# Biologically Inspired Coalition Formation of Multi-Agent Systems[*]

## (Extended Abstract)

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## ABSTRACT

We model the multi-level alliance forming ability of male bottlenose dolphins to develop a decentralized multi-level coalition formation algorithm for a multi-agent system. The goal is to produce a model that is rich enough to capture the biological phenomenon of forming alliances, yet remain simple so that it can be implemented on engineered systems, such as network of unmanned vehicles.

## Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*Intelligent agents, Multiagent systems*

## General Terms

Algorithms, Design

## Keywords

Biologically-inspired methods, Coalition formation

## 1. INTRODUCTION

Coalition formation is an important coordination problem in multi-agent robotics when a particular task cannot be accomplished by a single robot. Moreover, there are situations where the success rate of accomplishing a task by a single coalition is low. For these tasks, we need to create coalitions of coalitions and to develop our multi-level coalition formation algorithm, we draw inspiration from male bottlenose dolphins, which form varied levels of alliances to increase their chances of mating. We draw inspiration from such a biological system as it is scalable, robust, and decentralized - characteristics that are desirable for engineered systems. Existing algorithms to form coalitions too often rely on the availability of a central control (e.g. [5]) to process the requests to form coalitions by other agents. Unfortunately, the failure of such an agent will render the entire network useless. On the other hand, our dolphin inspired algorithm will produce a *decentralized* method to form 1) coalitions among agents and 2) coalitions of coalitions.

Although coalitions collaborating with each other is a nascent concept, it has several applications. For example, consider the suppression of enemy air defenses (SEAD) missions conducted by the navy using only autonomous vehicles. This mission involves gathering intelligence on the enemy's air defenses (e.g., nature, location, etc.) and neutralizing these threats [1]. The intelligence gathering aspect of the mission will be carried out by a team of UAVs and the expectation is that High Altitude Endurance (HAE) UAVs will collaborate with Low Altitude Endurance (LAE) UAVs to paint a complete picture of the battleground. The other aspect of the mission - neutralizing threats - is accomplished by teams of Unmanned Combat Aerial Vehicles (UCAVs); thus, requiring coalitions to coordinate with other coalitions in the network.

In this work, we only produce a model of the alliance forming behavior of dolphins; hence, future work will require us to tailor this model so that it can be applied to engineered systems.

## 2. MULTI-LEVEL ALLIANCE MODEL

Male bottlenose dolphins form two levels of alliances: first-order and second-order [2]. The first-order alliance consists of $2-3$ dolphins that tend to share a strong bond with each other and the goal of such an alliance is to herd a female swimming by itself. Whereas, a second-order alliance consists of two first-order alliances. When a first-order alliance is attracted to a captured female, it realizes that the outcome of a fight with a similar-sized alliance is unpredictable; as a result, it tries to recruit another first-order alliance in order to steal the female [2].

In our previous work, a model of the first-order alliance was produced, where each agent builds candidate sets, based on "association coefficients" [3], that contain up to two other agents in the network and a hybrid automaton was produced for each agent based on the status of requests sent to candidates to form a coalition. Such an approach can become cumbersome if used to model the second-order alliance, where interaction rules for female agents (free and captured) with solitary male agents, first-order alliances (searching,

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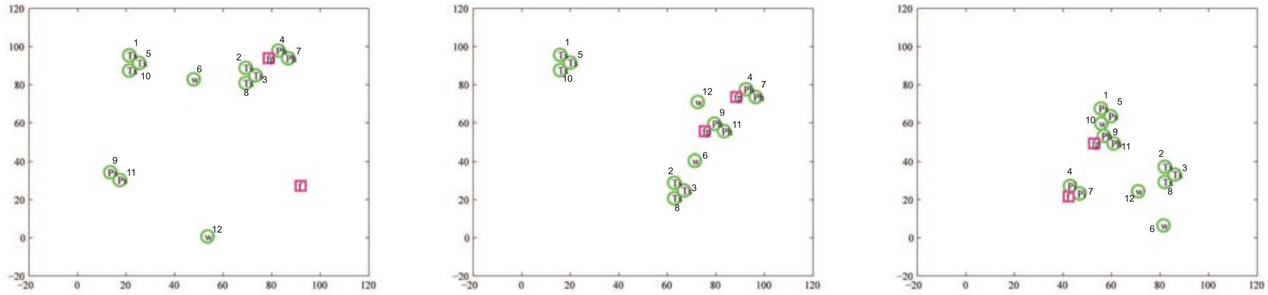

(a) Wanderers, pairs, and triplets are labeled $P$, $T$, and $w$, respectively.

