CoMIX: A Multi-agent Reinforcement Learning Training Architecture for Efficient Decentralized Coordination and Independent Decision-Making

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Abstract

Robust coordination skills enable agents to operate cohesively in shared environments, together towards a common goal and, ideally, individually without hindering each other's progress. To this end, this paper presents Coordinated QMIX (CoMIX), a novel training framework for decentralized agents that enables emergent coordination through flexible policies, allowing at the same time independent decision-making at individual level. CoMIX models selfish and collaborative behavior as incremental steps in each agent's decision process. This allows agents to dynamically adapt their behavior to different situations balancing independence and collaboration. Experiments using a variety of simulation environments demonstrate that CoMIX outperforms baselines on collaborative tasks. The results validate our incremental policy approach as effective technique for improving coordination in multi-agent systems.

1 Introduction

Multi-agent systems pose a significant challenge because of the complexity of employing actors and managing their interactions (Long Ma et al., 2015). In particular, as the number of agents increases, coordination among them become more and more difficult. At the same time, it represents a fundamental aspects of this class of systems, regardless of whether the agents act as individuals or cooperatively. It is also critical for a series of practical application domains, namely autonomous driving (Prabuchandran et al., 2014; Sadigh et al., 2018; Falsone et al., 2020) and robotics (Yan et al., 2013; Yu et al., 2023), in particular in systems of mobile robots (Chen & Luh, 1994; Sousa et al., 2021) and drone fleets (Alfeo et al., 2018; Qin & Pournaras, 2023).

Previous research has focused primarily on information sharing strategies to facilitate coordination among multiple entities (Groen et al., 2007; Pesce & Montana, 2020; Kim et al., 2021). Indeed, agents often find themselves having to make decisions based on an incomplete understanding of the world in which they operate, for instance, due to limited perception ability or scarce computational resources - these are typical examples of *bounded rationality* (Simon, 1996). In this context, effective communication plays a key role. In fact, coordination emerging from indiscriminate communication may not always be the best solution: an overabundance of shared information can overwhelm agents and slow down decision-making, negatively affecting coordination among the agents.

In addition, there are cases where coordination itself can hinder optimal task execution. For example, popular solutions such as IC3Net (Singh et al., 2019), BicNet (Peng et al., 2017), and ATOC (Jiang & Lu, 2018) do not explicitly grant agents the autonomy to operate outside the given cooperative scheme by limiting the exploration of the entire action space and the exploitation of individual capabilities. Allowing agents to occasionally pursue local strategies could be beneficial to achieve the overall shared collective goal, as agents can help discover more optimal solutions for the team as a whole. For example, in a multi-agent navigation task, a robot periodically exploring new potential paths on its own could provide useful information to others. This raises an important question that we aim to address in this study:

Can agents acting in a shared environment with the ability to communicate autonomously learn coordinated behaviors in order to effectively and efficiently perform a group collaborative task, while also allowing individual decision-making?

In order to address this problem, in this paper, we present the design, implementation and evaluation of *Coordinated QMIX (CoMIX)*[1], a novel framework for decentralized multi-agent reinforcement learning (MARL) combining group and individual decision-making. The conventional approach to addressing the coordination problem in MARL systems is to prioritize group choices over individual ones. Although a solution that give more importance to group dynamics can be more effective when cooperation is critical for success, it might be detrimental when agents could benefit from acting independently to achieve a given goal, or in complex environments with a vast space of possible interactions. For instance, in crowded or sparsely rewarded settings, enforcing top-down coordination on all agents may hinder convergence to an optimal joint policy. In contrast, allowing potential independent local choices, rather than mandating group coordination, can lead to emergent collaboration arising naturally where needed, with benefits for both the individual and the group as a whole. CoMIX embodies this principle by allowing agents to choose whether to co-operate with others or to act independently, first communicating their own action intentions derived from previously acquired and current information alone (e.g., sensory data). These are then combined with the intentions of other agents in order to reduce uncertainty and achieve coordination.

By considering a variety of challenging MARL environments, we demonstrate CoMIX's ability to efficiently choose between collaboration and independent action, and, consequently, to coordinate with a large number of agents effectively. Moreover, CoMIX is based on storing a weighted record of neighbors' previous action intentions for coordination, which makes the method interpretable in terms of agent choices and resilient to communication disruptions. Overall, our findings highlight the effectiveness of CoMIX in facilitating coordination among agents, by enabling them to selectively coordinate in pursuit of a shared goal, allowing at the same time independent decision-making when beneficial.

