Design of intelligent surveillance systems: a game theoretic case

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Introduction

- **Intelligent security** for physical infrastructures

  - *Our objective*: provide protection to physical environments with many targets against threats.

  - *Our means*: security resources.

  - *Our constraints*: resources are limited, targets are many

Introduction

- What's the challenge for a computer scientist?

- Design an intelligent system where autonomous agents are capable of providing **protection** against possible threats**:**
  - Detection: localize a threat;
  - Response: neutralize it.

- A strategy prescribes and describes what agents should do or would do:
  - *How to assign limited resources to defend targets?*
  - *What's the worst case damage that can be done in the environment when adopting some given strategy?*

- **Computing and characterizing effective strategies is a scientific/technological challenge**

Literature Overview

- Involved scientific communities include:

- Search Theory
  - **Contact investigation**: Stone and Stanshine, J. App. Math, 1971
  - **Search with false contacts**: Dobbie, Operations Research, 1973
- Operations Research
  - **Index policies for patrol**: Lin et al., Operations Research, 2013
- Game Theory
  - **Search Games:** Gal and Alpern, Int. Series in OR & Management Science, 2003
  - **Security Games**: Basilico and Gatti, Artificial Intelligence, 2012

Foundations

- Robotics
  - **Algorithmic queueing theory**: Bullo et al., IEEE Proceedings, 2011
  - **Variable resolution patrolling**: Basilico and Carpin, ICRA, 2012
  - **Live-fly validation of sensor model**: Carpin et al., JFR, 2013

Applications

Literature Overview

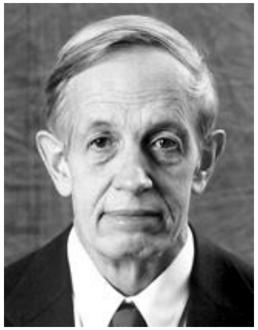
- Research can be roughly divided into two paradigms, depending on the kind of threat one assumes to face:

- **Strategic:** the threat is the output of a rational decision maker usually called adversary. The adversary can observe, learn and plan before deciding how to attack. *(Example: terrorists)*

- **Non-Strategic:** the threat is the output of a stochastic process described under probabilistic laws. *(Example: wildfires)*

Game Theory


John von Neumann


John Nash

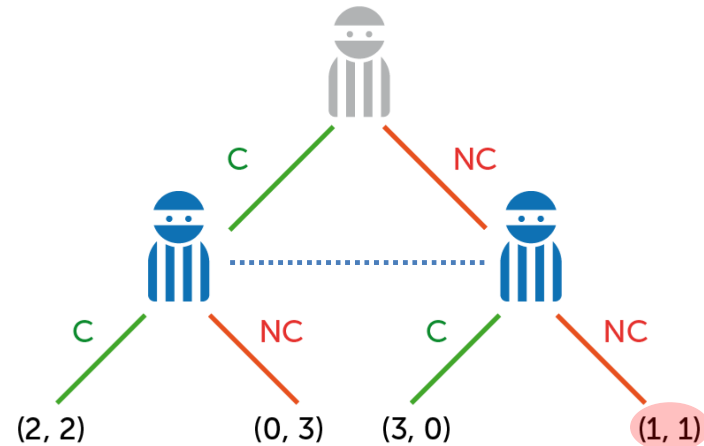
- Game Theory provides elegant mathematical frameworks to describe interactive decision making in multi-agent systems
- Applications: economics, business, political science, biology, psychology, law, urban planning
- It gives tools to define what intelligent and rational decision makers would do (solution concepts)
- The most popular solution concept: Nash Equilibrium (NE)

The Prisoner’s Dilemma

Strategic (normal) form

	C	NC
C	(2, 2)	(0, 3)
NC	(3, 0)	(1, 1)

Extensive form



- A **strategy profile** tells the probability with which each player plays some action
- Nash Equilibrium strategy profile: no player unilaterally deviates from its strategy
- How to use this formalism for security scenarios?

Security Games

Museum (value = 2)

Bank (value = 5)

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Defender:
its objective is to protect some areas

Attacker:
its objective is to compromise some area without being detected by the defender;

Security Games

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Attacker

Defender	Attacker: bank	Attacker: museum
bank	7 -1	0 2
museum	0 5	7 -1

Security Games

		Attacker: bank	Attacker: museum
Defender	bank	7 -1	0 2
	museum	0 5	7 -1

Nash Equilibrium:

D = {0.67; 0.33}, A = {0.5; 0.5})

What if the attacker can wait, observe, and **then** strike?

Security Games

Defender \ Attacker	bank	museum
bank	7, -1	0, 2
museum	0, 5	7, -1

Nash Equilibrium:
D = {0.67; 0.33}, A = {0.5; 0.5})

What if the attacker can wait, observe, and **then** strike?

Leader-Follower scenario

- The defender declares: "I'll go to the bank": commitment to **D = {1; 0}** (observability)
- The game has a trivial solution in pure strategies: **D = {1; 0}**, **A = {0; 1}** with payoffs (**0**,**2**)
- The Leader declares her strategy ex ante and knows that the follower will receive this information
- What's the best strategy to commit to?
  - It's never worse than a NE [Von Stengel and Zamir, 2004]
  - At the equilibrium the attacker always plays in pure strategies [Conitzer and Sandholm, 2006]

Computing a NE

- Zero-sum games: can be done efficiently with a linear program [von Neumann, 1920]

- General-sum games: no linear programming formulation is possible

- With two agents:
  - Linear complementarity programming [Lemke and Howson, 1964]
  - Mixed integer linear program (MILP) [Sandholm, Giplin, and Conitzer, 2005]
  - Multiple linear programs (an exponential number in the worst case) [Porter, Nudelman, and Shoham, 2004]

- With more than two agents?
  - Non-linear complementarity programming
  - Other methods

- Complexity:
  - The problem is in NP
  - It is not NP-Complete unless P=NP, but complete w.r.t. PPAD (which is contained in NP and contains P) [Papadimitrou, 1991]
  - Commonly believed that no efficient algorithm exists

Computing a LFE

- Zero sum games: linear programming

- General sum games:
  - Multiple linear programs (a polynomial number in the worst case) [Conitzer and Sandholm, 2006]
  - Alternative MILP formulations [Paruchuri, 2008]

Does it really work?

LAX checkpoints and canine units (2007)

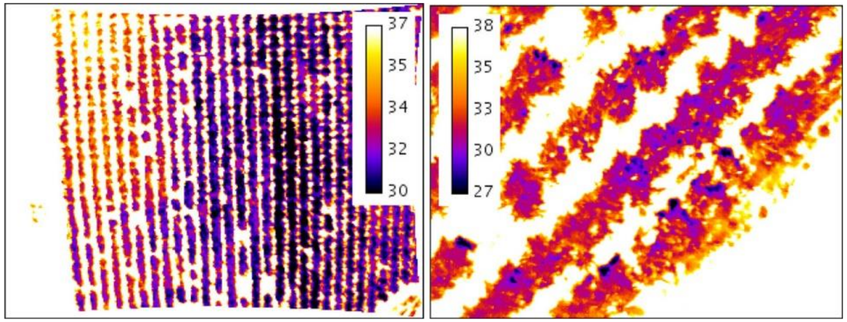
Boston coast guard (2011)

Federal Air Marshals (2009)

Our Scenario

- We assume to have an environment extensively covered with sensors (continuous spatially distributed sensing)
- Examples:

Forests



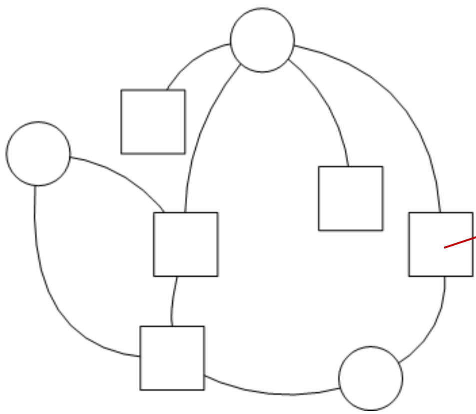
Agriculture fields

- These scenarios can require surveillance on **two levels:**
  - **Broad area level:** sensors tells that something is going on in some area (spatial uncertain readings);
  - **Local investigation level:** agents should be dispatched over the “hot” area to find out what is going on.

