regularization, and it does also reflects some real-world scenarios. A faulty machine may perform sub-optimal actions even when the observation is correct, and a spy may perform any action that can sabotage the team, as long as he/she doesn't do this frequently.

4 Methodology

4.1 Rule based sparse attack is sub-optimal

Some prior work about sparse attack in RL used rule based method to choose the attack step. For example, one calculates $\delta_t = \max_a \pi(a|s_t) - \min_a \pi(a|s_t)$ [11] or $\delta_t = \sum_{i=0}^m \frac{p(a_t^i) \cdot \log p(a_t^i)}{\log m}$ [20] first and then attacks t with high δ_t . For Q learning, both the methods used softmax(Q) to calculate δ_t . These two methods have a certain intuitive meaning: higher δ_t means policy has higher confidence in its optimal action, which potentially means step t is more important and more worthwhile to be attacked. But both the methods are sub-optimal, at least for attacking Q learning agent. Here's an example:

Example 1 Consider a $\{0, 1\}$ action game with total T timesteps. At timestep t there are 2^t states. The state transit function is deterministic and different action sequences will lead to different states.

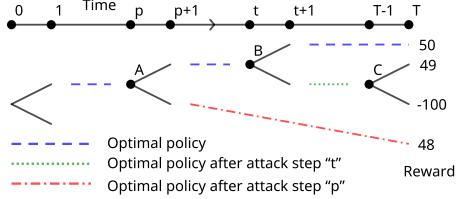


Figure 1: Example 1

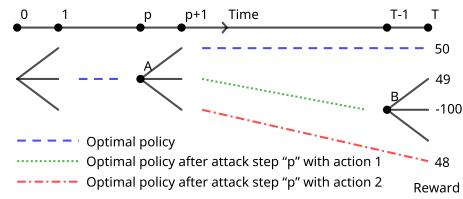


Figure 2: Example 2

The game can be described by a binary tree. The agent only receives reward at the last step, with no discount factor.

Consider a reward function like Figure 1. All other terminal states have a reward in $[0, 47]$.

For this game, if the sparse attack budget is not less than 2, the only optimal attack policy is attacking points B and C, resulting -100 reward.

But $Q_B^*(0) = 50, Q_B^*(1) = 49, Q_A^*(0) = 50, Q_A^*(1) = 48$. The Q function at point B has less difference than point A. Therefore these two methods are both sub-optimal.

□

Some other existing works used RL to learn the sparse attack timesteps. For example, Behzadan and Hsu [2] perturbed the action to $\arg \min_a Q(s_t, a)$ if the attacker decided to attack at timestep t ; Qiaoben et al. [19] used RL to learn the sparse attack timesteps with fixed adversary perturbation $h(s)$.

These methods could also be sub-optimal, because the learnt Q function describes the optimal reward after having performed certain action, so perturbing action to $\arg \min_a Q$ only minimize the upper bound of the reward, not the lower bound. Here's an example:

Example 2 The environment setting is the same as Example 1, except the action space is $\{0, 1, 2\}$. The game can be described by a ternary tree.

Consider a reward function like Figure 2. All other terminal states have a reward in $[0, 47]$.

For this game, if the sparse attack budget is not less than 2, the only optimal attack policy is attacking point A with action 1 and point B with action 1, resulting -100 reward.

But $Q_A^*(0) = 50, Q_A^*(1) = 49, Q_A^*(2) = 48$, the optimal attack policy is not the one with the lowest Q value. Therefore this method is sub-optimal.

□

The detailed calculation of these two examples can be found in Appendix A.1

4.2 Using (MA)RL algorithm to solve the optimal sparse attack policy

The fundamental reason why rule-based sparse attacks are sub-optimal is that, the Q function only describes optimal reward in certain case and it contains little information about the worst reward. So in order to obtain the optimal sparse attack policy, one way is to use a (MA)RL algorithm to solve the regularized optimization problem.

Set $R'(s_t, \mathbf{a}_{k,t}) = -R(s_t, \mathbf{a}_{k,t}, \mathbf{a}_{-k,t}^*) - \lambda \sum_{i=1}^m 1_{[a_{k_i,t} \neq a_{k_i,t}^*]}$ and $P'(s_{t+1}|s_t, \mathbf{a}_{k,t}) = P(s_{t+1}|s_t, \mathbf{a}_{k,t}, \mathbf{a}_{-k,t}^*)$. Then the regularized optimization problem (2) becomes a standard (M)MDP in the original environment, with agent k_1, \dots, k_m , state transition function P' , and reward R' . Under some regularity assumptions, a optimal policy of the MDP exists [18], therefore we call this optimal policy as "optimal sparse attack policy".

This (M)MDP can be solved by any existing (MA)RL algorithm.