2 Related Work

In this section, we discuss the relevant related work with a focus on mechanisms for group coordination and efficient information sharing in multi-agent systems.

Coordination. Multi-Agent Reinforcement Learning (MARL) frameworks are designed to overcome the added complexity resulting from the presence of multiple interacting entities in an environment (Tuyls & Weiss, 2012; Zhang et al., 2021). In particular, we are interested on those that adopt information sharing mechanisms (Gronauer & Diepold, 2021; Hernandez-Leal et al., 2019) to achieve flexible coordination without introducing central entities that could create failure points or bottlenecks. CommNet (Sukhbaatar et al., 2016) demonstrates remarkable performance by simply collecting messages and averaging them, then using the additional information in each agent's policy. IC3Net (Singh et al., 2019) adds a mechanism for instructing agents to learn when to communicate, through the adoption of a gating mechanism to allow access to a communication channel. However, poor utilization of the communication channel limit the ability to coordinate and may not lead to effective policies when many agents participate in communication. BicNet (Peng et al., 2017) uses a more complex mechanism to leverage incoming information by adopting a bidirectional module, and, like others approaches (Jiang & Lu, 2018; Das et al., 2019), is characterized by an architecture based on recurrent modules to maintain consistency in outputs generated in subsequent steps. However, these solutions are designed only for cooperative tasks (Mao et al., 2017; Foerster et al., 2018; Singh et al., 2019; Zhang et al., 2020; Li et al., 2022) and, therefore, lead to policies not considering the independence of agents or allowing them to exploit possibly better solutions by diverging from team executions. Our approach builds on this body of work, with a specific focus on flexible coordination and communication efficiency.

Information Sharing. Communication can be implemented as a direct message sent through a private channel (Niu et al., 2021), or as a broadcast transmission (Sukhbaatar et al., 2016; Lin et al., 2021). How-

[1]The code is available at the following URL: *[the code will be released upon acceptance]*.

ever, the latter solution may prevent agents from distinguishing information that is valuable for them from irrelevant or even potentially misleading one in case of different action dynamics or goals. In general, the information received can be considered valuable if it enhances an agent's understanding and coordination by providing relevant updates on the environment state, goals, intentions, and other factors that aid decision-making and coordination. ATOC (Jiang & Lu, 2018) proposes a communication model with a gate mechanism for communication efficiency. Instead, (Das et al., 2019; Li et al., 2022; Kim et al., 2021) act on the listener's side, adopting different attention mechanisms to filter out irrelevant messages. However, they generally consider each message in isolation rather than in the context of all the others in the communication channel, missing opportunities to coordinate responses among multiple agents as it is often essential for effective teamwork. Some approaches rely on the formation of groups of agents and focus on inter- and intra-communication to limit computational efforts and improve coordination performance (Jiang & Lu, 2018; Liu et al., 2020; 2021; Niu et al., 2021), while others reduce the number of messages sent by learning in which situations communication is really necessary and/or when the available information is redundant and therefore communication can be avoided over time (Ding et al., 2020; Liu et al., 2020; Kim et al., 2021; Kalinowska et al., 2022). In contrast, CoMIX aims at creating simplified communication channels directly based on environment observations, not requiring agents to make assumptions about the senders or receivers, thus making them potentially deployable even with unseen agents.

Information Representation. The format of a message is a crucial aspect of communication, as it must effectively encode information in order to reduce uncertainty and facilitate coordination with the recipient. The information conveyed through the message may encompass various aspects of communication and decision-making, ranging from agent intentions, such as requests, questions, and plans, to contextual information and conversational messages. Some existing work relies on the transmission of internal state vectors (Sukhbaatar et al., 2016; Peng et al., 2017; Singh et al., 2019; Wang & Sartoretti, 2022), which are typically used by agents to encode their own history, but the reuse of such individual state representations for communication may not be suitable. In (Das et al., 2019; Li & Zhang, 2024), targeted messages are used to convey information to individual agents. Simpler communication approaches (Liu et al., 2020; Kim et al., 2021) include current or time-delayed observations – plain or encoded – as content for the communication message. This allows for more flexible interaction dynamics since the information is transmitted without any additional processing or filtering. CoMIX belongs to this class of solutions, since it relies on sharing observations paired with the agent's action decision, in order to guide coordination among agents.

3 Background

In this section, we introduce the notation and concepts at the basis of our approach, which will then be presented in detail in the following section.