The Basic Model

- Idea: a game theoretical setting where the Defender is supported by an alarm system installed in the environment

- Environment: undirected graph



Target t:
- *v(t)* value
- *d(t)* penetration time: time units needed to complete an attack during which capture can happen

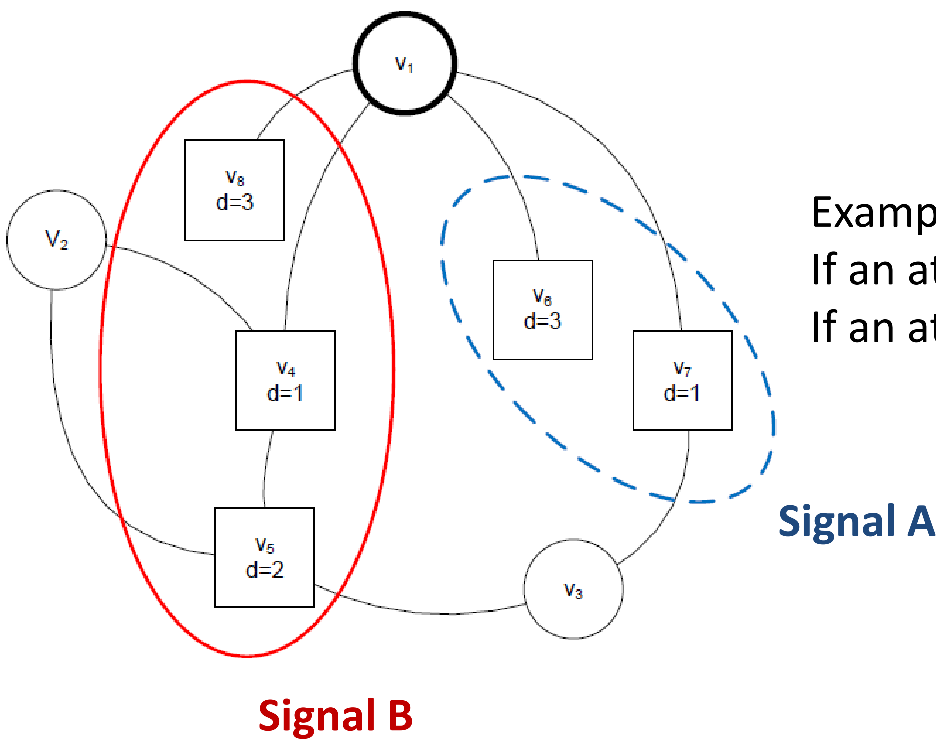
- At any stage of the game:

The Defender decides where to go next

The Attacker decides whether to attack a target or to wait

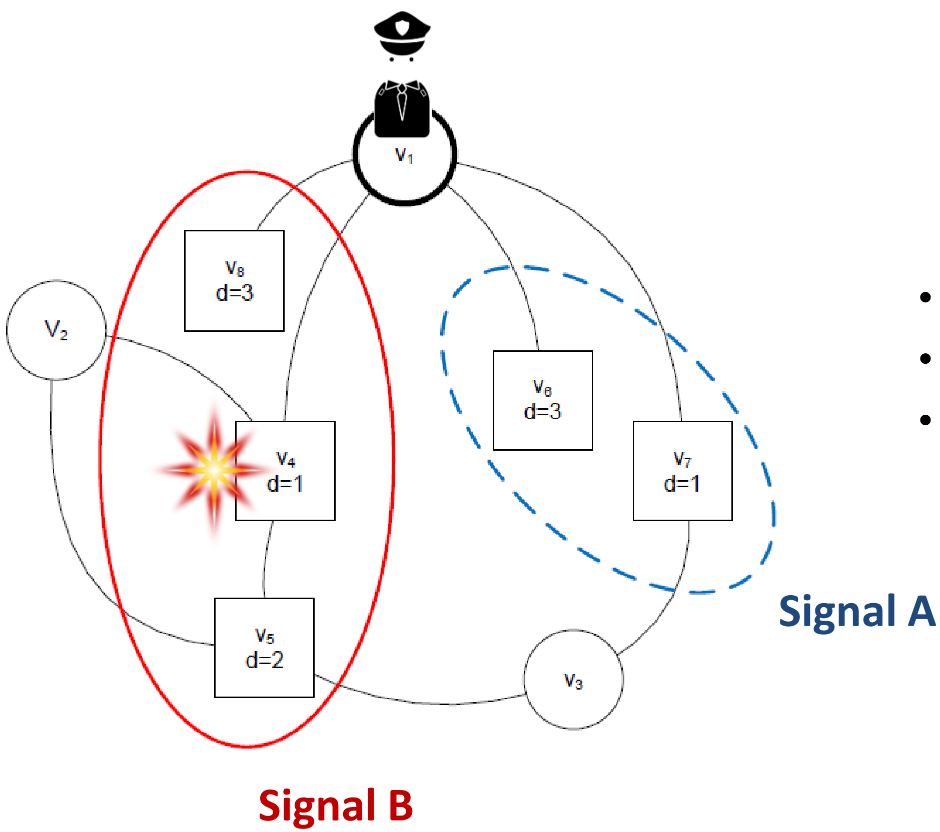
The Alarm System

- Each attack at a target t probabilistically generates a signal that is sent to the Defender
- If the Defender receives a signal it must do something (Signal Response Game)
- Otherwise it must normally patrol the environment (Patrolling Game)



Example (deterministic):
If an attack is present on tagets {8,4,5} generate B
If an attack is present on tagets {6,7} generate A

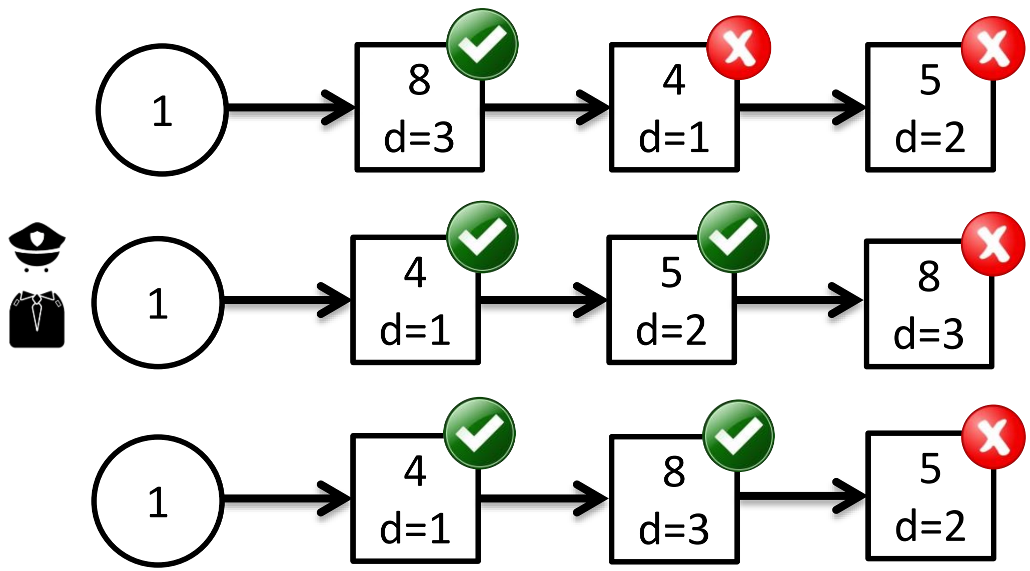
The Alarm System



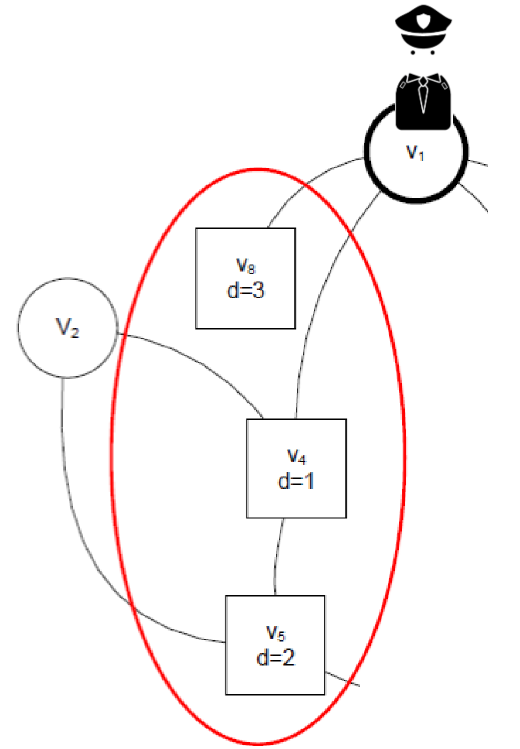
- The Defender is in 1
- The Attacker attacks 4
- The Alarm system generates with prob. 1 **signal B**