For $m = 1$, this is a partially observable single agent RL problem. Most common settings in partially observable RL assume that the true state is unknown. But in this case, the environment is still the

original multi agent environment, in which the global state is known during the training period. We can take advantage of this feature and use the global state to help training. For example, we can apply the QMIX algorithm into this single agent case.

Algorithm 1 shows the learning procedure.

Algorithm 1 Optimal sparse attack

Require: Attack agents k_1, \dots, k_m ; Optimal Q function Q_1^*, \dots, Q_n^* ; Hyperparameter λ

Ensure: Optimal sparse attack Q function $Q_{k_1}^{adv}, \dots, Q_{k_m}^{adv}$

Initialize replay buffer $\mathcal{D} = \emptyset$

for each epoch **do**

for sampling loop **do**

 Obtain current s_t and \mathbf{o}_t . Compute optimal actions $a_{i,t}^* = \arg \max_a Q_i^*(o_{i,t}, a)$ for $i = 1, \dots, n$.

 Roll out attacked agents' action $a_{k_i,t}^{adv}$, using ε -greedy or other method, with $Q_{k_i}^{adv}(o_{k_i,t}, a)$ for $i = 1, \dots, m$

 Perform action $\mathbf{a}_{\mathbf{k},t}^{adv}, \mathbf{a}_{-\mathbf{k},t}^*$ and get r_t, s_{t+1} and \mathbf{o}_{t+1} .

 Compute attacked agents' reward $r'_t = -r_t - \lambda \sum_{i=1}^m 1_{[a_{k_i,t}^{adv} \neq a_{k_i,t}^*]}$

 Store transition $(s_t, \mathbf{o}_{\mathbf{k},t}, \mathbf{a}_{\mathbf{k},t}^{adv}, r'_t, s_{t+1}, \mathbf{o}_{\mathbf{k},t+1})$ into \mathcal{D}

end for

for training loop **do**

 Sample a minibatch \mathcal{M} from replay buffer \mathcal{D} .

 Compute $Q_{k_i}^{adv}(o_{k_i}, a_{k_i})$ for $i = 1, \dots, m$.

 Compute $Q(s, \mathbf{a}_{\mathbf{k}})$ using QMIX's mixer.

 Perform an update step.

end for

end for

Comparison with existing works. Except for sub-optimal rule based sparse attack discussed earlier, Sun et al. [28] used RL to learn the optimal sparse attack either, and Lin et al. [10], Guo et al. [5], Pham et al. [17] used RL to learn the optimal attack in cMARL system. The main difference between our work and theirs is:

- Sun et al. [28] only considered attacking single agent RL policy. Our work focuses on attacking multi agent RL policy, and testing on many different environments. Their work used hard constrain applied to the environment to control the sparsity, i.e., the attacker will fail to attack if maximum of attack step reached. Our work uses soft regularization to control the sparsity.
- Both Lin et al. [10], Guo et al. [5], Pham et al. [17] considered the dense attack, and the first two works only attempted to attack one agent in the team. Our work focuses on sparse attack, and attempts to attack both single agent and multiple agents.

5 Experiments

5.1 Experiment settings

We evaluate our optimal sparse attack method on SMAC environment [24] with different maps. For maps with only a few agents, we only attempt to attack a single agent; For maps with many agents, we attempt to attack both single agent and multiple agents.

Environment and experiment settings SMAC [24] is an MIT-licensed multi agent partially observable environment based on the StarCraft II game. Each agent can only observe a part of the global state within a circular area around it. Please refer to the SMAC paper for more details.

We use QMIX [21] to train the base policy to be attacked. We mainly focus on attacking QMIX policies, but we also try attacking VDN [29] and QTRAN [26] policies in some maps. The base policy is trained with the same settings and same parameters as in the QMIX paper. We also use

QMIX to train the optimal sparse attack policy. The optimal sparse attack policy is also trained with the same settings and same parameters as in the QMIX paper, except the number of agents is changed.

Map selection SMAC environment contains many different maps, but only those maps that QMIX can achieve good performance are suitable for evaluating the performance of the sparse attack policy. We evaluate our method on different kinds of maps:

- Maps with a few agents: 3m and 3s_vs_4z. In these two maps, we only attack single agent. Because all the agents are homogeneous, we just choose agent 0 as a representative agent.
- Maps with a medium number of agents: 2s3z, 8m, 1c3s5z, so_many_baneling. In these maps, we attempt to attack both single agent and multiple agents. For homogeneous map 8m and so_many_baneling, we just randomly choose the representative agent; for heterogeneous map, we choose the representative agent based on agent type.
- Maps with a large number of agents: 25m and bane_vs_bane. In these maps, we attempt to attack both single agent and multiple agents. Since the number of agents is large, we just randomly choose the representative agent.

Some detailed explanation can be found in Appendix A.2.

Evaluation criteria and baselines We use the winning rate of 1000 episodes and the average number of attack steps as our evaluation criteria. The attack policy with fewer attack steps and a lower winning rate has better performance.