Deep Reinforcement Learning. The problem is modeled as a decentralized partially observable Markov decision process (Dec-POMDP) (Oliehoek & Amato, 2016), which is defined by the tuple $(K, S, \mathcal{A}, P, \mathcal{R}, \gamma)$, where K is the set of n interacting agents, S is the set of observable states s, $\mathcal{A}$ is the joint action space consisting of individual action spaces A_i of actions a, for each agent $i \in K$, $P : S \times A \to P(S)$ is the transition probability function that describes the chance of a state transition, $\mathcal{R}$ is the joint set of reward functions R_i associated with each agent $i \in K$, and $\gamma \in [0, 1)$ is the discount factor. At each time step, each agent selects an action based on its individual policy $\pi_i : S \to P(A_i)$. The system evolves from joint state $\mathbf{s} = \{s_1, \ldots, s_n\}$ to the next state $\mathbf{s}'$ under the joint action $\mathbf{a} = \{a_1, \ldots, a_n\}$ with respect to the transition probability function P, while each agent receives an immediate reward $\mathbf{r} = \{r_1, \ldots, r_n\}$ as feedback following a state transition. The objective is to construct an independent policy π_i for each agent $i \in K$ with the goal of maximizing the expected discounted return. The optimal policy $\pi^*(s)$ is obtained indirectly during the iterative process by considering a state-action function $Q_i : S \times A_i \to R_i$, associated with each agent, which estimates the expected return of taking an action a in a state s. The learning algorithm is based on a Deep Q-Network (DQN)(Mnih et al., 2013): the Q-function is parametrized by a neural network presenting recurrent neural network (RNN) modules to keep memory of sequences of choices. The Dec-POMDP setting is then extended with a broadcast communication channel allowing agents to exchange messages to overcome partial observability effects. The individual policies are learned as state-action functions $Q_i(s_i, h_i, \mathbf{m}, a_i)$ evaluating

the possible actions a_i in the current local state s_i with the hidden state h_i, and the exchanged messages $\mathbf{m} = \{m_1, \ldots, m_n\}$, where m_i is sent by agent $i \in K$.

Centralized Training with Decentralized Execution. Centralized training with decentralized execution (CTDE) with Q-value optimization is a popular approach for solving MARL problems (Lowe et al., 2017; Foerster et al., 2018; Rashid et al., 2020). During training, a central mixer network is used to represent the value of the state of the entire system. We adopt QMIX (Rashid et al., 2020), which learns a non-linear mixing function to map individual Q-values of agents $\mathbf{q} = \{Q_1, \ldots, Q_n\}$ to the global Q-value, denoted as Q_{TOT}. Hypernetworks (Ha et al., 2016) are used to compute a set of mixing weights for each agent, ensuring that a global argument of the maxima (argmax) operation produces the same result as individual argmax operations. This is achieved through a monotonicity constraint between Q_{TOT} and individual value Q_i:

$$\frac{\partial Q^{TOT}}{\partial Q_i} \geq 0, \forall i \in [i, n] \tag{1}$$

4 The CoMIX Training Architecture

In the following we will describe CoMIX, a framework that allows agents to adopt both individual and group strategic behavior by selectively communicating via a shared channel, letting coordination arise from continuous interaction and without making prior assumptions about other agents. The overall architecture of CoMIX is depicted in Figure 1.

4.1 Architecture

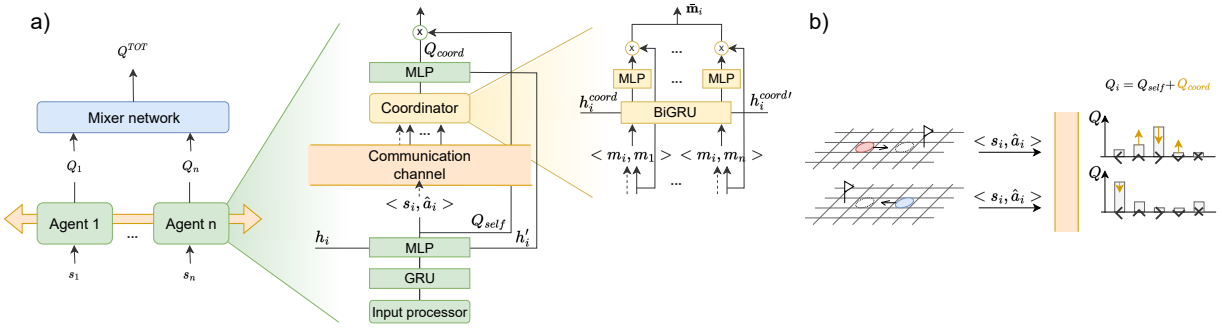


Figure 1: CoMIX training architecture. (a) The system is illustrated by breaking down its components with the information flow from left to right. Each agent observes a partial state of the world, processes it, and determines the next action to be taken. After transmitting this information $< s_i, \hat{a}_i >$ through the communication channel, they receive and filter the $\mathbf{m}$ messages from other agents using a coordination module. The filtered messages $\bar{\mathbf{m}}_i$ are then used to compute weights to rescale the original state-action pairs and select the best action. Decisions are made locally. (b) A practical example demonstrates the interpretability of the method by showing how two agents, sharing the same portion of the map and with opposite goal directions, change their initial action intentions based on information received from other agents.