The Alarm System

- Upon receiving the signal, the Defender knows that the Attacker is in 8, 4, or 5
- In principle, it should check each target no later than d(t)



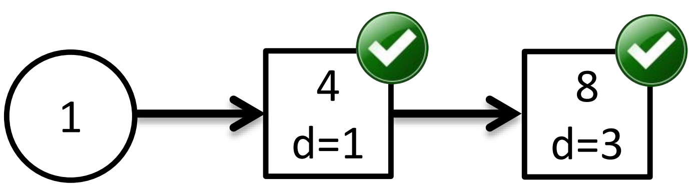
Covering routes



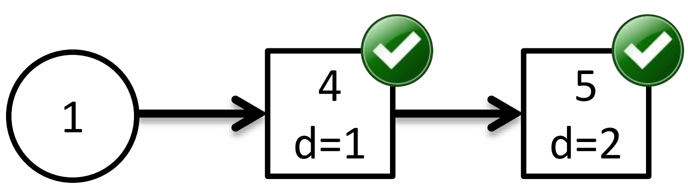
The Alarm System

- Covering routes: a permutation of targets which specifies the order of first visits (covering shortest paths) such that each target is first-visited before its deadline

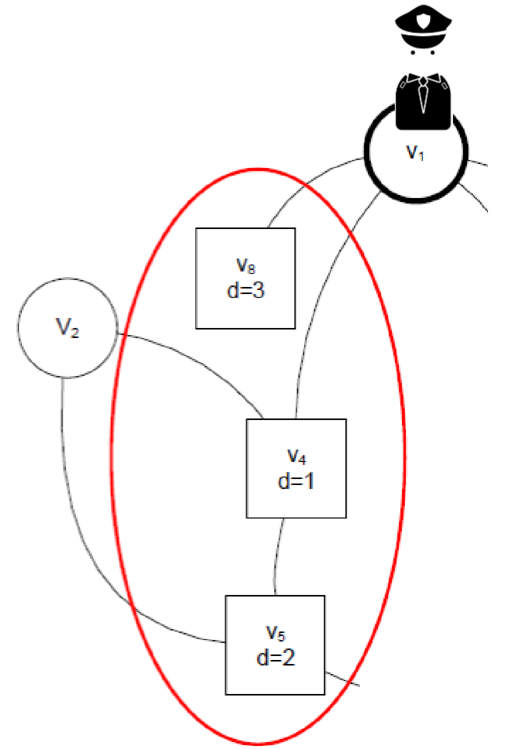
- Example



Covering route: **<4,8>**

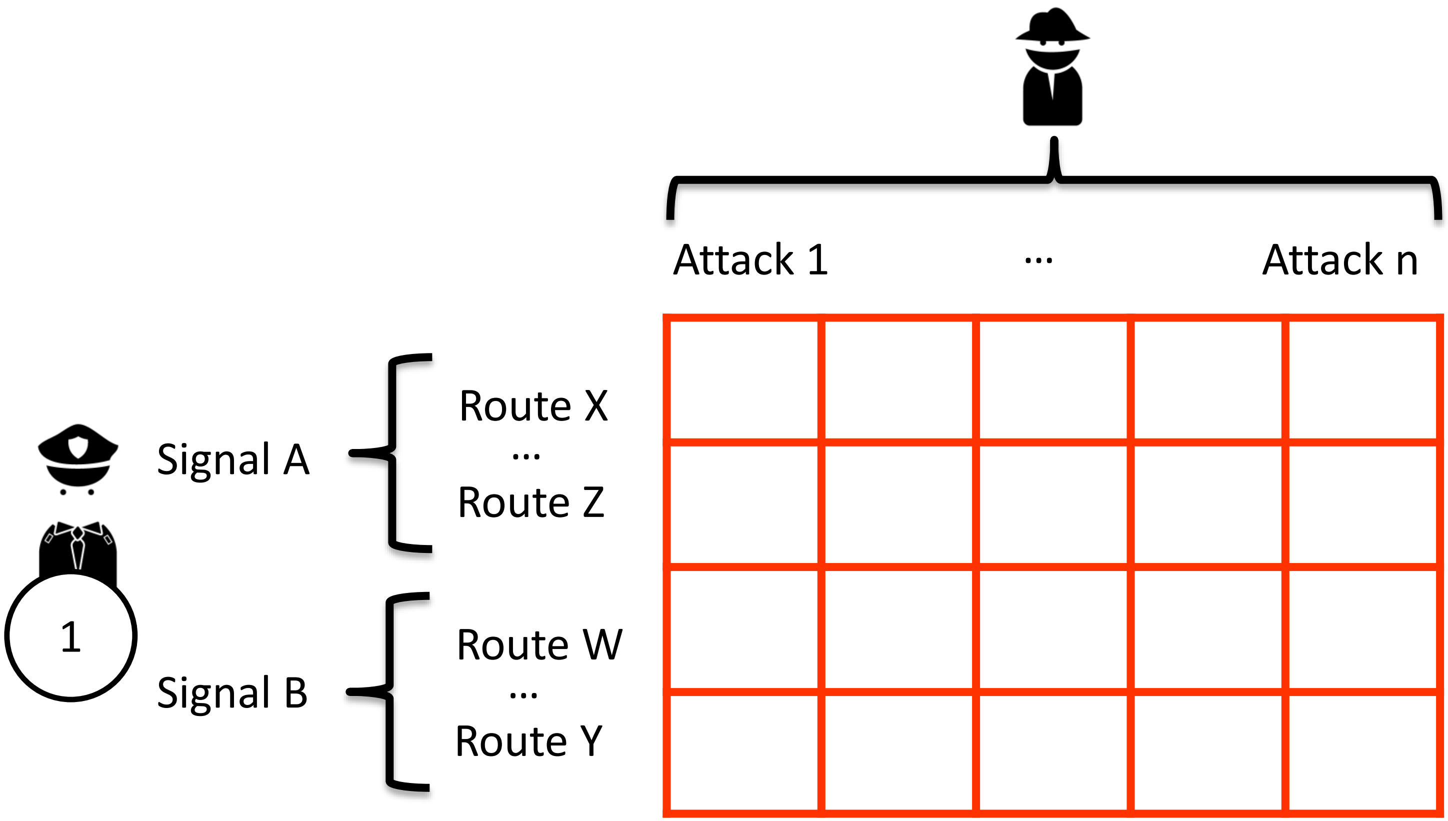


Covering route: **<4,5>**



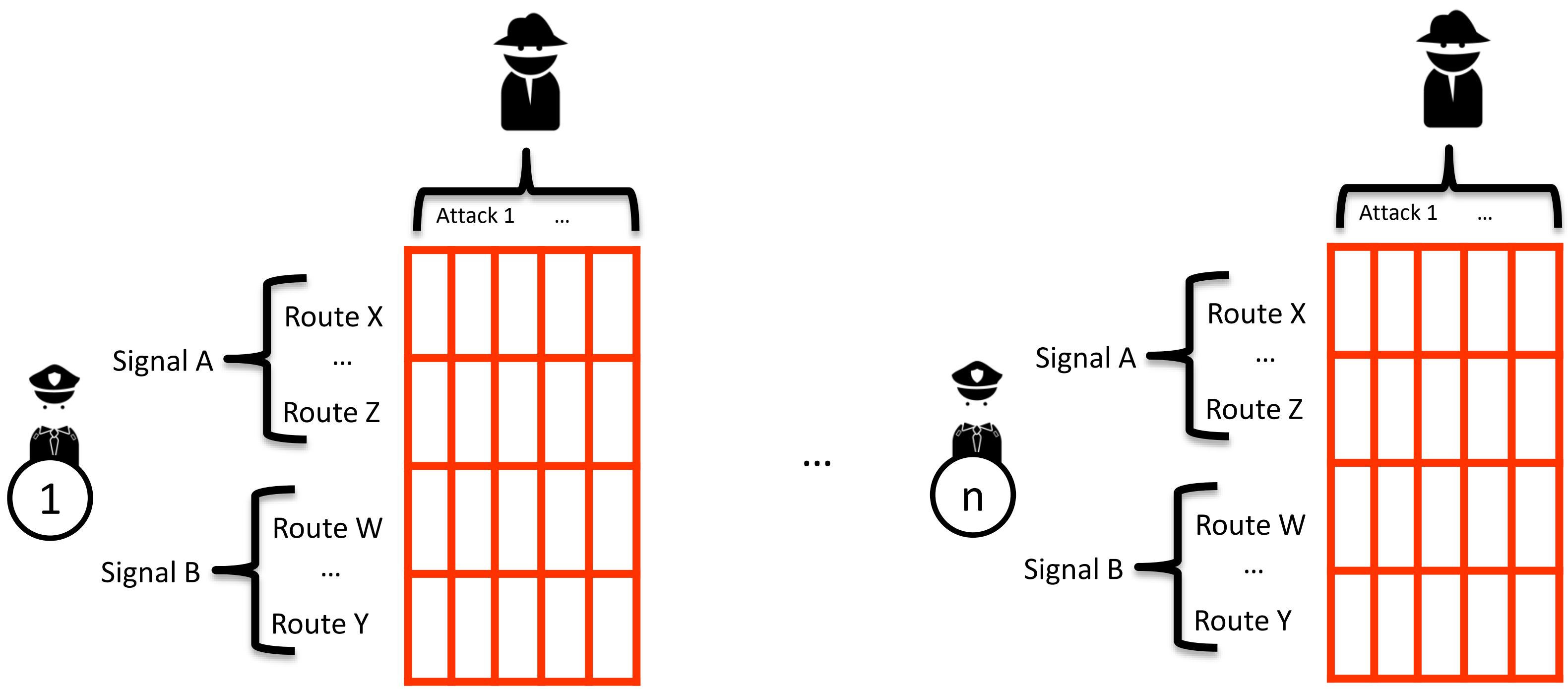
The Signal Response Game

- We can formulate the game in strategic (normal form), for vertex 1