To evaluate the stability of the experiment, we run each (MA)RL training 5 times with different randomly selected random seeds, discard the policy with the highest and lowest winning rate, and report the result of the rest 3 policies.

We evaluate our result with these baselines:

- **Random sparse attack.** At each timesteps we randomly attack it with a certain probability, with either random action, or use the action that have the lowest Q value. We use the abbreviation Ra-R or Ra-L to represent them.
- **Rule based sparse attack.** Following Lin et al. [11], we compute $\delta = \max_a \text{softmax}(Q) - \min_a \text{softmax}(Q)$ and attack those timesteps with high δ_t and with the action that have the lowest Q value. We use the abbreviation Ru-B to represent it.
- **RL with fixed attack policy.** Following Behzadan and Hsu [2], we use RL to learn the attack timesteps, and then attack those timesteps with the action that have the lowest Q value. We use the abbreviation RL-F to represent it. In Behzadan and Hsu [2] they fixed the attack cost c_{adv} to 1 per attack step, but in order to make these result comparable, we may adjust c_{adv} to control the attack sparsity.
- **Rule based dense attack.** Attack every timesteps with the action that have the lowest Q value. This baseline is only used in a few case, because it is a much stronger attack. We use the abbreviation Ru-D to represent it.

We use the abbreviation OPT to represent our method: **optimal sparse attack**. For hyperparameter λ , we train different attack policies with different λ , and choose the one that can significantly lower the winning rate. Results below show that larger λ leads to less attack.

5.2 Maps with a few agents

Table 1 shows the result of the 3m map and the 3s_vs_4z map. For these two maps, the winning rate without adversarial attack is 97.2% and 90.8% respectively. We can see that, for 3m map, OPT can lower the winning rate to 0% with only around 18% of timesteps being attacked, and 1.8% with around 14%. For 3s_vs_4z map, the winning rate cannot be as low as 3m map, but OPT can still significantly lower the winning rate with around 10%-15% of timesteps being attacked.

These results show that OPT outperforms Ra-R/Ra-L and Ru-B. In 3m map, the performance of OPT and RL-F is similar, but in 3s_vs_4z OPT significantly outperforms RL-F. Note that, for Ru-B and RL-F, we do not need to accurately select a threshold or c_{adv} to let them attack exactly the same

Table 1: Maps with a few agents

Map	3m Agent 0			3s_vs_4z Agent 0			
	Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 1$	0.0	4.278/23.249		$\lambda = 0.1$	56.5	10.123/167.604
		0.0	4.336/23.067		$\lambda = 0.1$	58.3	15.993/171.329
		0.0	4.329/23.356		$\lambda = 0.1$	59.9	9.404/165.055
	$\lambda = 5$	1.8	3.464/24.906		$\lambda = 0.01$	46.0	22.085/163.402
		1.4	3.640/24.975		$\lambda = 0.01$	49.0	24.480/175.448
		1.4	3.460/25.436		$\lambda = 0.01$	46.7	20.370/167.866
Ra-R	-	85.3	20%		-	90.5	15%
		88.4	15%			91.6	10%
Ra-L	-	48.6	20%		-	87.2	15%
		60.3	15%			90.5	10%
Ru-B	Threshold 0.25	26.7	15.657/39.389		Threshold 0.04	66.2	30.794/159.433
	Threshold 0.258	41.1	12.475/35.468		Threshold 0.05	90.4	19.811/136.088
RL-F	$c_{adv} = 1$	0.0	3.997/40.113		$c_{adv} = 0.1$	78.6	15.958/150.592

number of timesteps as OPT. If OPT attacks fewer timesteps than Ru-B or RL-F, and achieves a lower winning rate, then OPT just outperforms them.

5.3 Maps with a medium number of agents

For 8m, 2s3z, 1c3s5z, so_many_baneling map, we attempt to attack both single agent and multiple agents. The winning rate of these 4 maps without adversarial attack is 87.9%, 97.5%, 99.5%, 95.0% respectively.

Attacking single agent We pick one agent for each map to report here, and more experimental results can be found in Appendix A.3.

Table 2 shows the result of these 4 maps. OPT can lower the winning rate in all these 4 maps. Especially in 1c3s5z, OPT lowers the winning rate to less than 1% in only less than 10% of timesteps being attacked.

In both maps, OPT outperforms Ra-R, Ra-L and Ru-B. In 8m map, the performance of OPT and RL-F is similar, and in the other 3 maps, OPT significantly outperforms RL-F.

Attacking multiple agents Table 3 shows the result of multiple agent attack, and additional results can be found in Appendix A.3. In these maps, OPT can significantly lower the winning rate, and outperforms all baselines including RL-F. In 1c3s5z map, OPT outperforms Ru-D. In maps with heterogeneous agents, different types of agents contribute differently to the team, small agents play less of a role in the team. Compared to previous result, in 1c3s5z map, “c” is large agent and “s” / “z” are small agents, so attacking “s” / “z” requires more attack steps than attacking “c”.