4.1.1 Action Policy

Each agent predicts Q-values as the product of two terms: $Q_i = Q_{self} Q_{coord}$. This is the result of a two-step computation within the Q network. In the first step, Q_{self} is obtained by considering only the internal state of the agent h_i and the current observation s_i. After communication, the second term Q_{coord} is computed by the Q network to weight the estimated value for each action. Specifically, $Q_{coord}(h'_i, \bar{\mathbf{m}}_i, a_i)$ takes h'_i, the hidden state updated in the current step, and $\bar{\mathbf{m}}_i$, the messages filtered by the Coordinator module for agent i that will be discussed in detail in the following section. The messages are averaged in order to form

a single vector concatenated with the hidden state and processed in a fully connected network to obtain a bounded weight value. It is worth noting that the raw observation is first passed through an input processing module to extract features from the inputs and reduce the state space. Following (Lin et al., 2021), this is implemented with shared weights among all agents to allow them to reason about data from the same distribution. The final formula representing the output of the Q network of each agent is the following:

$$Q_i(s_i, h_i, \bar{\mathbf{m}}_i, a_i) = Q_{self}(s_i, h_i, a_i) Q_{coord}(h'_i, \bar{\mathbf{m}}_i, a_i) \tag{2}$$

4.1.2 Coordinator

The Coordinator module is responsible for determining the relevance of other agents' communications in relation to the agent's intentions by generating a coordination mask used to filter out incoming messages. A message is defined as the communicated intention of an agent to take a certain action to achieve an objective, $\hat{a}_i = \arg\max_a Q_{self}(s_i, h_i, a)$, and is represented by the tuple $m_i =< s_i, \hat{a}_i >$. Consequently, we define $\mathbf{m} = \{m_1, \ldots, m_n\}$, as the set of incoming messages sent by n agents at a certain timestep and $\bar{\mathbf{m}}_i$ as the filtered set for agent i obtained from the application of the coordination mask $\mathbf{c}_i$, computed by the Coordinator module:

$$\mathbf{z}_i = \{< m_i, m_1 >, \ldots, < m_i, m_n >\}^{-<m_i, m_i>} \tag{3}$$

$$\mathbf{c}_i = Coord(\mathbf{z}_i) \tag{4}$$

$$\text{where } \mathbf{c}_i = \{c_{i,1}, \ldots, c_{i,n}\}^{-c_{i,i}} \text{ and } c_{i,j} = \begin{cases} 1 & \text{if agent } i \text{ coordinate with agent } j, \\ 0 & \text{otherwise} \end{cases}$$

$$\bar{\mathbf{m}}_i = \mathbf{m} \odot \mathbf{c}_i \tag{5}$$

As previously proposed by (Jiang & Lu, 2018), such module is implemented using a BiGRU layer (Wang et al., 2017). It receives the messages sent by all the other agents, within the same global context of coordination. The individual scores produced by this layer are then used to calculate an independent probability of communication through a two-way softmax operation.

4.2 Training

4.2.1 Centralized Temporal Difference Supervision

The agents' Q-policy networks are trained end-to-end by adopting a CTDE framework that estimates the state-action value of the entire system. We adopt the QMIX central network (Rashid et al., 2020), which despite the monotonicity constraint limiting its representation capacity, has been shown to achieve state-of-the-art performance on various MARL tasks. Additionally, its computational simplicity enables it to effectively manage large joint action spaces. The update rule for θ^Q parameters follows the popular implementation of (Rashid et al., 2020), with the computation of a temporal difference error:

$$L_Q(\theta^Q) = |y^{TOT} - Q^{TOT}(\mathbf{s}, \mathbf{q}; \theta^Q)|, \tag{6}$$

where $y^{TOT} = \mathbf{r} + \gamma \max_{\mathbf{q}'} Q^{TOT}(\mathbf{s}', \mathbf{q}'; \theta^{Q\prime})$ and θ^Q, $\theta^{Q\prime}$ are respectively the parameters of the online policy network and target policy network, periodically copied from θ^Q as in standard DDQN (Van Hasselt et al., 2016). Employing a centralized function that accounts for all agent actions can lead to a decrease of the policy gradient estimate variance compared to using individual Q-networks per agent, as separate Q-networks may inaccurately assess the local Q-function. Then, after training, the central training function is not used anymore, and policy execution is fully decentralized.