(b) $(9, 11)$ switches from search to herd mode.

(c) Second-order $(9, 11, 1, 5, 10)$ is initiated by $(9, 11)$ in response to $(2, 3, 8)$'s threat.

**Figure 1: Multi-level coalition formation.**

herding, or idle), and second-order alliances must be prescribed. Thus, we use *embedded graph grammars* (EGGs) to develop the multi-level alliance model from a higher level of abstraction.

An EGG is a formalism that takes a vertex-labeled graph as an input and yields another vertex-labeled graph as an output, based on a rule set (see [6] for a formal definition). In our model, the vertex-labeled graph will be defined as $\mathcal{G} = (\mathcal{V},\ \mathcal{E},\ l,\ \Sigma)$, where $\mathcal{V}$ is the set of all agents (male and female), $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$ is the set of edges, and the function $l$ assigns a label from the label set, $\Sigma$, to the agents in the network.

Associated with $G$ is a set of transition rules, $\Phi$. Each rule in the set $\Phi$ is given by a pair $r = (L \rightharpoonup R)$, where $L$ and $R$ are subgraphs. Furthermore, there is a guard associated with each rule $r$ that evaluates to either `true` or `false`. If the guard condition associated with rule $r$ is `true`, then the application of the rule $r$ on the original subgraph $L$ produces the subgraph, $R$. In fact, the guard conditions are state-dependent since the evaluation of a guard condition depends on the geometric adjacency of the nodes in the subgraph.

A total of 13 rules are required to model the multi-level alliance (see [4] for details) and here, we present the first two rules that allow us to build first-order alliances. Let the set of all solitary male dolphins, first-order pairs, and first-order triplets be denoted by $\mathcal{D}$, $\mathcal{P}$, and $\mathcal{T}$, respectively. For first-order alliances, the label set is defined as $\Sigma^1 = \{w,\ p,\ t\}$, where the labels $w$, $p$, and $t$ represent the modes *wander*, *pair*, and *triplet*, respectively. Building first-order alliances is represented by the following grammar transition rules:

$$\Phi^1 = \left\{ \begin{array}{ccccccc} w & & w & \rightharpoonup & p \text{ —— } p & & (r_1), \\ & p & & & & t & \\ / & & & \rightharpoonup & / & & \backslash \\ p & & w & & t & \text{——} & t \quad (r_2), \end{array} \right. \qquad (1)$$

where $l(i) = w, \forall i \in \mathcal{D}$. For two wandering agents $i$ and $j$, i.e., $l(i) = w$ and $l(j) = w$, if the guard condition for $r_1$ is `true`, then the outcome of applying $r_1$ is $(i,\ j) \in \mathcal{P}$, where $l(i) = p$ and $l(j) = p$. For a wanderer and a first-order pair, i.e., $l(i) = p$, $l(j) = p$, and $l(k) = w$, such that $(i,\ j) \in \mathcal{P}$, if the guard condition for $r_2$ is `true`, then the outcome of applying rule $r_2$ is $(i,\ j,\ k) \in \mathcal{T}$, where $l(i) = t$, $l(j) = t$, and $l(k) = t$. The rules $r_1$ and $r_2$ are evaluated using the method prescribed in [4] and based on our model of dolphin alliances, we have the following results:

THEOREM 1. *In a network consisting of three first-order alliances in three different modes (search, herd, and idle) and a single captured female, if the alliance that is herding the female loses it to a steal, then it cannot unilaterally steal back the female.*

COROLLARY 1. *In a network consisting of three first-order alliances in three different modes and a single captured female, the only way to recapture a lost female is to form a new second-order alliance.*

These results stem from the fact that in our model, alliances prefer to join other alliances with which they share a higher "performance index."

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