5.4 Maps with a large number of agents

For 25m and bane_vs_bane map, we also attempt to attack both single agent and multiple agents.

Table 4 shows the result of the 25m map. The winning rate of the 25m map without adversarial attack is 98.4%. More results can be found in Appendix A.3.

When attacking only one agent in a team with 25 agents, OPT can lower the winning rate a little bit with around 80% of timesteps being attacked. This still outperforms Ru-D and RL-F. Ru-B has no baseline in this case, because we fail to find a threshold that can attack more than 80% but not near 100% of timesteps. When attacking 5 agents in the team, OPT can significantly lower the winning

Table 2: Attacking single agent

Map	8m Agent 4			so_many_baneling Agent 6		
Attack type	Parameter	Winning rage (%)	Attacked steps / Total steps	Parameter	Winning rage (%)	Attacked steps / Total steps
OPT	$\lambda = 1$	0.2	7.109/26.876	$\lambda = 0.5$	8.4	4.688/24.229
		0.2	7.153/27.393		6.6	4.720/24.259
		0.1	5.008/26.373		7.9	4.711/24.054
Ra-R	-	71.4	25%	-	89.8	25%
Ra-L	-	33.7	25%	-	87.1	25%
Ru-B	Threshold 0.13	24.1	8.291/33.548	Threshold 0.03	78.0	11.440/24.830
RL-F	$c_{adv} = 0.25$	0.6	6.431/99.718	$c_{adv} = 0.1$	53.6	7.245/25.194
Map	1c3s5z Agent 0			2s3z Agent 1		
Attack type	Parameter	Winning rage (%)	Attacked steps / Total steps	Parameter	Winning rage (%)	Attacked steps / Total steps
OPT	$\lambda = 1$	0.0	4.097/44.122	$\lambda = 0.1$	0.4	11.413/119.696
		0.1	4.134/44.389		0.5	10.942/119.577
		0.0	4.019/45.706		0.5	11.528/119.454
	$\lambda = 5$	0.3	3.617/46.609	$\lambda = 1$	7.2	11.116/113.693
		0.3	3.458/45.725		2.2	10.062/118.165
		0.3	3.452/45.555		2.5	10.193/117.992
Ra-R	-	96.8	10%	-	97.1	10%
Ra-L	-	94.7	10%	-	91.1	10%
Ru-B	Threshold 0.1	45.7	5.83/64.444	Threshold 0.1	50.8	12.709/56.991
RL-F	$c_{adv} = 0.3$	2.5	4.602/48.968	$c_{adv} = 0.1$	22.1	32.688/88.48

Table 3: Attacking multiple agents

Map	so_many_baneling Agent 0 and 6			1c3s5z Agent 1 and 7		
Attack type	Parameter	Winning rage (%)	Attacked steps / Total steps	Parameter	Winning rage (%)	Attacked steps / Total steps
OPT	$\lambda = 0.5$	3.7	5.643,1.204 /21.219	$\lambda = 0.1$	48.3	16.265,13.545 /106.380
		2.3	5.755,5.150 /21.199		49.6	15.507,15.621 /110.040
		3.3	5.988,1.344 /21.276		48.2	15.729,14.188 /112.490
		6.4	5.405,1.037 /21.044		29.1	57.834,58.535 /79.101
	$\lambda = 1$	8.1	5.423,1.015 /21.299	$\lambda = 0.01$	29.7	53.077,56.998 /78.544
		8.9	5.600,1.090 /21.200		24.9	54.735,48.304 /78.564
		-	-		-	-
Ra-R	-	90.0	30%, 10%	-	97.9	15%, 15%
Ra-L	-	84.8	30%, 10%	-	98.3	15%, 15%
Ru-D	-	-	-	-	37.7	100%, 100%
Ru-B	Threshold 0.05, 0.1	74.4	11.714,2.460 /29.005	Threshold 0.04, 0.05	68.8	23.486,27.912 /73.038
RL-F	$c_{adv} = 0.1$	17.5	4.783,6.286 /25.019	$c_{adv} = 0.01$	37.0	77.475,85.843 /118.839

Table 4: 25m map

Map	25m Agent 10		
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 0.01$	69.3	30.302/46.582
		68.1	37.845/48.739
		70.8	44.589/56.135
	$\lambda = 0.001$	67.0	51.887/63.311
		73.8	45.496/56.599
		65.7	49.720/63.385
Ra-R	-	83.7	70%
Ra-L	-	73.8	70%
Ru-D	-	71.8	100%
RL-F	$c_{adv} = 0$	70.7	42.459/62.132
Map	25m Agent 0,5,10,15,20		
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 1$	16.2	3.700,3.840,3.567,4.051,3.467/58.801
		16.2	3.575,3.928,3.651,3.999,3.484/59.101
		19.3	3.938,3.715,3.608,3.881,3.465/56.315
Ra-R	-	96.5	7%, 7%, 7%, 7%, 7%
Ra-L	-	89.4	7%, 7%, 7%, 7%, 7%
Ru-B	Threshold 0.16,0.13,0.11,0.13,0.15	42.8	6.729,4.721,6.189,6.855,5.341/50.164
RL-F	$c_{adv} = 0.2$	35.9	7.335,36.529,6.959,2.511,2.530/101.708

rate with each agent around 7% of timesteps being attacked. All these results outperform all baselines including RL-F.