4.2.2 Self-supervision

The parameters of the Coordinator module are updated using a self-supervised learning scheme. The underlying idea is that an efficient coordinator, functioning as a filter over the communication channel, would ease the work of the individual policy, thus resulting in more accurate expectations of future rewards. Given

an approximation of the optimal Q-function, we extract the loss signal by comparing the state-action values obtained using different coordination masks. We define the update formula of the Coordinator's parameters θ^C as the clipped difference between the maximum value between the state-action pairs obtained with filtered messages $\tilde{\mathbf{m}}_i$ using the predicted coordination mask, and the estimated value obtained from messages filtered by a mask with reversed probabilities of communication. That is, $\tilde{\mathbf{c}}_i = (1 - Coord(\mathbf{z}_i; \theta^C))$ and $\tilde{\mathbf{m}}_i = \mathbf{m} \odot \tilde{\mathbf{c}}_i$ from Eq. 4 and Eq. 5.

$$L_C(\theta^C) = \sum_{i=1}^{n} w_i \Delta Q_i = \sum_{i=1}^{n} w_i \max(0, \max_{a_i} Q_i(s_i, h_i, \tilde{\mathbf{m}}_i, a_i) - \max_{a_i} Q_i(s_i, h_i, \bar{\mathbf{m}}_i, a_i)) \tag{7}$$

However, at each communication stage there are 2^{n-1} combinations of values for $\tilde{\mathbf{c}}_i$, each of which could represent a stronger optimization signal. Therefore, instead of using a single coordination mask for each agent, we instead consider $n-1$ masks, taking into account the loss for each of them. These are obtained by inverting the probability associated to the communication with a single agent and then averaging the results. The choice is further discussed later in a dedicated section (Sec. 5.4.1). The additional weighting term w_i is obtained by means of QMIX, which, by design, maps states into a set of values in the hidden space for each individual agent.

4.2.3 Training Details

We optimize the weights of the Q and Coordinator networks by adopting Adam with learning rates of $1e^{-4}$ and $5e^{-5}$, respectively. To mitigate the risk of catastrophic forgetting and overfitting, a weight decay value of $1e^{-3}$ is used as regularization term, while to capture the uncertainty of the predictions and further explore the coordination possibilities, we introduce randomness into the Coordinator's training process by applying the Gumbel Softmax (Jang et al., 2017) to the two decision logits. The learning algorithm is also sensitive to the number of recurrent steps considered during training and the update rate of the target network. For this reason, we train the network on multiple recurrent steps depending on the complexity of task coordination and performed an update every 40,000 steps to stabilize Q-learning. Additional details about hyperparameters optimization, the simulation environments, and the algorithm at the basis of the CoMIX training loop can be found in the Supplementary Material.

5 Experiments

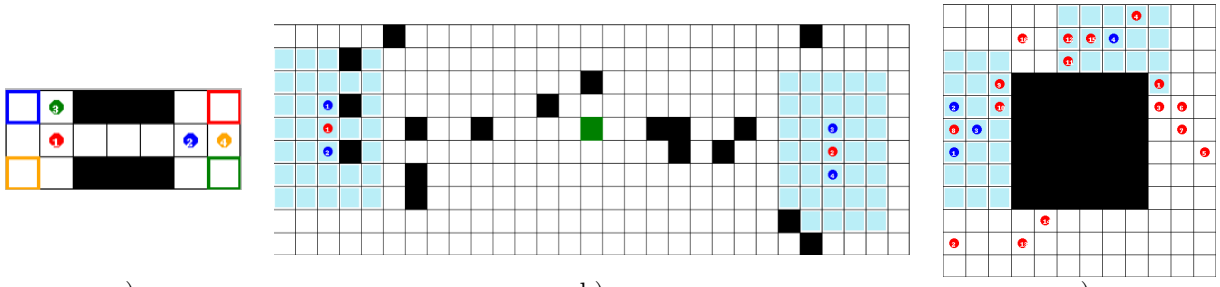
We evaluate CoMIX in three distinct environments, which allow us to assess different dimensions of the problem, including scalability and robustness to potential disruptions.