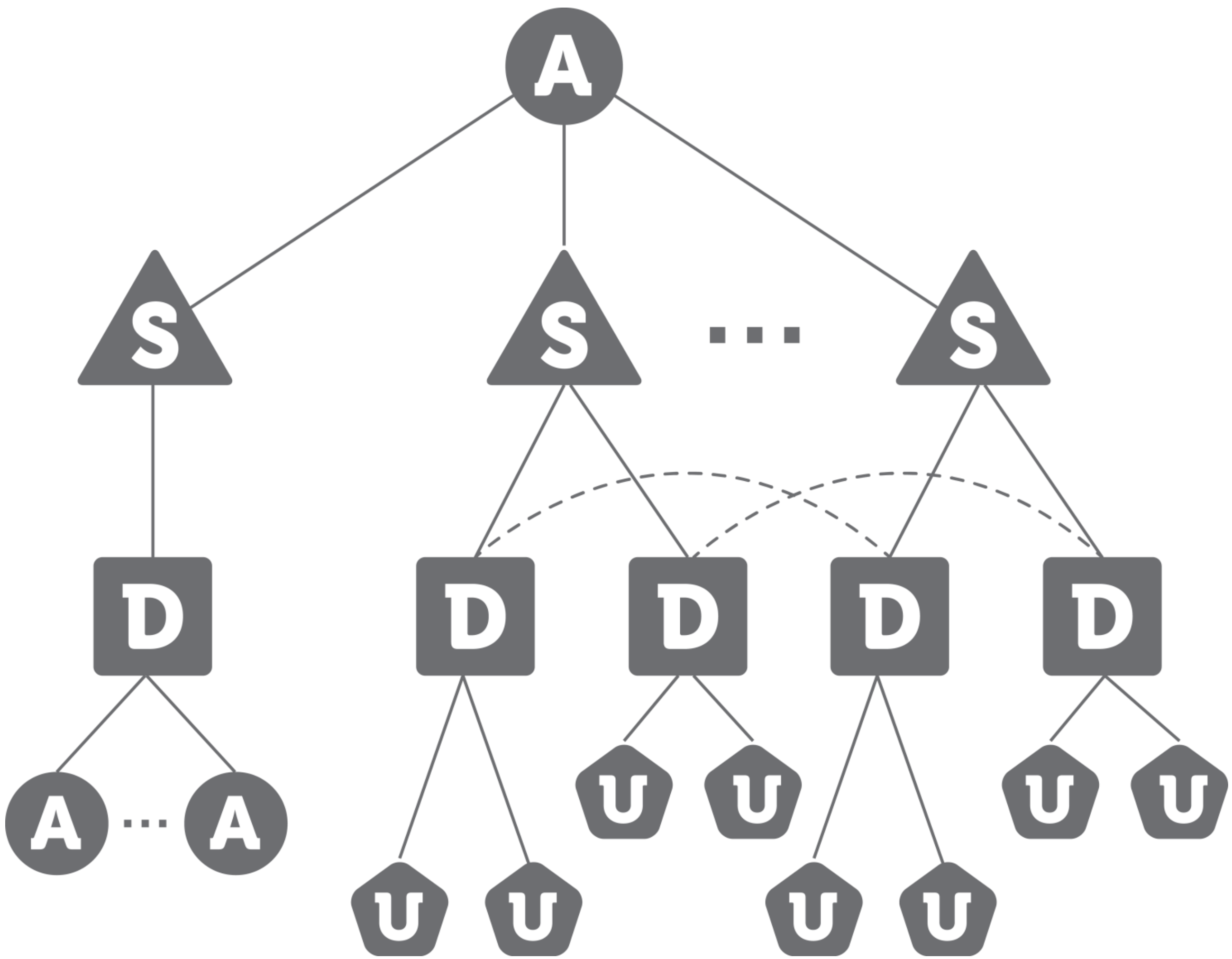
The Signal Response Game

- We can formulate the game in strategic (normal form), for all vertices

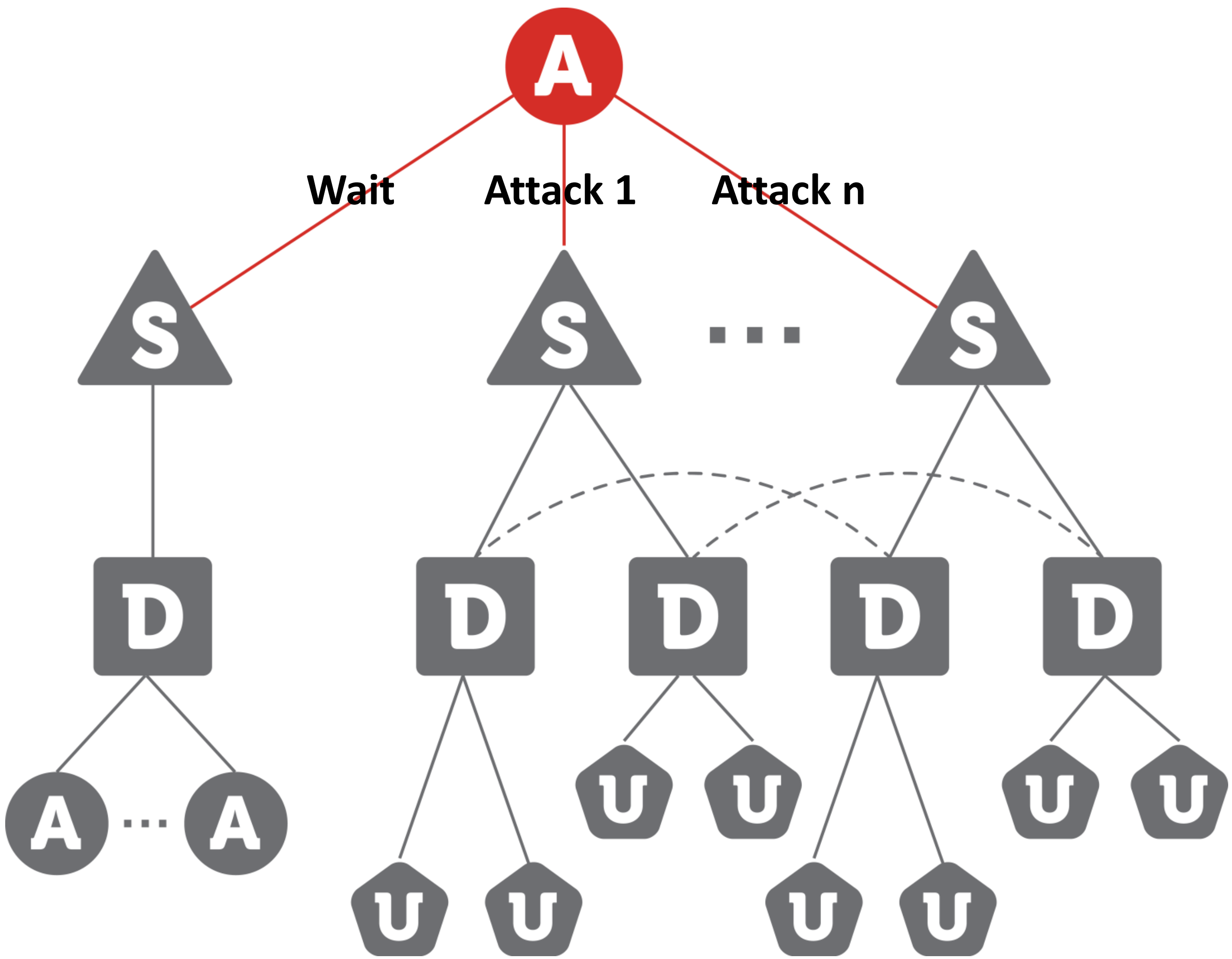


- Extensive form?

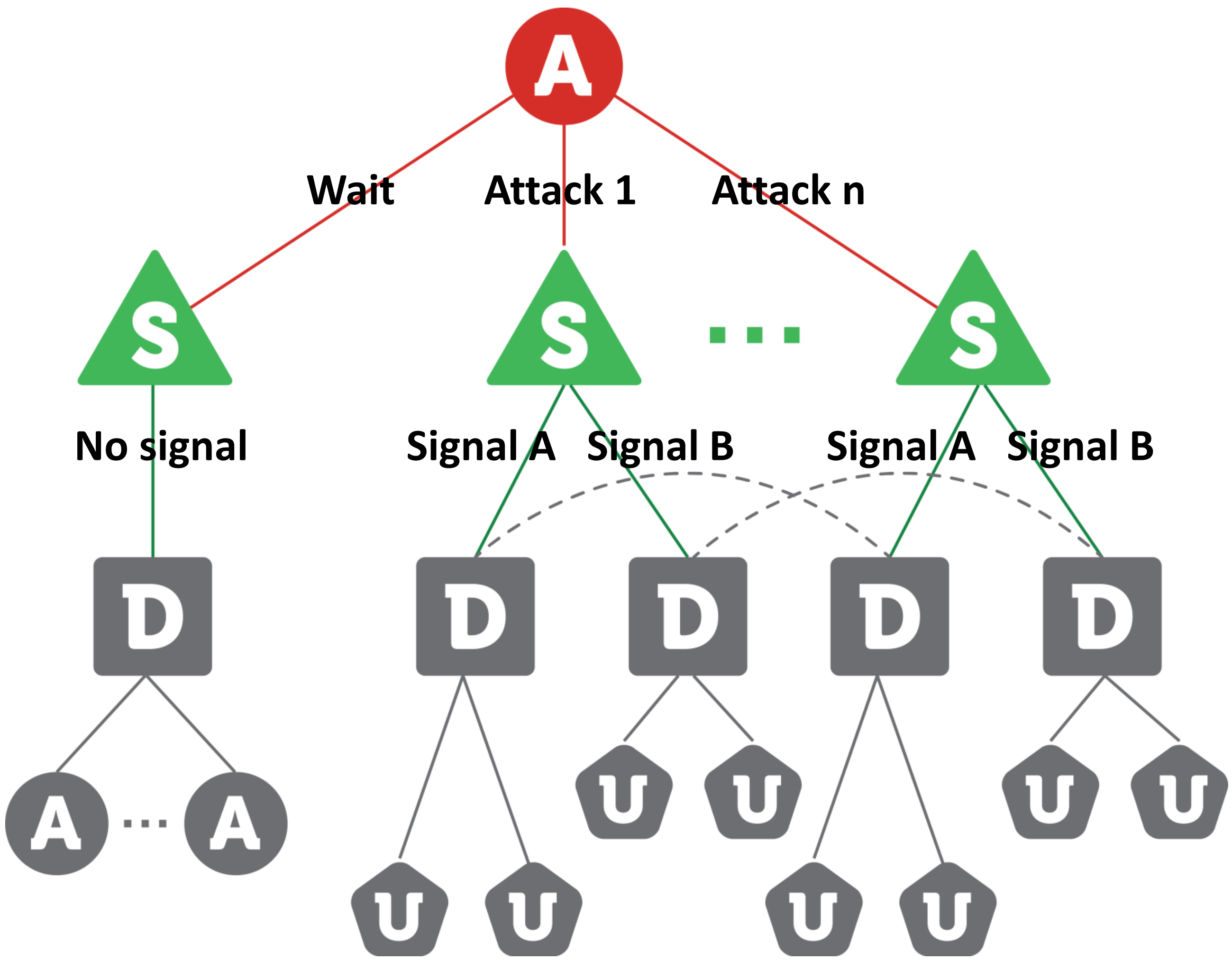
The Game Tree



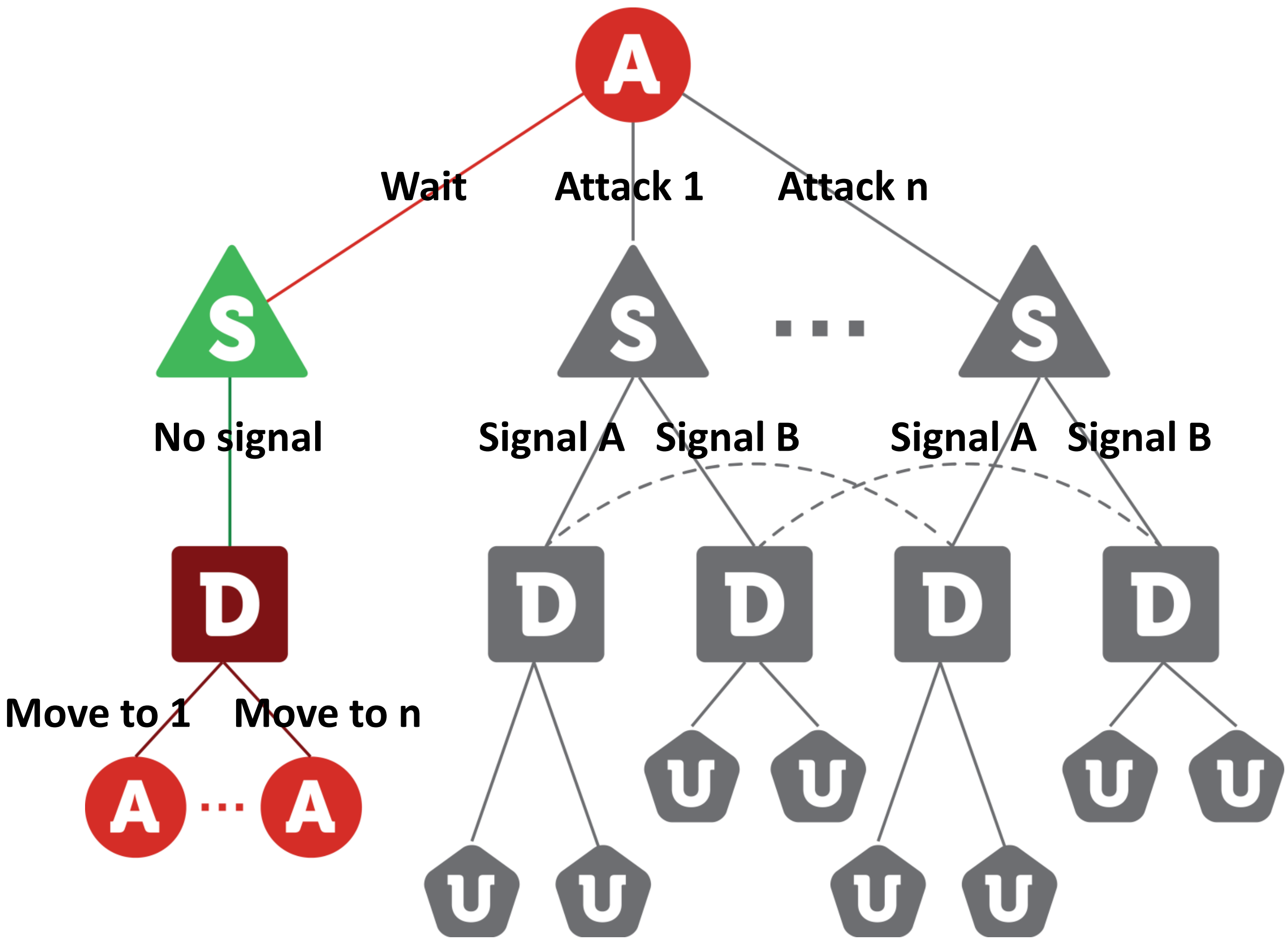
The Game Tree (Attacker)