5.5 Attacking VDN and QTRAN policies

We also attack VDN and QTRAN policies in two maps: 1c3s5z and 25m, i.e., one homogeneous map and one heterogeneous map. Results can be found in Appendix A.3. The result is similar to QMIX policies. Both VDN and QTRAN policies can perform awful under sparse attack, and OPT outperforms all baseline methods.

6 Conclusion and Future works

In this work we have been concerned with sparse attack in multi agent reinforcement learning. We have used (MA)RL algorithms to learn the optimal sparse attack policy and evaluated them in SMAC environments. In most of our experiments, our method outperformed all baselines, which indicated that rule based sparse attack method is sub-optimal. Our experiments have shown that the policy trained by the QMIX / VDN / QTRAN algorithm can obtain poor performance when only one or a few agents in the team are attacked at a few timesteps.

Our results implied that existing cMARL algorithms, at least QMIX / VDN / QTRAN, may not be robust enough to deploy to real applications. So one straightforward future work is to find some ways to defend this kind of attack. To the best of our knowledge, this work is the first work about sparse attack in MARL. As a first-step work, we fixed the target agent and then learn the optimal sparse attack policy. A more general attack problem is to take k_1, \dots, k_m into the min operator, i.e., the attacker must decide both the agent to be attacked and the attack policy. This problem is a mixed integer programming problem, and is also a possible future work.

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A Appendix

A.1 Detailed derivation

Example 1 Since the game can be described by a binary tree, we can just use action sequence to denote each state, i.e., action sequence a_0, a_1, \dots, a_{t-1} will lead to state $s_{a_0, a_1, \dots, a_{t-1}}$ at timestep t . The reward function at terminal step T can be denoted by $r_{a_0, a_1, \dots, a_{T-1}}$.

Consider this reward function:

- Choose an action sequence a_0^*, \dots, a_{T-1}^* as optimal policy, and set $r_{a_0^*, \dots, a_{T-1}^*} = 50$
- Choose some $p < t < T - 1$. Choose another action sequence $a'_{t+1}, \dots, a'_{T-2}$, and set $r_{a_0^*, \dots, a_{t-1}^*, 1-a_t^*, a'_{t+1}, \dots, a'_{T-2}, 1} = 49$, $r_{a_0^*, \dots, a_{t-1}^*, 1-a_t^*, a'_{t+1}, \dots, a'_{T-2}, 0} = -100$
- Choose another action sequence $a''_{p+1}, \dots, a''_{T-1}$, and set $r_{a_1^*, \dots, a_{p-1}^*, 1-a_p^*, a''_{p+1}, \dots, a''_{T-1}} = 48$
- For any other terminal state, set its reward to any value between $[0, 47]$

For this game, if the sparse attack budget is not less than 2, the only optimal attack policy is to attack step t and step $T - 1$, with reward -100:

- $r_{a_0^*, \dots, a_{t-1}^*, 1-a_t^*, a'_{t+1}, \dots, a'_{T-2}, 1} = 49$, and any other terminal state's reward is at most 48. If we first attack step t and change its action to $1 - a_t^*$, then the rest optimal policy is $a'_{t+1}, \dots, a'_{T-2}, 1$.
- Then we attack step $T - 1$ and change its action from 1 to 0, agent will receive -100 reward, which is the only worst reward of the whole game (Any other terminal state's reward is at least 0).

Now let's calculate some Q^* function:

- At timestep t , $Q_t^*(s_{a_0^*, \dots, a_{t-1}^*}, a_t^*) = 50$, $Q_t^*(s_{a_0^*, \dots, a_{t-1}^*}, 1 - a_t^*) = 49$ (The rest optimal policy is $a'_{t+1}, \dots, a'_{T-2}, 1$, which will receive 49 reward)
- At timestep p , $Q_p^*(s_{a_0^*, \dots, a_{p-1}^*}, a_p^*) = 50$, $Q_p^*(s_{a_0^*, \dots, a_{p-1}^*}, 1 - a_p^*) = 48$ (The rest optimal policy is $a''_{p+1}, \dots, a''_{T-1}$, which will receive 48 reward. Any other policy can only get at most 47 reward.)