5.1 Environments

In this subsection, we introduce the environments used in our experimental evaluation, providing an overview of their main characteristics and discussing the criteria for their selection. For a full description of the experimental settings of the environments, please refer to the Supplementary Material.

5.1.1 Switch

The Switch environment is a gridworld environment in which 4 agents spawn in corners and must reach target positions on the opposite side of the map. It consists of a rectangular grid with a long narrow corridor in the center which can only be crossed by a single agent at a time. The vertical position of the corridor is randomized for each episode to increase unpredictability. The reward is given only upon reaching the destination, and its value is determined by how quickly the task is completed. This environment specifically can be used to evaluate the agents' abilities to balance aggressive and coordinated strategies since taking the initiative to traverse the corridor earlier leads to better rewards, but risks potential gridlock if agents collide. The agents can only observe their current position and target distance, but not other agents, so they must communicate to coordinate. Therefore, in order to complete the task, it is necessary to balance individual and collaborative behavior. In addition, we would also like to note that partial observability forces agents to communicate and adapt their policies based on the actions of others.



a) b) c)

Figure 2: Environments used for experimental evaluation. From left to right (a) Switch; (b) Cooperative Load Transportation, 2 loads (red) and 4 agents (blue) with an equal distance of 15 steps to the final position (green), and 10% of cells as obstacles; (c) Predator-Prey, 4 agents (blue), 16 prey (red) in a 12x12 map. The spatial observability of agents is shown in light blue.

5.1.2 Cooperative Load Transportation

This environment involves pairs of agents synchronizing to transport a load to a goal location while avoiding obstacles. It requires close coordination to move in the same direction and effective communication to prevent interference from other agent pairs. Agents observe their absolute coordinates, distance to the goal, and proximity to obstacles. Small rewards are given for moving the load closer to the goal and a large reward upon completion. We select this environment since it requires very fine-grained coordination and the capability of screening out "distracting" signals from other agents.

5.1.3 Predator-Prey

This is a classic MARL environment (Gupta et al., 2017) adapted to encourage interactions between agents. The environment is a grid world in which agents, the predators, chase randomly moving entities, the prey, with the aim of capturing them. The predators' visibility is limited to a range of two units in each direction from their positions and they move at the same speed as the prey. The agents must decide whether to act independently by trying to occupy the same cell of a prey, receiving small rewards, or collaborating in groups to surround the prey on all four axes and receive a much larger reward. Agents should therefore focus on maximizing long-term cumulative rewards through coordinated hunting rather than prioritizing short-term individual rewards. We study such emergent collaborative behavior by evaluating our method in this environment. This allows to analyze its general applicability in tasks that require teamwork.

5.2 Baselines

For the evaluation, as comparators, we select a straightforward "vanilla" implementation of PPO in a multi agent setting, *IPPO* (Schroeder de Witt et al., 2020), and two representative MARL methods that implement attentional communication, namely *IC3Net* (Singh et al., 2019) and *ATOC* (Jiang & Lu, 2018). In particular, the choice of PPO, is motivated by its demonstrated ability to excel in certain scenarios characterized by specific forms of environmental nonstationarity, thus allowing IPPO to exhibit robustness when dealing with cooperative tasks that can be solved through sequences of independent actions selected locally. Compared with ours, IC3Net utilizes a gating mechanism on incoming communications, wherein it aggregates all additional information by computing the average into a single vector that is then used in the internal policy to generate two output heads: one for the actions' probabilities and the other for the individualized probability of communication. On the other hand, ATOC adopts a two-step policy: first reasoning about incoming partial observations, then forming semi-persistent communication groups by considering each other agent individually, and employing a BiLSTM (Graves & Schmidhuber, 2005) module to compute the final action. Unlike these, IPPO was chosen because it is competitive with state-of-the-art MARL algorithms, letting each agent estimate its value function only from its local observation and without further communication.