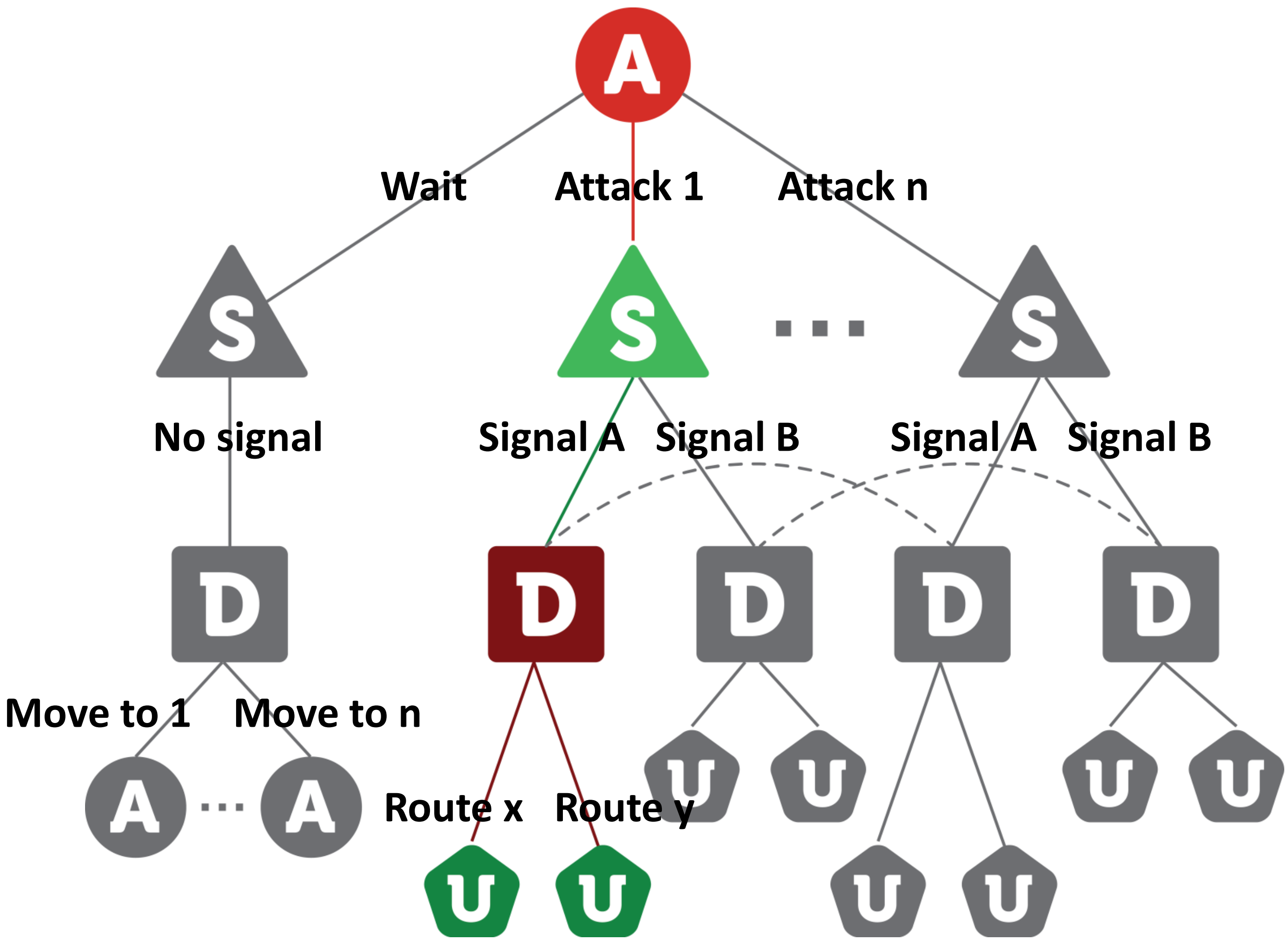
The Game Tree (Alarm System)



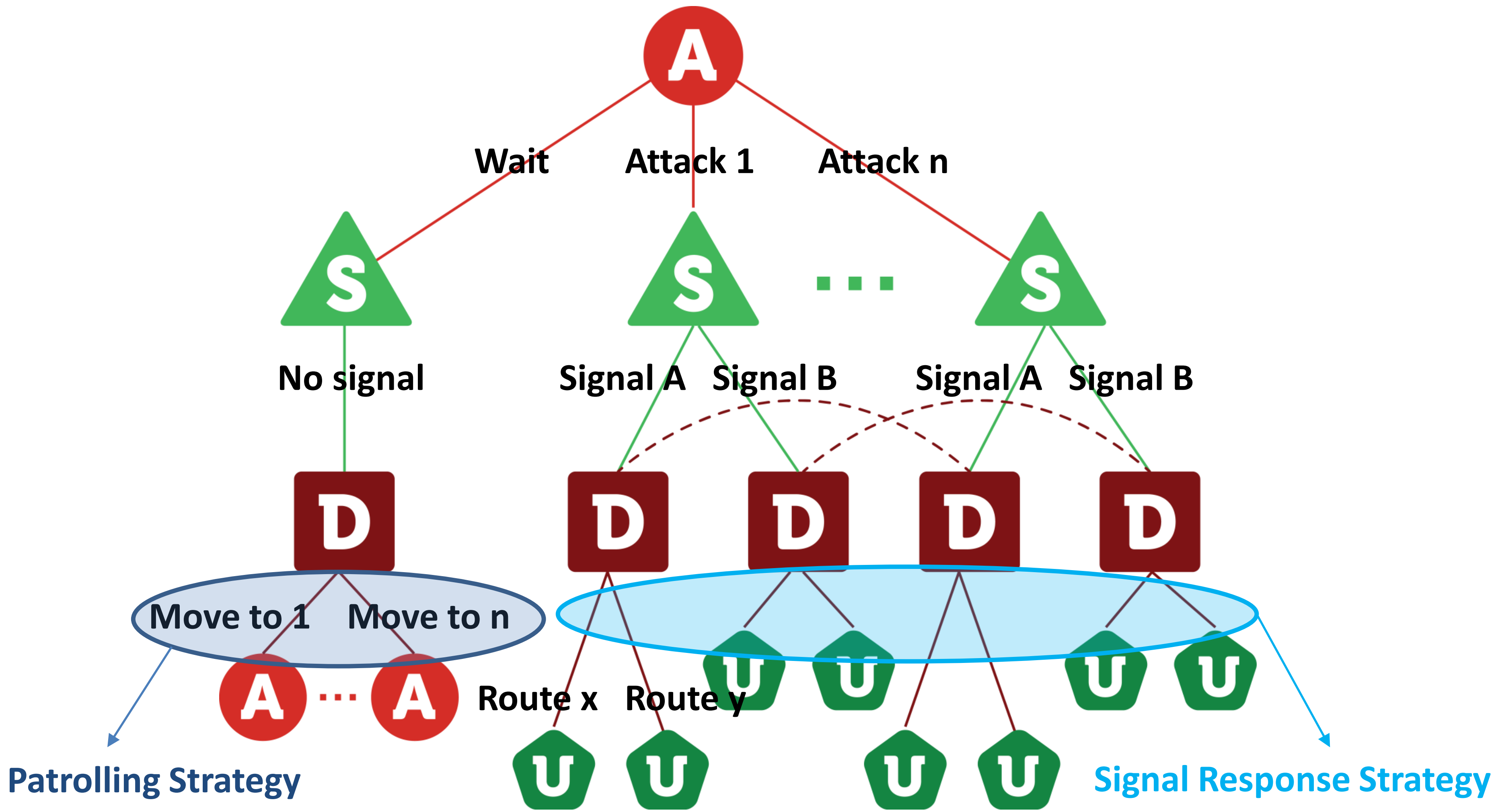
The Game Tree (Patrolling Game)