Now, no matter what rule we choose, δ_p is larger than δ_t , which means that the rule based sparse attack using δ is sub-optimal. Since the optimal attack policy requires attack at t while do not attack at p , which is not possible.

Example 2 Similar to Example 1, we use action sequence to denote each state and reward function.

Consider this reward function:

- Choose an action sequence a_0^*, \dots, a_{T-1}^* as optimal policy, and set $r_{a_0^*, \dots, a_{T-1}^*} = 50$
- Choose some $p < T - 1$. Choose another action sequence $a'_{p+1}, \dots, a'_{T-2}$, and set $r_{a_0^*, \dots, a_{p-1}^*, (a_p^*+1) \bmod 3, a'_{p+1}, \dots, a'_{T-2}, 1} = 49$, $r_{a_0^*, \dots, a_{p-1}^*, (a_p^*+1) \bmod 3, a'_{p+1}, \dots, a'_{T-2}, 0} = -100$
- Choose another action sequence $a''_{p+1}, \dots, a''_{T-1}$, and set $r_{a_0^*, \dots, a_{p-1}^*, (a_p^*+2) \bmod 3, a''_{p+1}, \dots, a''_{T-1}} = 48$

- For any other terminal state, set its reward to any value between $[0, 47]$

For this game, if the sparse attack budget is not less than 2, the only optimal attack policy is to attack step p and step $T - 1$, with reward -100:

- $r_{a_0^*, \dots, a_{p-1}^*, (a_p^*+1) \bmod 3, a_{p+1}', \dots, a_{T-2}', 1} = 49$, and any other terminal state's reward is at most 48. If we first attack step p and change its action to $(a_p^* + 1) \bmod 3$, then the rest optimal policy is $a_{p+1}', \dots, a_{T-2}', 1$
- Then we attack step $T - 1$ and change its action to 0, agent will receive -100 reward, which is the only worst reward of the whole game (Any other terminal state's reward is at least 0)

Now let's calculate some Q^* function:

- $Q_p^*(s_{a_0^*, \dots, a_{p-1}^*}, a_p^*) = 50$
- $Q_p^*(s_{a_0^*, \dots, a_{p-1}^*}, (a_p^*+1) \bmod 3) = 49$ (The rest optimal policy is $a_{p+1}', \dots, a_{T-2}', 1$, which will receive 49 reward)
- $Q_p^*(s_{a_0^*, \dots, a_{p-1}^*}, (a_p^*+2) \bmod 3) = 48$ (The rest optimal policy is $a_{p+1}'', \dots, a_{T-1}'', 1$, which will receive 48 reward. Any other policy can only get at most 47 reward.)

Now, if the agent decide to attack at step p with no attack before, the optimal attack action $(a_p^* + 1) \bmod 3$ is not the one that has the lowest Q value.

A.2 Map selection

The following factors are considered when choosing maps:

- The performance of the QMIX algorithm. If QMIX itself performs poorly in a map, then there is little value in performing an adversarial attack on it.
- Both homogeneous maps and heterogeneous maps should be chosen.
- The difficulty of the map. Since the more difficult the map itself, the easier for adversarial attack. Therefore we prefer simple maps than difficult maps.

Also, since we focus on attacking multi agent systems, we do not choose the environment with only two agents.

The first factor excludes 5m_vs_6m, MMM2, 3s5z_vs_3s6z, corridor, 6h_vs_8z. See QMIX paper for specific.

For homogeneous maps, we choose 3m, 8m, 25m, 3s_vs_4z, and so_many_baneling. We do not choose 8m_vs_9m, 10m_vs_11m, or 27m_vs_30m, since they are more difficult than the chosen "m" maps because the team has fewer agents than the enemy. The 3s_vs_3,4,5z maps are similar, so we just choose one of them.

All other maps are heterogeneous. 2s3z, 3s5z, and 1c3s5z have some similarity (both contains "s" and "z" agent), and we choose 2s3z and 1c3s5z. For the rest two maps, we choose bane_vs_bane since it is the only heterogeneous map with a large number of agents.

A.3 Additional experiment results

Table 5 shows additional experiment results of the 2s3z map. OPT can lower the winning rate to less than 10% in both cases. All results outperform all baselines.

Table 6 shows additional experiment results of the 1c3s5z map. In this map, "c" is a large agent and "s"/"z" are small agents, therefore "c" is more important to the team. Compared to previous results, these results show that attacking "s" (agent 1) or "z" (agent 7) is more difficult than attacking "c" (agent 0). For agent 7, OPT outperforms all baselines including Ru-D and RL-F. For agent 1, the result is just so-so, but with $\lambda = 0.1$ OPT still outperforms Ru-B and RL-F.