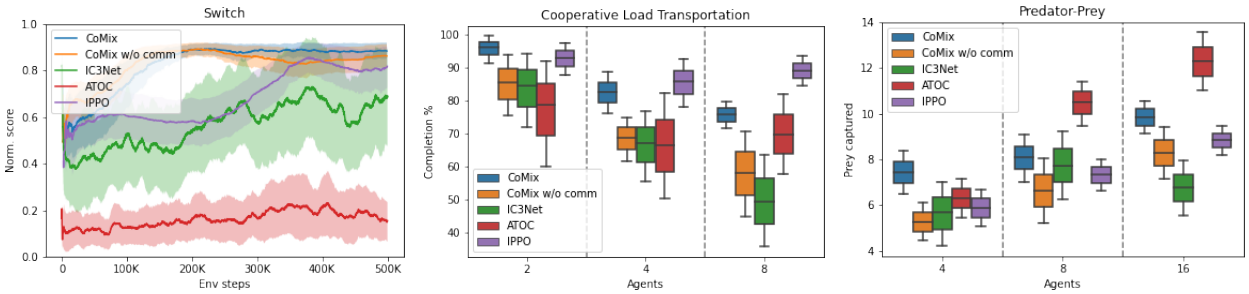


Figure 3: Training results in the three environments used for evaluation. In Switch we consider the sum of rewards obtained by all agents normalized to 1. In Cooperative Load Transportation, the metric of completeness is the distance of the load to the docking area. In Predator-Prey, we keep the number of prey constant at 16 and scaled the map size and number of agents, respectively: 12x12 with 4 agents, 14x14 with 8 agents, and 16x16 with 16 agents. The standard deviation is relative to the average results of 5 different seeds.

5.3 Experimental Results

Figure 3 shows a comparison of the performance of CoMIX to presented baselines and a variant in which the communication channel has been disabled. In the Switch environment, the agents do not require complex strategic actions. In this case, communication is mainly used to signal the presence of an agent. However, different agent behaviors can lead to very rapid task completion or longer episodes due to collisions and mutual blocking of agents, which increase the variance of reported results. In this case, CoMIX consistently enables all agents to learn behaviors that allow for faster map navigation. Instead, IC3Net, adopting a simpler approach to coordination, learns deterministic action sequences causing agents to behave with much variability. In contrast, ATOC's performance is affected by its inability to handle policies with conflicting goals, which is a consequence of weight sharing between agents. Finally, IPPO shows competitive performance but bounded by the partial observability of the agents. We further evaluate CoMIX considering the Cooperative Load Transportation and Predator-Prey tasks at incremental scales reporting the average performance and standard deviation for all methods. In Cooperative Load Transportation, CoMIX outperforms ATOC and IC3Net baselines, demonstrating good abilities in reaching the goal location avoiding obstacles along the way. Even with an increasing number of agents, we demonstrate that it is able to maintain good performance overall by filtering the communication channel from irrelevant messages coming from other agents. IPPO, on the other hand, shows clear superiority in resolution, being unaffected by external communication noise and taking advantage of the lack of marked randomness in the task objective. In the last environment, CoMIX learns how to coordinate both small and large numbers of agents by covering incremental portions of the map, whose size scales accordingly, while the number of preys remains constant. Interestingly, while ATOC does not perform well in coordinating few resources, it outperforms the other methods with 16 agents distributed more sparsely in the map. Meanwhile, CoMIX shows more compactness in the teams, and both IC3Net and IPPO underperform as agents act strictly locally.

Table 1: Effects of communication channel disruption. We show as baseline the performance of our method and the results obtained after the fine-tuning procedure. We show how, depending on the environment, we are able to achieve better performance with a smaller number of messages.

Comm channel usage	Switch		Transport (4 agents)		Predator-Prey (4 agents)	
	baseline	+fine-tuning	baseline	+fine-tuning	baseline	+fine-tuning
100% - Full comm	0.871	∼	79.83	∼	8.66	∼
50%	0.873 ∼	0.875 ∼	78.65 ↓	80.45 ↑	8.73 ↑	8.65 ∼
25%	0.874 ∼	0.876 ∼	78.24 ↓	81.94 ↑	8.30 ↓	8.60 ∼
10%	0.877 ∼	0.873 ∼	78.18 ↓	82.87 ↑	7.75 ↓	8.78 ↑
0% - No comm	0.879 ∼	0.877 ∼	79.25 ↓	78.92 ↓	7.41 ↓	8.29 ↓

5.4 Analysis

5.4.1 Coordinator Loss

We compared the effectiveness of our loss scheme for our Coordinator module by training the full model using variants of the proposed streategy. Our evaluation includes 1) all-positive mask, which allows communication with all agents; 2) a single coordination mask per agent with inverted probabilities; and, finally 3) a mask without the weighting term provided by the adoption of the QMIX central network. While we refrain from asserting an unequivocal implementation as the optimal solution, our experiments highlight the potential for implementing a more advantageous loss scheme depending on the dynamics of the environment. We hypothesize that all-positive mask could be effective only when all agents have a shared objective, as in the Predator-Prey environment. A single coordination mask per agent with inverted probabilities might represent a more efficient solution in environments where an incorrect coordination decision has no long-term impact. On the other hand, we observe that incorporating the term provided by QMIX to weight the mask can yield a slight positive impact on the rate of convergence of agent policies.