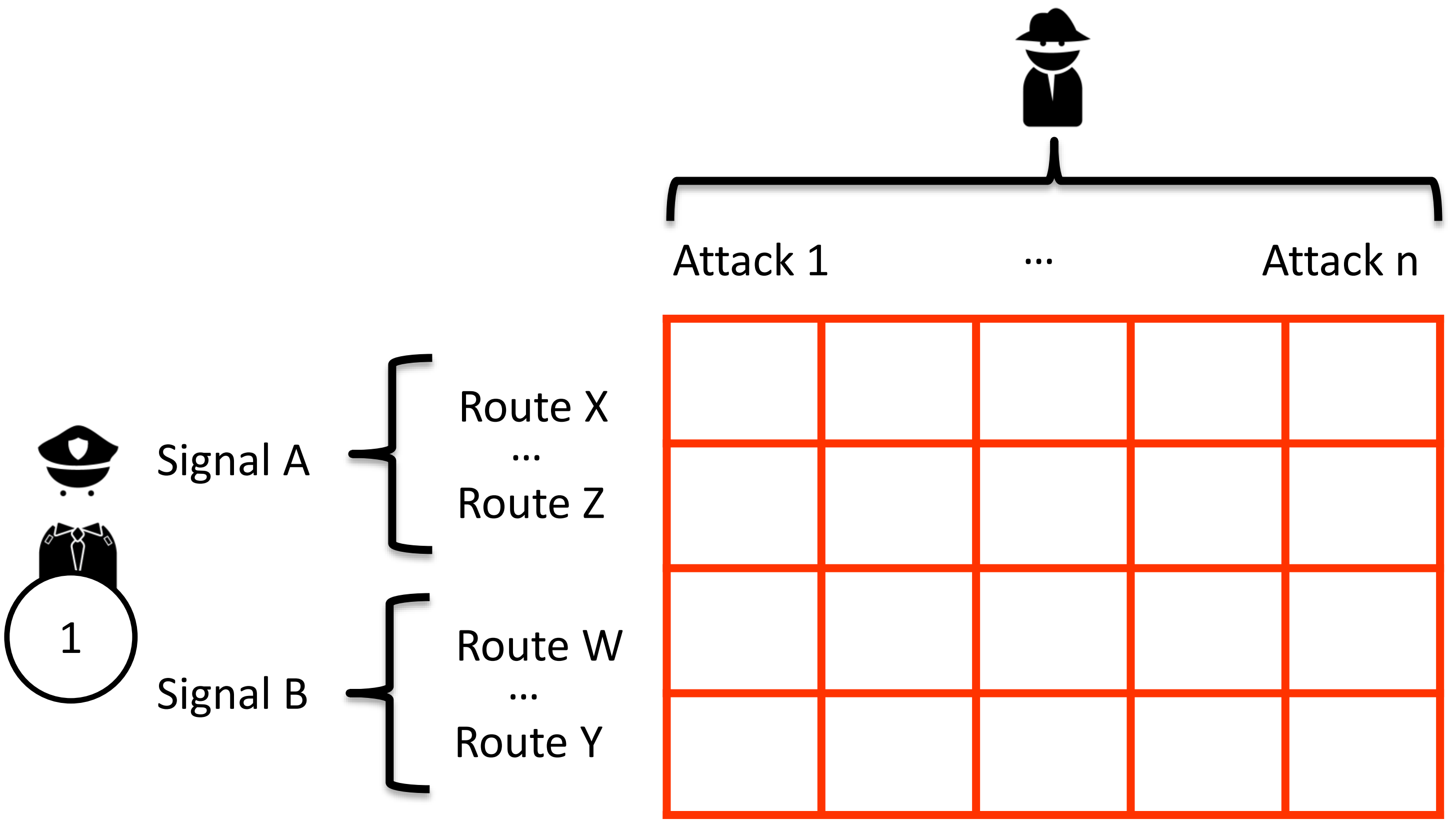
The Game Tree (Signal Response)



The Game Tree (Equilibrium Strategies)



Solving the Game



- Zero sum game: we can efficiently compute Nash Equilibrium ☺
- How many covering routes do we need to compute? ☹

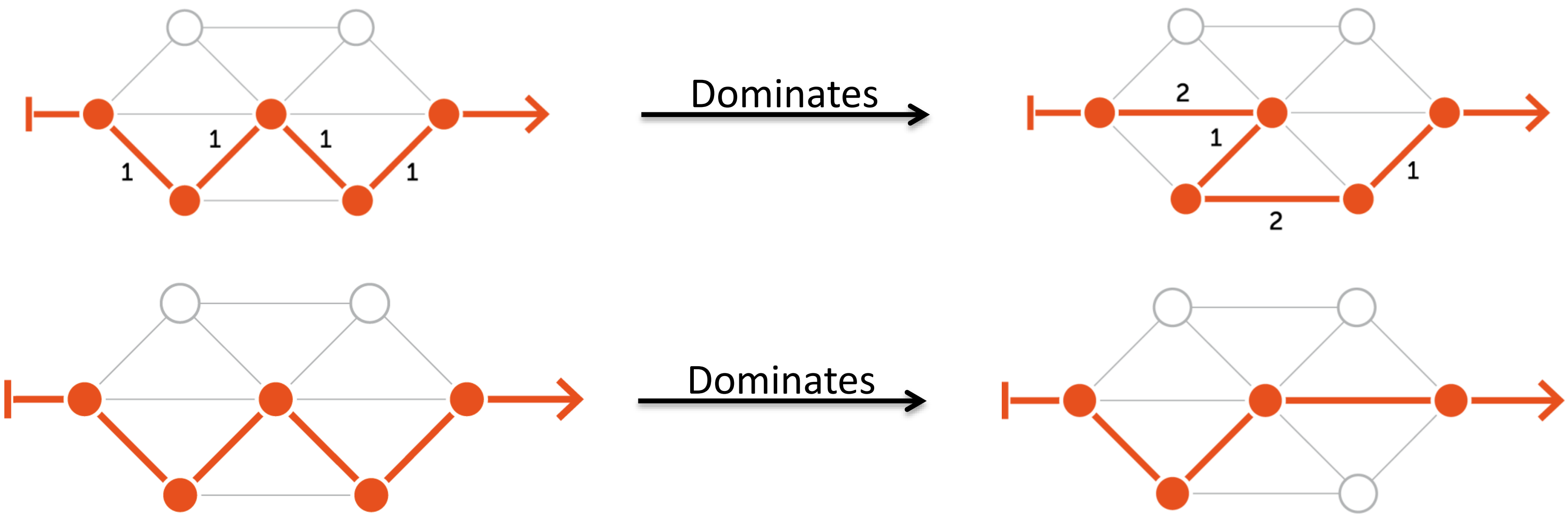
Building the Game

- The number of covering routes is, in the worst case, prohibitive: $O(n^n)$ (all the permutations for all the subsets of targets)

Building the Game

- The number of covering routes is, in the worst case, prohibitive: $O(n^n)$ (all the permutations for all the subsets of targets)

- Should we compute all of them? No, some covering routes will never be played



- Even if we remove dominated covering routes, their number is still very large

Building the Game

- Idea: can we consider **covering sets** instead?