Table 7 shows additional result of the 8m and bane_vs_bane map. The winning rate of the bane_vs_bane map without attack is 84.0%. For 8m map, OPT outperforms Ra-R/Ra-L and Ru-B, its

Table 5: 2s3z map

Map	2s3z Agent 2			2s3z Agent 1 and 2		
	Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps	Parameter	Winning rate (%)
OPT	$\lambda = 0.1$	0.0	21.715/44.057	$\lambda = 0.1$	0.0	17.782,16.216/43.321
		0.0	24.301/46.361		0.0	17.294,19.044/44.120
		0.0	22.063/43.904		0.0	17.501,16.134/43.904
	$\lambda = 0.5$	11.1	12.547/48.199	$\lambda = 0.5$	0.4	9.142,8.593/81.301
		1.5	13.875/46.908		0.9	6.161,12.821/48.101
		5.0	13.363/49.769		0.1	7.277,12.651/44.000
Ra-R	-	91.3	15%	-	76.0	10%, 30%
	-	41.7	50%			
Ra-L	-	84.5	15%	-	39.5	10%, 30%
	-	5.4	50%			
Ru-B	Threshold 0.07	7.2	15.052/52.341	Threshold 0.087,0.115	3.9	10.030,12.258/47.077
RL-F	$c_{adv} = 0.2$	17.6	16.584/76.338	$c_{adv} = 0.1$	12.3	19.444,10.877/96.483

Table 6: 1c3s5z map

Map	1c3s5z Agent 7			1c3s5z Agent 1		
	Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps	Parameter	Winning rate (%)
OPT	$\lambda = 0.1$	92.6	10.407/48.971	$\lambda = 0.1$	83.6	13.408/69.093
		92.7	10.907/48.597		83.8	14.504/68.233
		92.5	9.013/49.212		84.2	14.731/65.389
	$\lambda = 0.01$	78.6	42.252/60.875	$\lambda = 0.01$	84.2	48.083/60.750
		79.7	42.170/55.780		86.4	45.741/59.606
		77.1	45.324/58.568		79.8	51.944/67.537
Ra-R	-	98.0	20%	-	98.1	20%
					96.9	80%
Ra-L	-	98.5	20%	-	98.6	20%
					87.8	80%
Ru-D	-	89.5	100%	-	78.4	100%
Ru-B	Threshold 0.05	96.9	16.756/48.097	Threshold 0.05	89.3	15.301/57.828
RL-F	$c_{adv} = 0.01$	90.1	51.914/61.215	$c_{adv} = 0.05$	84.3	34.966/63.480

result is similar to RL-F. For bane_vs_bane map, with $\lambda = 0.1$, OPT result is similar to Ru-B, and with $\lambda = 0.01$ OPT outperforms RL-F.

Table 8 shows additional multi agent attack result of 25m and bane_vs_bane map. The winning rate of these 2 maps without adversarial attack is 98.5% and 84.0% respectively. For 25m map, when attacking 3 agents, OPT can lower the winning rate to around 45% with each agent less than 10% of timesteps begin attacked, and it outperforms all baselines including RL-F. For bane_vs_bane map, when attacking 3 or 5 agents, OPT can lowerer the winning rate, and it outperforms Ra-R/Ra-L and RL-F. But OPT and Ru-B cannot compare directly, since we cannot find a thshold to let Ru-B attack as many timesteps of agent 0 as OPT does.

Table 9 10 shows additional result of attacking VDN and QTRAN policies. During our experiments, we found QTRAN performs not very well in the 25m map, so we only attack VDN policies in the 25m map. The result is similar to QMIX policies. In most cases, OPT outperforms all baselines, and in some cases it outperforms Ru-D.

Table 7: 8m and bane_vs_bane map

Map	8m Agent 3 and 6			bane_vs_bane Agent 10			
	Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 1$	12.8	2.001, 1.464/26.848		$\lambda = 0.1$	80.1	7.124/74.455
		8.9	2.319, 1.459/26.121			79.1	9.015/73.818
		8.4	2.258, 1.467/26.332			81.9	7.618/73.672
	$\lambda = 5$	21.1	1.692, 1.428/27.900		$\lambda = 0.01$	76.0	21.749/85.297
		20.3	1.675, 1.401/27.311			78.5	20.925/82.861
		21.4	1.721, 1.421/27.446			76.7	18.996/78.974
Ra-R	-	97.6	15%		-	81.8 82.8	15% 25%
Ra-L	-	88.6	15%		-	84.1 80.8	15% 25%
Ru-B	Threshold 0.18	47.0	12.180/72.400	Threshold 0.05	79.2	9.21/76.463	
RL-F	$c_{adv} = 1$	23.0	1.896, 1.013/28.429	$c_{adv} = 0.01$	78.6	35.670/83.136	