5.4.2 Efficiency

An efficient algorithm should learn to avoid inappropriate communications by considering only relevant ones, thus reducing the effects of information overload. Figure 4 shows how many messages are typically considered when agents are asked to coordinate with others. Average usage varies depending on the task at hand, and we emphasize that we achieve this behavior by fully learning communication without imposing external constraints. In line with the task rules we observe significant reductions in the number of messages used in Switch and Cooperative Load Transportation. More interestingly, we also notice similar behavior for the Predator-Prey task: although all agents share the general goal of capturing prey, the policy restricts each agent to communicating with only a subset of other agents, enabling the formation of smaller, more efficient subgroups to coordinate actions rather than requiring communication across every actor. As a further evaluation, we added "noisy" agents to the environments, which send a sequence of randomly generated bits, thus increasing the noise in the communication channel in the form of irrelevant messages. We note that their introduction does not substantially affect the average utilization of the communication channel, as expected, since such agents do not contribute to the solution of the task.

5.4.3 Communication Resilience

Finally, we present a study of the CoMIX's ability to operate with a disrupted communication channel, in which messages are not delivered at every step, since packet drops and intermittent availability of communications are not uncommon in the real world. Table 1 reports as baseline the results of average performing models trained in normal communication settings and evaluated reducing messages exchanges, up to complete drop of the communication channel. By doing so, we provide agents with "outdated" messages by randomly dropping sequences of messages and reusing past ones. As expected, we notice a slight drop in performance that increases with decreasing communication, therefore we adopt a fine-tuning procedure that allows us to reverse the trend and even achieve improvements, as highlighted in Table 1. We freeze the Coordinator weights and let the individual policies learn how to act using the incoming messages, scaling the extracted intentions proportionally to reflect their relevance over time. The fine-tuning process is performed until the performance with full communication matches the original model prior to ablation. We use a learning rate lowered by an order of magnitude, training for a number of episodes based on observed convergence rates. Again, Switch agents demonstrate to not rely particularly on the communication channel, while in the Predator-Prey and Cooperative Load Transportation environments we observe improved results after fine-tuning, with the latter presenting a reduction of the communication cost up to 92%. We also highlight the improved performance of agents trained with communication, which are then able to communicate at execution time (Table 1, last row), compared to agents trained without communication (Figure 3).

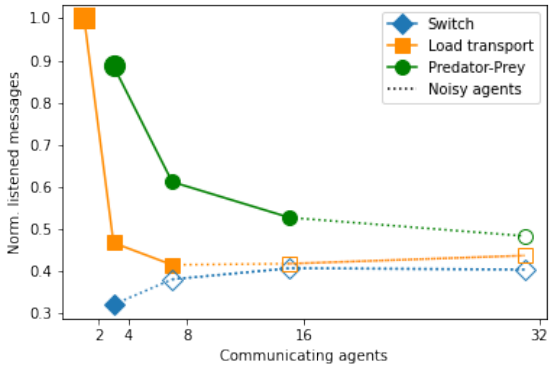


Figure 4: Average usage of the communication channel normalized by the number of true agents available for message exchange.

6 Conclusion

In this paper, we have introduced CoMIX, a new training architecture that effectively addresses coordination in multi-agent systems by separating selfish from collaborative behaviors. Compared with existing approaches that impose strict coordination, CoMIX offers a greater degree of flexibility and autonomy at the individual agent level while achieving high coordination performance when needed. This flexibility is particularly important for tasks in which agents can operate independently for periods of time, but need to collaborate effectively when opportunities arise. This is also beneficial in environments characterized by large action spaces, for example due to potentially vast sets of interactions. Moreover, in sparsely rewarded settings or in environments characterized by a large number of agents, enforcing top-down coordination on all of the agents may hinder convergence to an optimal joint policy. In contrast, allowing independent local choices, rather than mandating group coordination, leads to emergent forms of collaboration, which benefits both for the individual and the group as a whole. By means of extensive experimental evaluation by means of a variety of environments, we have shown the applicability of CoMIX to different tasks, and highlight its ability to improve the performance of individual agents' policy in performing collaborative tasks in a decentralized fashion. In addition, we have demonstrated CoMIX's robustness to communication interruptions and its effectiveness in filtering communications, which are important characteristics for potential real-world deployments.

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