From $\langle t_1, t_2, t_3 \rangle$ to $\{t_1, t_2, t_3\}$

- Covering sets are in the worst case: $O(2^n)$ (still exponential but much better than before)

- Problem: we still need routes operatively!

- Solution: we find covering sets and then we try to reconstruct routes

Building the Game

INSTANCE: a covering set that admits at least a covering route

QUESTION: find one covering route

This problem is not only NP-Hard, but also *locally* NP-Hard: a solution for a *very similar* instance is of no use. ☹☹

Building the Game

- Idea: simultaneously build covering sets and the shortest associated covering route
- Dynamic programming inspired algorithm: we can compute all the covering routes in $O(2^n)$!

Algorithm 1 ComputeCovSets (Basic)

$\forall t \in T, k \in \{2, \ldots, |T|\}, C_t^1 = \{t\}, C_t^k = \emptyset$
$\forall t \in T, c(\{t\}) = \omega_{v,t}^*, c(\emptyset) = \infty$
for all $k \in \{2 \ldots |T|\}$ **do**
  for all $t \in T$ **do**
    for all $Q_t^{k-1} \in C_t^{k-1}$ **do**
      $Q^+ = \{f \in T \setminus Q_t^{k-1} \mid c(Q_t^{k-1}) + \omega_{t,f}^* \leq d(f)\}$
      for all $f \in Q^+$ **do**
        $Q_f^k = Q_t^{k-1} \cup \{f\}$
        $U = Search(Q_f^k, C_f^k)$
        if $c(U) > c(Q_t^{k-1}) + \omega_{t,f}^*$ **then**
          $C_f^k = C_f^k \cup \{Q_f^k\}$
          $c(Q_f^k) = c(Q_t^{k-1}) + \omega_{t,f}^*$
        end if
      end for
    end for
  end for
end for

Is this the best we can do?
If we find a better algorithm we could build an algorithm for Hamiltionan Path which would outperform the best algorithm known in literature (for general graphs).

Building the Game (some numbers)

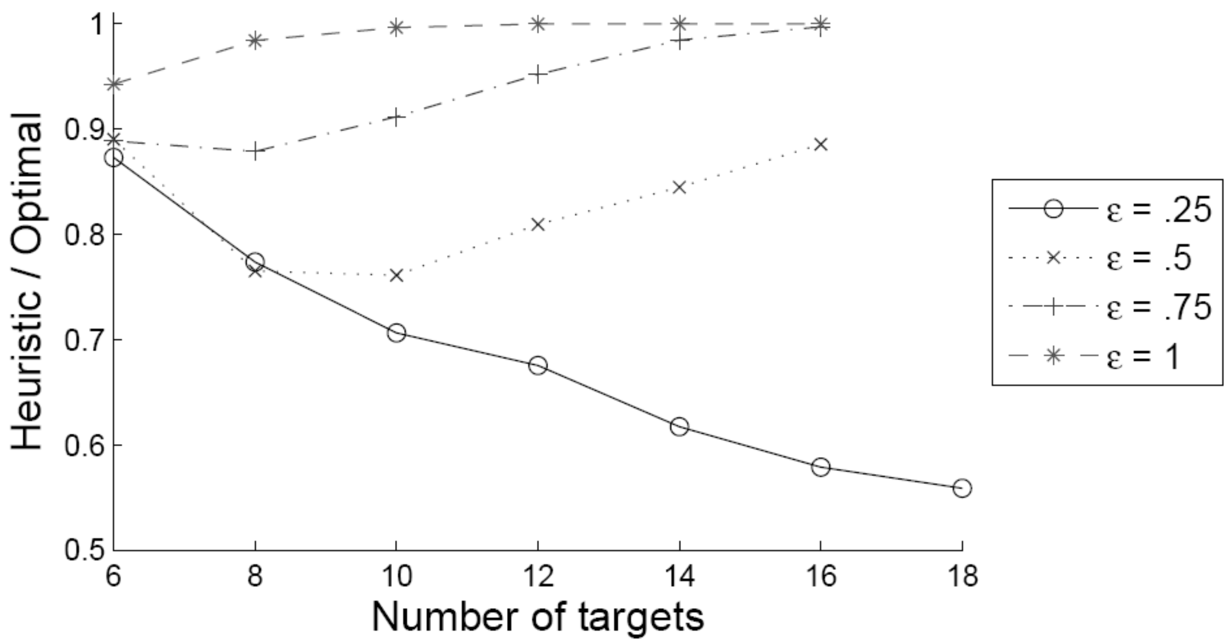
		$\vert T\vert$						
		6	8	10	12	14	16	18
ε	.25	0,07	0,34	1,91	11,54	82,26	439,92	**4068,8**
	.5	0,07	0,38	4,04	53,14	536,7	**4545,4**	≥ 5000
	.75	0,09	0,96	11,99	114,3	**935,74**	≥ 5000	≥ 5000
	1	0,14	1,86	17,46	143,05	**1073,**	≥ 5000	≥ 5000

- The edge density is a critical parameter. The more dense the graph, the more difficult to build the game.

		$\vert T(s)\vert$		
		5	10	15
m	2	-	17,83	**510,61**
	3	-	33	**769,3**
	4	0,55	35,35	**1066,76**
	5	0,72	52,43	**1373,32**

Building the Game (some numbers)

- Comparison with an heuristic sub-optimal algorithm.



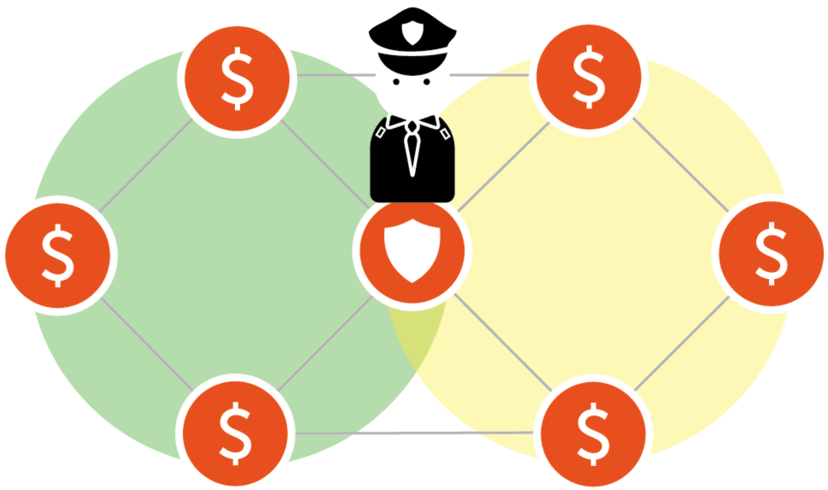
- Good news: the heuristic method seems to perform better where we the exact algorithm requires the highest computational effort

The Patrolling Game

- Solving the signal response game gives the Defender’s strategy on how to react upon the reception of a signal
- Patrolling game: what to do when no signal is received?
- It’s a Leader-Follower scenario: the Attacker can observe the position of the Defender before playing (we can solve it easily)
- What is the equilibrium patrolling strategy in the presence of an alarm system?

The Patrolling Game

- Suprising result
  - if the alarm system covers all the targets
  - if no false positive are issued
  - if the false negative rate below a certain threshold



- The equilibrium patrolling strategy is not to patrol! The Defender places at the most “central” vertex of the graph and waits for something to happen.
- If we allow false positives and arbitrary false negatives, things become much more complicated.

Open Problems

- Detection errors (false positive, false negatives) , can they be exploited by an attacker?
- Approximability: very unlikely, trying to prove non-approximability (APX-Hardness)
- Study Complexity of particular classes of graphs (trees, grids, etc…)
- Attackers with limited rationality
- Attackers with limited observation capabilities
- …