Optimal graph exploration with partial observations in a stochastic and competitive environment

Laboratoire Informatique d'Avignon
Avignon Université

General information

Duration: 5-6 months, stipend of around 600 euros.
The internship will work at the Computer Science Lab, University of Avignon, in Avignon, France. It is possible to negotiate about some teleworking periods.
PhD: A 3 years PhD program will follow this project.

Project description

This intern subject is related to stochastic optimization problems in graphs with strategic entities. The problem is to control a random walk on a graph that aims to reach a specific node as soon as possible. This project builds on research carried out in [1]. This problem is related to security issues and lateral movement types of cyber-attacks [2]. In our setting, one decision-maker controls an exploration process without full knowledge of the position of the random walk process relative to the targeted node. Therefore, in the first step, a stochastic optimization framework like *Partially Observable Markov Decision Process* (POMDP) [3] can be a first approach to tackle the problem. The main key of the POMDP modeling is to integrate the belief update algorithm into the framework such that the decision-maker can take smart actions at each time step of the decision process. Considering a simple linear topology, numerical simulations show that an optimal strategy for the exploration process is to continue to explore until a threshold (number of steps) is reached. To prove that such a policy is optimal is not straightforward and depends on properties of the value function of beliefs.
In the second step of the work, another decision-maker comes into the picture and aims to slow down the progression of the random walk by changing the graph online (adding new edges, nodes, etc.). Then, the overall system can be studied as a non-cooperative game in which two decision-makers, i.e., players, have their actions and objectives. The first one, namely the attacker, wants to reach a targeted node in a graph starting from another node by adapting an exploration stochastic process based on current knowledge of its position in the graph related to the target; and the second one, the defender, modifies the graph topology to slow down the attacker by adding new links to deceive attacker's knowledge. A *Partially Observable Stochastic Game* (POSG) [4] seems natural to model such a competitive scenario. Several assumptions have to be discussed and are not trivial to answer:

- Does the attacker have knowledge of the entire topology?
- Does the defender know the position of the attacker in real-time?

The goal of this intern position is to start to deal with the PO models: first considering one decision maker and second, two decision makers in competition. The following steps will be considered:
1. To model the control of the exploration process with partial knowledge with a POMDP and to prove that the optimal control policy has a threshold for specific linear graph topology.
2. To generalize the results of task 1 for general acyclic graphs.
3. To model the problem with two decision-makers as a partially observable stochastic game.

Required skills

The candidate should have a scientific profile with very good skills in mathematics in Stochastic Optimization (dynamic programming techniques) and Graph Theory. Knowledge in Game Theory would be a plus.

Application procedure

Please send to yezekael.hayel@univ-avignon.fr your application containing the following items:

1. a cover letter written specifically for the topic, outlining their research interests and relevant experience,
2. a detailed CV,
   academic transcripts (including Bachelor & Master's/Engineering courses and rankings),
3. up to two reference letters from individuals who have supervised or worked closely with the applicant

Contacts

- Pr. Francesco DE PELLEGRINI, francesco.de-pellegrini@univ-avignon.fr
- Pr. Yezekael HAYEL, yezekael.hayel@univ-avignon.fr

References

[1] P. Charreaux, Y. Hayel, F. De Pellegrini, A. Reiffers-Masson, F. Sailhan, "Modeling Lateral Attack Containment via Honeypot Architectures in Virtualized Systems", proceedings of ValueTools, 2025.
[2] Q. Zhu, "Game theory for cyber deception: a tutorial". In Proceedings of the 6th Annual Symposium on Hot Topics in the Science of Security; 2019.
[3] E. Sondik, "The optimal control of partially observable Markov processes over the infinite horizon: discounted cost". Operations Research. **26** (2): 282–304, 1978.
[4] E. Hansen, D. Bernstein, and S. Zilberstein. "Dynamic programming for partially observable stochastic games." *AAAI*. Vol. 4. 2004.