Table 8: 25m and bane_vs_bane map: attacking multiple agents

Map	25m Agent 0, 10, 20		
attack type	parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 1$	43.9	4.924,3.491,3.060/51.127
		44.4	4.697,3.511,3.269/49.809
		44.8	4.826,3.318,2.982/52.125
Ra-R	-	95.4	10%, 10%, 10%
Ra-L	-	91.4	10%, 10%, 10%
Ru-B	Threshold 0.15, 0.1, 0.1	56.3	9.622,8.996,6.702 /52.410
RL-F	$c_{adv} = 0.23$	80.5	10.915,4.781,0.252/51.467
Map	bane_vs_bane Agent 0, 10, 20		
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 0.01$	41.3	104.218,21.053,17.397/143.964
		44.9	67.105,20.244,22.769/131.688
		27.4	102.376,16.529,17.030/160.459
Ra-R	-	90.2	75%, 15%, 15%
Ra-L	-	91.8	75%, 15%, 15%
Ru-B	Threshold 0.005, 0.01, 0.01	79.8	54.483,9.809,9.178 /78.794
RL-F	$c_{adv} = 0$	71.1	63.694,53.639,50.014/92.802
Map	bane_vs_bane Agent 0, 5, 10, 15, 20		
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 0.01$	23.5	119.952,19.067,21.522,15.708,16.029 /164.122
		20.2	87.203,25.645,21.332,22.612,22.143 /169.967
		26.7	88.507,21.880,16.905,10.793,10.950 /163.439
Ra-R	-	90.7	70%, 15%, 15%, 15%, 15%
Ra-L	-	92.2	70%, 15%, 15%, 15%, 15%
Ru-B	Threshold 0.005,0.005,0.005,0.005,0.005	78.5	63.232,9.479,9.048,10.210,11.273 /84.098
RL-F	$c_{adv} = 0$	67.1	37.091,31.063,18.260,27.080,20.191/109.740

Table 9: 1c3s5z map VDN / QTRAN

Map	1c3s5z Agent 0 VDN			1c3s5z Agent 0 QTRAN		
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 5$	3.6	5.038/60.800	$\lambda = 1$	0.0	4.156/69.583
		4.0	5.123/59.584		0.0	4.059/67.123
		4.4	5.483/60.106		0.0	4.005/69.318
Ra-R	-	95.5	10%		84.2	10%
Ra-L	-	89.4	10%		80.0	10%
Ru-B	Threshold 0.025	47.4	7.652/64.042	Threshold 0.045	37.5	10.996/86.140
RL-F	$c_{adv} = 0.3$	3.6	5.233/60.466	$c_{adv} = 0.1$	1.1	11.249/69.823
Map	1c3s5z Agent 1+7 VDN			1c3s5z Agent 1+7 QTRAN		
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 0.01$	5.7	60.854,58.683 /73.878	$\lambda = 0.01$	2.5	59.435,55.070 /75.038
		5.0	55.652,57.354 /75.560		2.0	59.885,57.792 /73.920
		5.4	58.902,58.434 /72.109		2.3	60.870,58.052, /72.261
Ra-R	-	81.5	80%,80%	-	58.8	85%,85%
Ra-L	-	39.4	80%,80%	-	17.6	85%,85%
Ru-D	-	24.5	100%,100%	-	6.3	100%,100%
RL-F	$c_{adv} = 0$	31.0	79.500,59.505 /119.208	$c_{adv} = 0$	11.9	121.312,44.639 /138.440

Table 10: 25m map VDN

Map		25m Agent 0 VDN	
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 0.01$	75.6	34.392/61.564
		73.1	40.409/64.335
		70.2	39.407/64.272
Ra-R	-	95.4	55%
Ra-L	-	88.4	55%
Ru-D	-	81.4	100%
RL-F	$c_{adv} = 0$	82.3	32.235/55.256
Map		25m Agent 0, 10, 20 VDN	
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 1$	13.0	3.384,3.758,3.199/45.249
		14.3	3.749,4.153,2.996/49.728
		11.1	3.493,3.648,3.148/45.895
Ra-R	-	96.7	10%, 10%, 10%
Ra-L	-	93.6	70%, 10%, 10%
Ru-B	Threshold 0.02,0.014,0.016	82.3	4.825,3.816,4.621/42.664
RL-F	$c_{adv} = 0.2$	79.3	6.462,6.787,1.411/53.820
Map		25m 0, 5, 10, 15, 20 VDN	
Attack type	Parameter	Winning rate (%)	Attacked steps / Total steps
OPT	$\lambda = 1$	1.3	5.145,4.456,3.901,4.382,3.114 /48.018
		1.2	4.837,4.328,3.964,4.392,3.177 /46.169
		0.9	4.835,4.805,4.206,4.103,3.240 /49.859
Ra-R	-	95.6	10%, 10%, 10%, 10%, 10%
Ra-L	-	86.7	10%, 10%, 10%, 10%, 10%
Ru-B	Threshold 0.019,0.015,0.015,0.015,0.015	50	9.677,5.401,6.301,5.445,5.343 /54.064
RL-F	$c_{adv} = 0.1$	9.3	5.370,12.808,18.994,11.546,30.295/116.817